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Mylonite development in the Hercynian basement of Sardinia (Italy)

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Abstract—Plastic deformation predominates over large areas in the Hercynian basement of Sardinia during Lower Carboniferous continental shortening. Mylonitization associated with ubiquitous top-to-south-southwest thrusting decreases from internal (central Sardinia) to foreland areas (southern Sardinia). In the Barbagia unit, mylonites completely obliterate all the previous structures; in the Meana Sardo unit, plastic deformation strongly overprints early folds; and in the Gerrei unit, mylonites are found only below the Meana Sardo thrust. A thick shear zone, the Baccu Locci mylonite zone, develops between the Gerrei and Riu Gruppa units. Inferences from deformation mechanisms in quartz mylonites suggest a temperature during deformation below 400°C along thrusts throughout the study area. Overprinting relationships between foliations, deformation of annealed microstructures and porphyroblasts with inclusion patterns indicate that crystal growth occurred after early thrusting events and before the main nappe emplacement phase.

Microstructural investigations in the Baccu Locci mylonites record two changes in the main deformation mechanism operating during progressive mylonitization. In the early stages of deformation, most of the strain is accommodated by dislocation creep in a fine-grained quartz matrix. At higher strain, dynamic recrystallization fully affects larger quartz crystals, producing pure quartz layers where plastic deformation and strain localize. Ongoing deformation together with syntectonic breakdown of feldspar producing mica leads to mineral changes, grain size reduction and reaction softening with strain localization in the fine matrix again. Dynamically deformed quartz is boudinaged in the later stages of mylonitization. Significant fluid infiltration during deformation can account for some of the large ore bodies hosted in the Baccu Locci mylonites. © 1998 Elsevier Science Ltd.

INTRODUCTION

Thrusting and nappe emplacement during continental collision in Early Carboniferous times are well documented in the Hercynian basement of southeastern Sardinia (Fig. 1). Shear sense indicators along nappe contacts consistently indicate that top-to-southwest thrusting prevails (Fig. 2). Greenschist facies mylonites and cataclasites were first reported by Carmignani and Pertusati (1977) along the Villasalto thrust, and then along the Meana Sardo thrust (Carmignani *et al.*, 1982). Cataclasites along minor thrust planes in the Barbagia unit were described in Dessau *et al.* (1982), together with polyphase isoclinal folding. Later work (Carosi *et al.*, 1990b; Carosi and Pertusati, 1990) concluded that non-coaxial deformation usually occurred just below thrust planes, involving both syntectonic recrystallization of quartz and cataclasis.

The purpose of this paper is to demonstrate, based on detailed field work and microstructural observations, that widespread mylonite development occurs over large areas in the Hercynian basement of southeast Sardinia during crustal shortening and not only below the main thrust planes. Mylonitic deformation increases towards the northeast, and is responsible for the complicated internal structure of most tectonic units in the area. Mylonitic foliation is the most evident tectonic foliation in these rocks, and the changes of deformation mechanisms during mylonitization in the Baccu Locci mylonites are discussed.

REGIONAL SETTING

A complete section of the Hercynian basement, from non-metamorphic rocks to migmatites, outcrops along a southwest–northeast profile across Sardinia (Fig. 1). The weakly to non-metamorphosed rocks of the foreland area outcrop in south-western Sardinia (Sulcis–Iglesiente units). Greenschist facies metamorphosed rocks are well exposed east of the Tertiary Campidano graben in central and southern Sardinia. Amphibolite to high-grade

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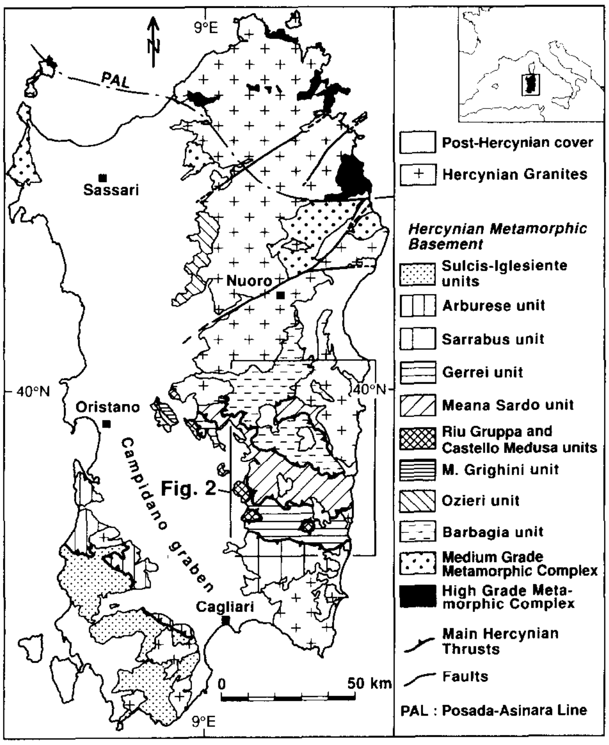


Fig. 1. Tectonic map of the Hercynian basement of Sardinia.

metamorphic rocks (gneisses, migmatites and eclogites) outcrop in the northern part of the island. Deformation in the Hercynian basement of Sardinia resulted from north–south collision, in present-day coordinates, between the Armorican and the Gondwana continents in Early Carboniferous times (Matte, 1986). The suture zone with oceanic crust remnants is now exposed in northern Sardinia along the Posada–Asinara line (Cappelli *et al.*, 1992). The Hercynian basement of central-southern Sardinia derives from deformation of the Gondwana margin (Carmignani *et al.*, 1994, also for complete reference list).

In southeastern Sardinia, the Hercynian basement is characterized by regional thrusting, southward nappe emplacement, km-scale isoclinal folding and syntectonic regional greenschist facies metamorphism. The presence of large-scale structures and nappe superposition has been well established over the past twenty years (Carmignani *et al.*, 1978, 1982, 1994). The deepest tectonic unit is the Castello Medusa–Riu Gruppa unit; directly above lies the Gerrei unit (Figs 2 & 3). The Gerrei unit is overridden by the Meana Sardo unit, in turn overthrust by the Barbagia unit. The southernmost unit is the Sarrabus unit, which lies above both the Gerrei and Meana Sardo units. After emplacement, the tectonic units of southeastern Sardinia suffered late-stage collisional deformation (Fig. 3c) that produced km-scale upright synforms and antiforms striking west-north-west–east-southeast (Flumendosa antiform and Barbagia synform), refolding older foliations and thrust planes. Figure 4 summarises the chronology.

After crustal thickening, all of the tectonic units underwent post-collisional deformation, late-orogenic extension and granite intrusion. Tectonic exhumation occurred through km-scale normal faulting, and vertical shortening led to overturned and recumbent folds (D_2), with northwest–southeast-oriented fold axes (Carmignani *et al.*, 1994). D_3 folding is present in the eastern part of the study area, with upright folds with northeast–southwest fold axes. Contemporaneous with granite emplacement, the Hercynian basement is affected by normal and strike-slip faulting, resulting in Upper Carboniferous–Lower Permian basin formation. The Mesozoic–Tertiary carbonate sequence unconformably overlies the Hercynian basement and shows little or no evidence of Alpine deformation, which is restricted to normal and strike-slip faulting along north–south faults. None of these post-collisional features (D_2, D_3, Alpine deformation) is discussed in this paper.

MYLONITIC DEFORMATION IN THE BARBAGIA, MEANA SARDO AND GERREI UNIT

The Barbagia unit consists of a thick monotonous sequence (apparent thickness > 2 km) of quartz-phyllites, schists and quartzites, with minor limestones and meta-volcanic rocks. Deformation and recrystallization have obliterated all of the primary features of these rocks, and fossil remains are very scarce (Vai and Cocozza, 1974; Dessau *et al.*, 1982). Polyphase deformation is well known in this unit, and two phases of isoclinal folding are described, together with mylonite development along its basal thrust, the Barbagia thrust (Dessau *et al.*, 1982; Carosi and Pertusati, 1990).

Field work in the area suggests major mylonitic deformation in the whole Barbagia unit, not only along the floor thrust. Highly-sheared rocks outcrop throughout, characterized by well-developed foliation, and north-northeast–south-southwest striking mineralogical and stretching lineations. The main regional foliation is a mylonitic foliation, and distributed non-coaxial plastic flow in the whole Barbagia unit is testified by consistent sense of shear (top-to-south) throughout the area (Fig. 2). Deformation style is characterized by large variations in strain intensity; less deformed pods of dominantly quartzites are surrounded by quartz-mylonites that form an anastomosing network. Isoclinal fold axes are nearly parallel to the stretching lineations, as is typical for mylonite belts, resulting from passive rotation of early buckle folds after large shearing strains (Escher and Watterson, 1974; Cobbold and Quinquis, 1980).

As most of this unit consists of quartz-rich rocks, syntectonic plastic deformation is clearly evident at outcrop scale in the form of the ductile deformation of quartz veins (Fig. 5a). In thin section, pure quartz layers show dynamic recrystallization of quartz through a rotation mechanism (Fig. 5b). No evidence of grain boundary migration recrystallization is found in the area, and following the calibration of Werling (1992) for

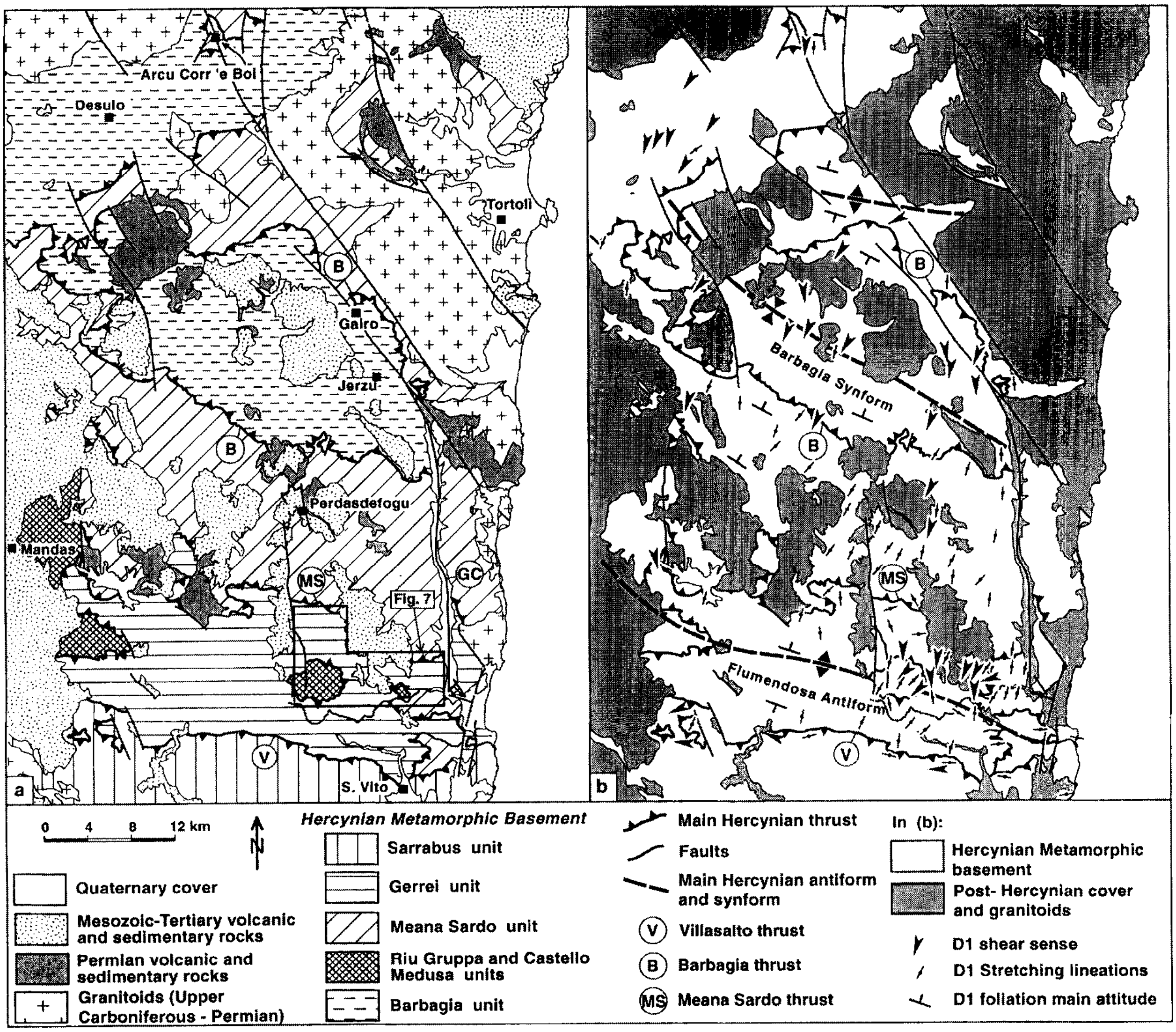


Fig. 2. (a) Tectonic map of the Hercynian basement of SE Sardinia, see Fig. 1 for location. (b) Structural map of the same area, showing D_1 stretching lineations and shear sense indicators in mylonites (from asymmetric porphyroclasts, shear bands, *S–C* fabrics, crystallographic preferred orientations, etc.). Arrows of shear sense indicators point to the transport direction of the hanging wall, irrespective of their plunge in the field.

the transition between rotation and grain-boundary-migration recrystallization, the temperatures did not exceed 400°C during deformation. Greenschist facies deformation is also indicated by syntectonic recrystallization of muscovite, quartz, albite and chlorite.

Plastic deformation and mylonitization are not only confined to quartz-rich rocks; they also affect carbonate rocks. Limestones have now been transformed into calcite mylonites, with a penetrative foliation and rotated porphyroclasts (Fig. 5c), indicating the occurrence of intense plastic deformation. The microstructures are those typical for calcite mylonites, with a strong shape preferred orientation of calcite crystals, lobate grain boundaries and diffuse twinning.

The Meana Sardo unit lies below the Barbagia unit and above the Gerrei unit (Fig. 2). Deformation here is not as strong as that in the Barbagia unit, but structural investigations of this tectonic unit (Bosellini and Ogniben, 1968; Minzoni, 1975; Carmignani *et al.*, 1982; Carosi and Pertusati, 1990; Gattiglio and Oggiano, 1990) reported, as in the Barbagia unit, isoclinal folding under greenschist facies conditions, producing a well-developed foliation and ubiquitous north-northeast–south-southwest-oriented stretching lineations. Fold axes are almost parallel to the stretching lineations, and folds often show the effects of strong shearing deformation. Fold limbs are extremely thinned, and completely sheared off folds hinges of the most competent formations (usually Ordovician metavolcanic rocks) are found in less competent, highly deformed rocks (Cambrian and Ordovician schists). The complicated internal structure of the Meana Sardo unit is usually regarded as resulting from isoclinal folding: instead, we infer that the mylonitic deformation prevails over large areas, and that isoclinal folds (syn-mylonitic) are only locally preserved in less deformed pods, totally enveloped by the mylonitic foliation. We regard these folds as having formed during continuous shear deformation and not as due to folding events.

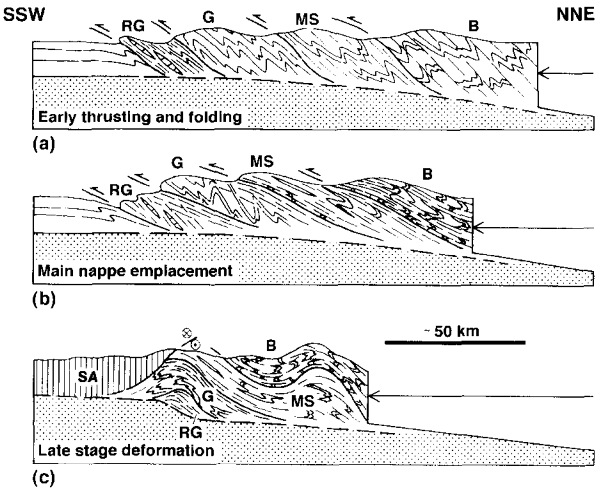


Fig. 3. Tectonic evolution of the Hercynian basement of SE Sardinia during continental collision, along a NNE–SSW profile. (a) Early overthrusting and folding stage: intense folding and pervasive mylonitic foliation develops in the Barbagia and Riu Gruppa units, and folding in the Gerrei and Meana Sardo units. (b) Main nappe emplacement stage: mylonitic deformation in the Barbagia and Meana Sardo unit, and foliation development in the Gerrei unit below the Meana Sardo thrust; small scale shear zones in the Riu Gruppa unit and development of the Baccu Locci mylonites. (c) Late stage deformation: large-scale, open antiforms and synforms, and no major recrystallization. RG: Riu Gruppa unit, G: Gerrei unit, MS: Meana Sardo unit, B: Barbagia unit, SA: Sarrabus unit, FA: Flumendosa antiform, BS: Barbagia synform.

TECTONIC SETTING	FEATURES	DEFORMATION PHASES	
Crustal thickening	Mylonitic deformation in the Barbagia and Riu Gruppa unit, folding and main regional schistosity in the Meana Sardo and Gerrei unit	D1	Early thrusting and folding
	Late mylonitic deformation, main foliation development in the Meana Sardo and Barbagia unit		Main nappe emplacement
	Antiformal stack, large-scale antiforms and synforms, crenulation cleavage		Late stage deformation
Tectonic exhumation	Normal faulting, NW-SE folds, crenulation cleavage	D2	
	NE-SW folds, crenulation cleavage	D3	

Fig. 4. Correlation of deformation events in the Hercynian basement of southeast Sardinia.

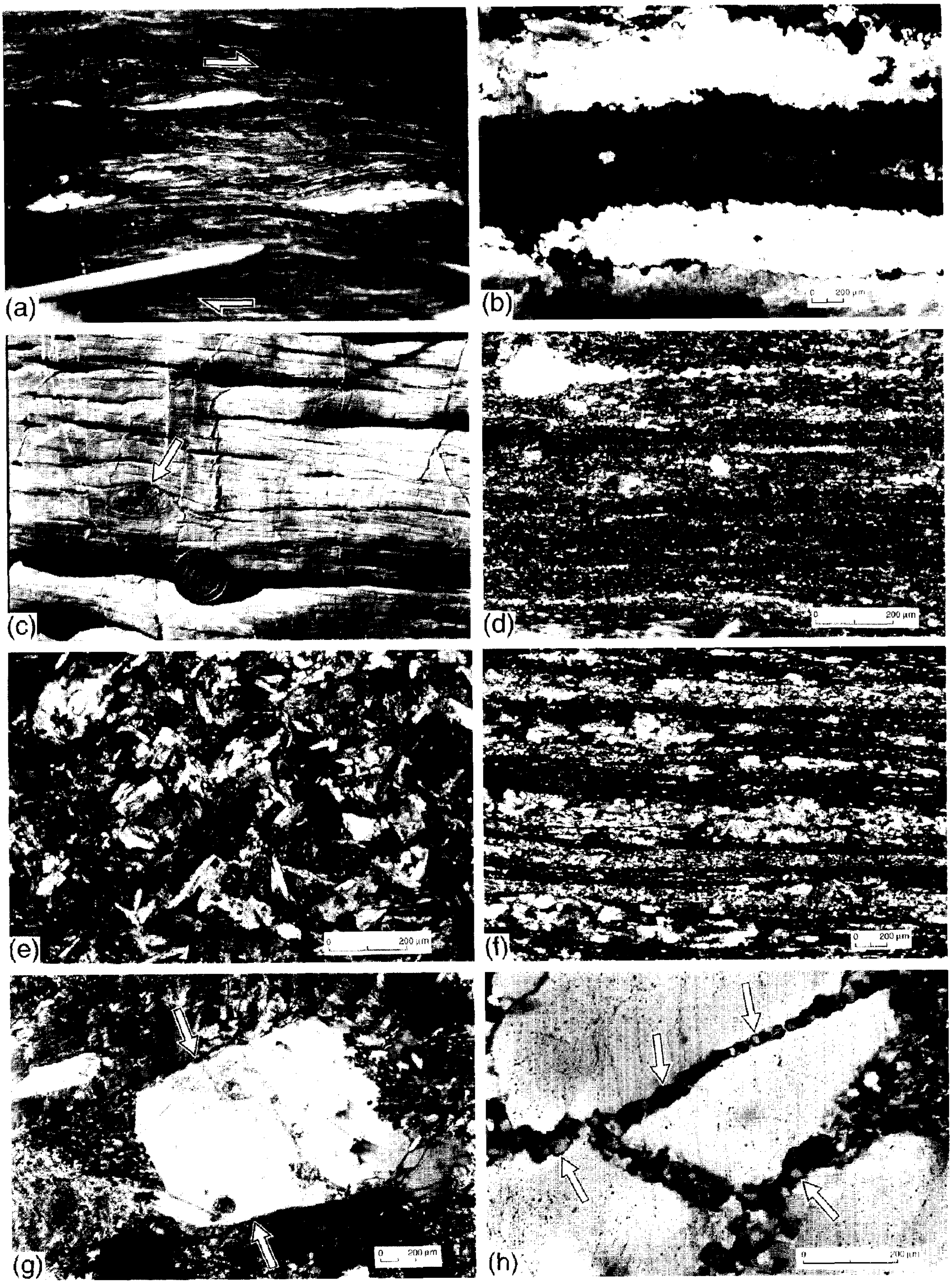
Mylonitic deformation in the Meana Sardo unit occurs by syntectonic dynamic recrystallization through subgrain rotation in quartz (Fig. 5d) and major microstructural changes in intermediate Ordovician volcanic rocks. In these rocks, the breakdown of plagioclase and mafic phases during mylonitization led to the formation of epidote–actinolite schists (Fig. 5e & f), with mica and accessory opaques, and light layers of quartz and albite-rich aggregates, in which the strain concentrates. Quartz and albite crystals are elongated (frequently long axis of 20–30 μm) and aligned parallel to the mylonitic foliation, suggesting that reactions involving plagioclase breakdown are not post-tectonic but occur during deformation. Since evidence of cataclasis is lacking in these rocks, viscous flow must be responsible for the deformation in the mixed albite–quartz layers. Crystal plasticity in quartz or in feldspar does not seem to be the dominant deformation mechanism, since no continuous monomineralic layers developed where recrystallization and shear deformation localized (Jordan, 1987; Handy, 1994). More likely is a viscous grain-boundary-sliding mechanism, involving mass transfer to accommodate sliding (Rutter, 1976; McClay, 1977; Stünitz and Fitz Gerald, 1993).

Emplacement of the Meana Sardo unit caused internal deformation in the underlying Gerrei unit. During the early thrusting stage (Fig. 3a), folding occurred in the Gerrei unit, producing km-scale anticlines and synclines, facing southwards. As deformation proceeded (Fig. 3b), a penetrative mylonitic foliation developed below and parallel to the Meana Sardo thrust, overprinting any earlier structure. In the Barbagia and in the Meana Sardo units, the mylonitic foliation developed during the main nappe emplacement stage is so intense that it obliterates any previous features. In the Gerrei nappe, relationships between early folding and thrust-related foliation are still preserved (Fig. 6).

THE BACCU LOCCI MYLONITES

Between the Gerrei and the underlying Riu Gruppa unit, a thick D_1 shear zone developed, the Baccu Locci mylonite zone (Fig. 7). Previous workers (Zucchetti, 1958; Schneider, 1972; Carmignani *et al.*, 1982; Bakos *et al.*, 1990; Gattiglio and Oggiano, 1990) mapped this area

Fig. 5. Shear-sense indicators and microstructures in mylonites from the study area. (a) Sheared quartz veins in the Barbagia unit near Jerzu indicating dextral (top-SW) shear. (b) Dynamically recrystallized quartz from a foliation-parallel quartz layer in the Barbagia unit, near Jerzu. Occurrence of subgrains indicates subgrain rotation to be the dominant recrystallization mechanism. Cross-polarized light. (c) Calcite–mylonite in the Barbagia unit, Arcu Correboi. Elliptical asymmetric quartz porphyroclasts (arrow) with tails and stair stepping geometry, indicating large shear deformation associated with dynamic recrystallization. Diameter of coin is 2.5 cm. (d) Dynamic recrystallization by subgrain rotation in quartz-mylonite in the Meana Sardo unit, near Cuccuru Is Argiolas, north-east of Perdasdefogu. This rock derives from the mylonitization of Ordovician acid volcanic rocks, large quartz grains of volcanic origin (upper left corner) are now completely recrystallized. Cross-polarized light. (e) Undeformed Ordovician volcanic rock (andesite) below the Barbagia thrust, East of Gairo. Cross-polarized light. (f) Mylonitized andesite rock below the Barbagia thrust, East of Gairo. Cross-polarized light. (g) Undeformed quartz crystal in acid metavolcanic rock from the Baccu Locci mylonites, near Baccu Locci. Resorption tubes in quartz indicate their volcanic origin. Dissolution acts on both sides of the crystal, with enrichment of insoluble material (arrows). Cross-polarized light. (h) Quartz porphyroclast in metavolcanic rocks from the Baccu Locci mylonites, near Baccu Locci. Narrow recrystallized bands through a quartz porphyroclast show alignment of subgrains and recrystallized grains (arrows). The undeformed large crystal is now separated into several parts. Cross-polarized light.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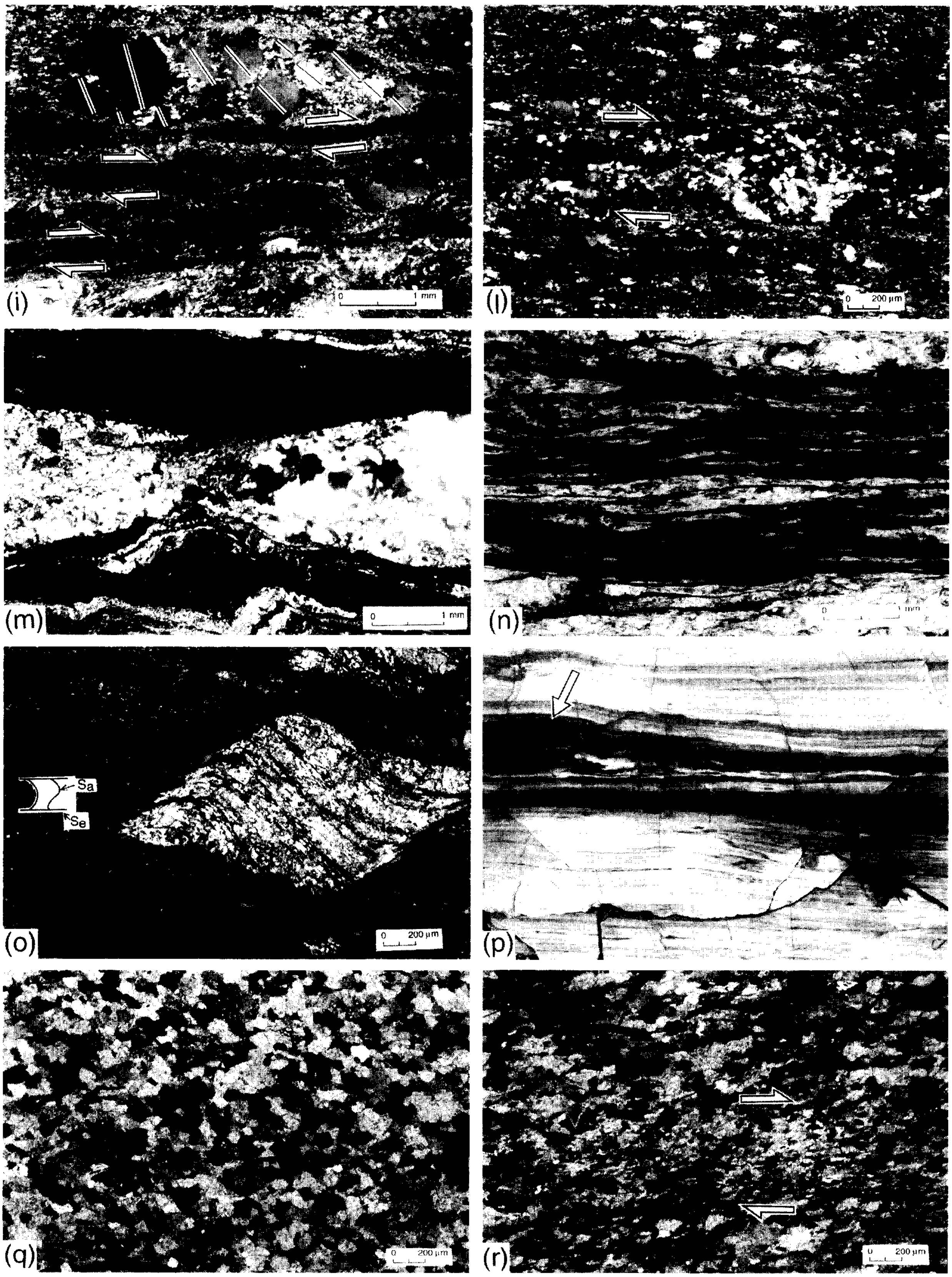
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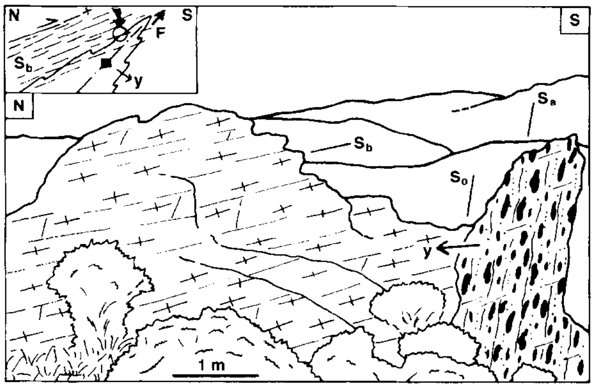

Fig. 6. Drawing after photograph of an outcrop in the Gerrei unit (North of Arcu'e Pesu, UTM coordinates 32SNJ38188168, see Fig. 7 for location) where the stratigraphic contact between Cambrian conglomerates ('Rio Ceraxa formation', on the right) and the younger metavolcanic rocks of the 'Porfiroidi formation' (on the left), is exposed. Normal limb of the D_1 Arcu 'e Pesu anticline. Two foliations are present in this outcrop, both folded by D_2 and D_3 folds: a steeply dipping foliation (S_a), parallel to the stratigraphic contact (S_0), cut by a spaced flat-lying crenulation cleavage (S_b). Field mapping has shown that S_b foliation is parallel to the Meana Sardo thrust and that the S_a foliation is the axial plane foliation (S_1) of the large-scale isoclinal D_1 folds in the Gerrei unit. S_b foliation is therefore thrust-related and developed during early stages of D_1 crustal thickening.

as a thick sequence of Silurian black shales and phyllites. We now regard this area as the final product of intense mylonitization of Cambrian sandstones and Ordovician volcanic rocks, the Baccu Locci mylonites. The Baccu Locci mylonites can be followed for more than 20 km along strike, from the Riu Corr 'e Cerbo to the Riu Gruppa valley. They outcrop near the hinge zone of the Riu Gruppa and Baccu Locci antiforms (Fig. 8), developed during the late stage of deformation of the D_1 phase (Figs 3c & 9). Antiforms refold the Gerrei unit, the Riu Gruppa unit and the Baccu Locci mylonites, which must therefore have developed during early D_1 stages.

The Baccu Locci mylonites are greenschist facies, fine-grained quartz-mylonites, usually of a black colour in the field. These mylonites surround less deformed bodies, up to 1.5 km long, of Ordovician metavolcanic rocks and Cambrian metasandstones, and subordinate slivers of Upper Ordovician and Silurian phyllites. Homogeneous plastic flow did not occur in the Baccu Locci mylonites: strain localized in an anastomosing network, that led to strong grain size reduction in the rocks. The fine-grained mylonites are the products of increasing strain as testified by a consistently penetrative mylonitic foliation, development of elongated quartz porphyroclasts, and boudinaged and dynamically recrystallized quartz veins, which appear to be less deformed outside the shear zones. The most deformed, fine-grained mylonites show a distinctive black colour. Syn-mylonitic folding occurred in the Baccu Locci mylonites: outcrop-scale isoclinal and sheath folds are present, and the mylonitic foliation is the axial plane foliation of folds. Due to polyphase folding during mylonitization, superposed foliations and older transposed foliations can often be recognized.

The contact of the Baccu Locci mylonites with the lower and upper tectonic units is not sharp, and a gradual transition can be observed into the Riu Gruppa and Gerrei units. The main mylonitic foliation in the Baccu Locci mylonites is parallel to the thrust-related foliation in the Gerrei unit, as can be recognized in the Riu Gruppa area. This observation, together with widespread NE–SW stretching lineations (Fig. 9f) and top-to-southwest sense of shear, lead us to infer that the Baccu Locci mylonites formed during the D_1 phase, contemporaneous with the emplacement and mylonite formation in the Meana Sardo and Barbagia units.

In order to gain information about the deformation mechanisms operating during mylonitization and the processes that led to the strong strain localization, microstructural investigations were performed on the Baccu Locci mylonites. Close attention was paid to the progressive mylonitization of these rocks, and for this purpose, profiles from the undeformed to the mylonitic rocks were sampled. Field observations indicate that strain and dynamic recrystallization localize preferentially where Ordovician metavolcanic rocks are present. Therefore, in the following we will deal with the progressive deformation of metavolcanic rocks, and

Fig. 5 (contd). (i) Recrystallized quartz porphyroclast in the Baccu Locci mylonites, near Baccu Locci. Porphyroclast has an elongate shape with undeformed and fully recrystallized areas. Only minor passive rotation has occurred in the unrecrystallized parts of the porphyroclasts, and they retain their original c-axes orientation (straight lines). Most recrystallization and strain occurred in pure quartz layers in the fine grained matrix (double arrows). Cross-polarized light. (l) Dynamically recrystallized quartz layer in the Baccu Locci mylonites, near Baccu Locci. Fully recrystallized quartz layers derive from complete recrystallization of porphyroclasts and not from grain growth of the matrix. Plastic deformation in quartz accommodated most of the strain in the rock. Cross-polarized light. (m) Boudinaged quartz layer, Baccu Locci mylonites, near Baccu Locci. Dynamically recrystallized quartz layers are now boudinaged, implying that the quartz is now stronger than the matrix. Plastic deformation in quartz is not the main deformation mechanism in this rock. Cross-polarized light. (n) Baccu Locci mylonite, near Baccu Locci. In the high strain areas, a well-developed mylonitic foliation is present. Black layers are phyllosilicate-rich layers where fine-grained oxides concentrate. Plane polarized light. (o) Albite porphyroblast in Ordovician intermediate volcanic rocks of the Riu Gruppa unit, below the Baccu Locci mylonites (south of Br.cu Stalladroxiu, see Fig. 7). Inclusions are straight in the centre of the porphyroblast, curved at the rim and in continuation with the external foliation (S_e). The porphyroblast grew over an existing foliation, and progressive deformation led to relative porphyroblast rotation with respect to a newly developed foliation (S_e) that obliterated the earlier foliation (S_a). Cross-polarized light. (p) Marble of the Sa Lilla complex in the Riu Gruppa unit along the Riu Gruppa river. Elongated dolomite boudins (arrow), rotated porphyroclasts, penetrative foliation and isoclinal folds parallel to stretching lineations indicate plastic deformation during large shear strain. Diameter of coin is 2.5 cm. (q) Marble of the Sa Lilla complex in the Riu Gruppa unit along the Riu Gruppa river, same outcrop as in (p). Static recrystallization in calcite destroyed earlier microstructure related to plastic deformation, and an isotropic fabric was formed. Cross-polarized light. (r) Shear zone in marbles of the Sa Lilla complex, along the Riu Gruppa river. Dynamic recrystallization postdates thermal peak and obliterated the annealed microstructure. Calcite grain size decreases from the shear zone boundary to its centre and develops an oblique grain shape preferred orientation (dextral shear in the photograph). Cross-polarized light.

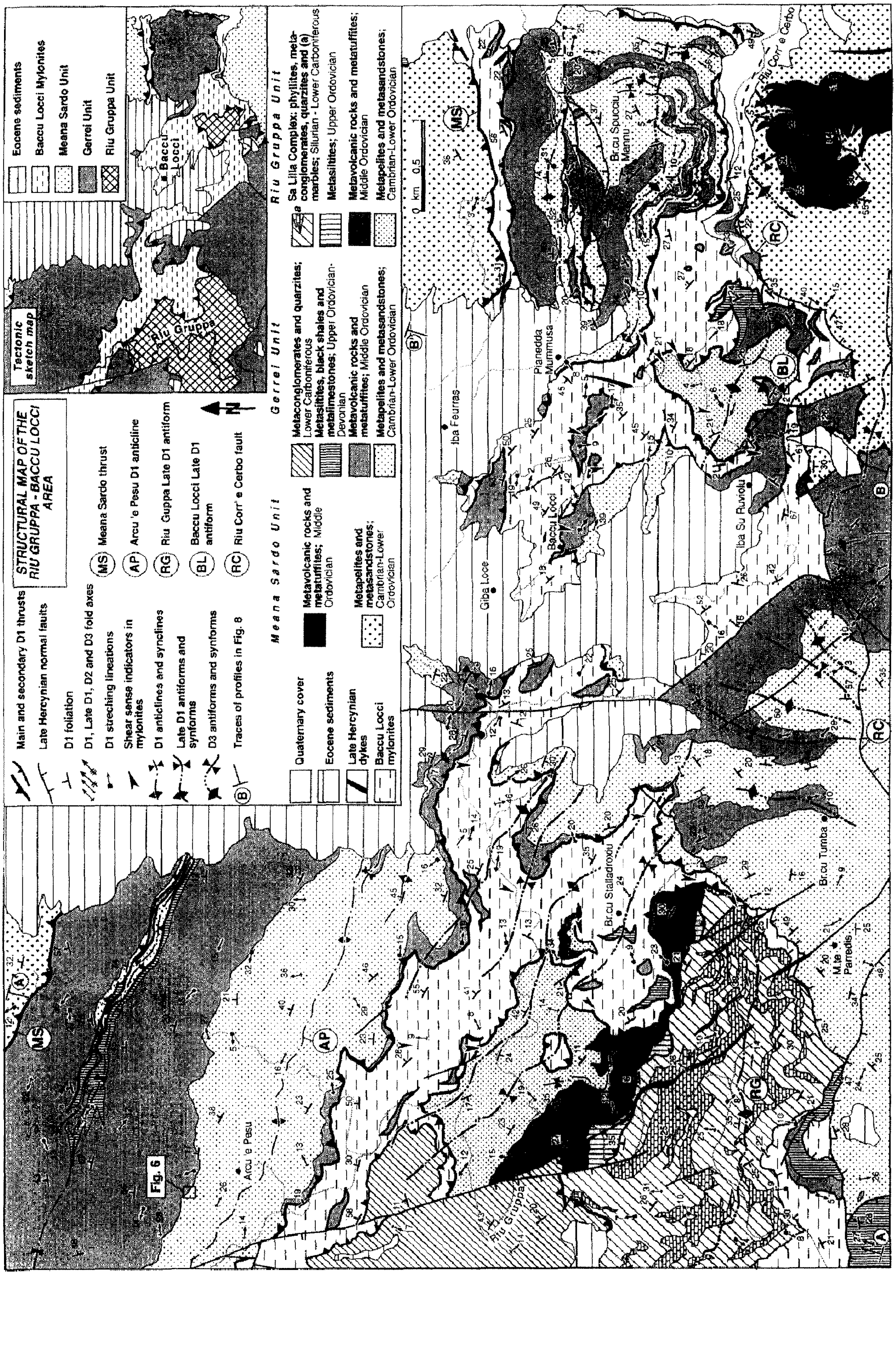

Fig. 7. Structural map of the Riu Gruppa–Baccu Locci area. See location in Fig. 2. Structural data from this area are plotted in Fig. 9.

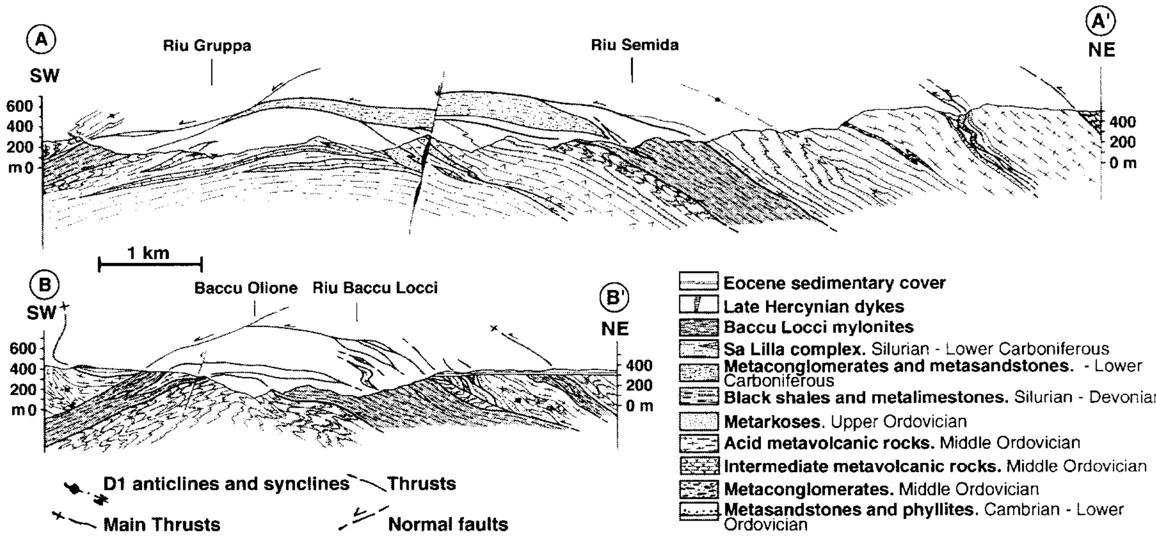

Fig. 8. Profiles in the Riu Gruppa–Baccu Locci area. See Fig. 7 for profile traces.

give microstructural descriptions of the process from undeformed to mylonitic rocks.

Ordovician volcanic rocks are frequently present as isolated lenses in the Baccu Locci mylonites. Less deformed bodies show many of the primary characteristics of the rock, with a fine matrix, almost unresolvable with the optical microscope, and large (average diameter 2–3 mm) subhedral quartz crystals (Fig. 5g), which can sometimes represent about the 30% of the total volume of the rock. Large feldspar porphyroclasts (2–3 mm) are subordinate. Deformation is restricted to dissolution around quartz crystals.

At larger strains, we observe dynamic recrystallization and a grain-size increase in the quartz-rich fine matrix along narrow bands, with quartz crystals of average size of 15–25 μm. Plastic deformation in these layers is testified also by a strong crystallographic preferred orientation. In the large quartz porphyroclasts, only

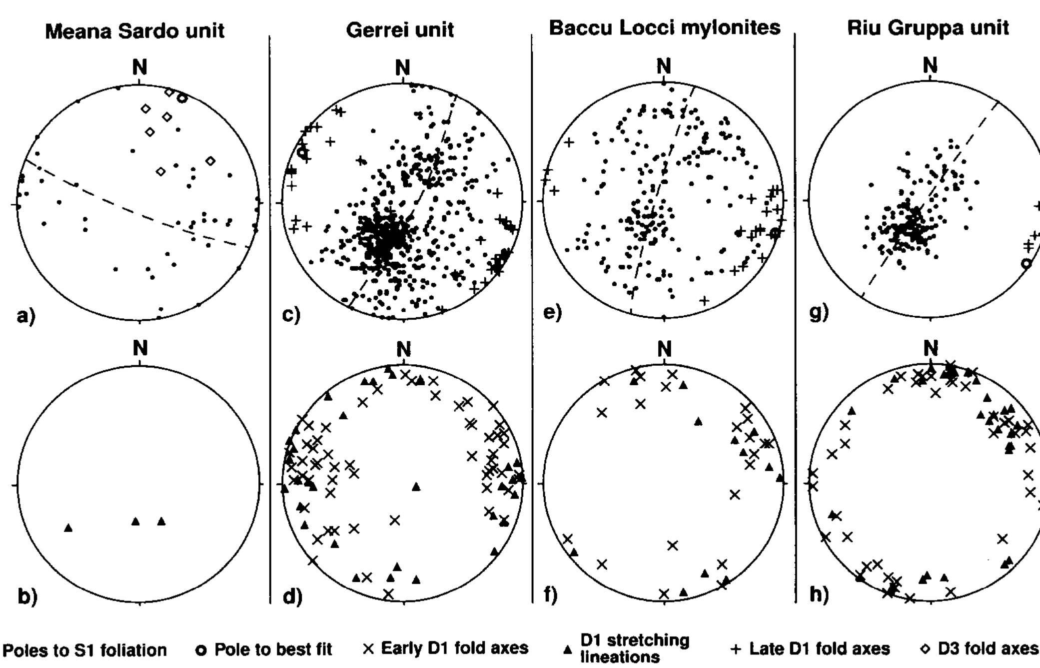

Fig. 9. Stereographic projections of structural data (equal area, lower hemisphere) from the Riu Gruppa–Baccu Locci area (Fig. 7). (a) Meana Sardo Unit: poles to S_1 foliation (40 data), D_3 fold axes (6 data), pole to best fit circle N22/6; (b) Meana Sardo unit: D_1 stretching lineations (3 data); (c) Gerrei unit: S_1 foliation (579 data), late D_1 fold axes (46), pole to best fit circle N296/8; (d) Gerrei unit: early D_1 fold axes (65 data), D_1 stretching lineations (29 data); (e) Baccu Locci mylonites: S_1 foliation (257 data), late D_1 fold axes (21 data), pole to best fit circle N106/5; (f) Baccu Locci mylonites: early D_1 fold axes (21 data), D_1 stretching lineations (12 data); (g) Riu Gruppa unit: S_1 foliation (167 data), late D_1 fold axes (5 data), pole to best fit circle N125/2; (h) Riu Gruppa unit: early D_1 fold axes (42 data), D_1 stretching lineations (34 data).

low-temperature crystal plasticity (dislocation glide) occurs, resulting in undulose extinction and deformation bands.

Increasing deformation led to syntectonic recrystallization of quartz porphyroclasts. Rotation recrystallization starts with subgrain and recrystallized grain formation along planes dissecting the porphyroclasts. Ongoing recrystallization along these planes led to the formation of fine-grained dynamically recrystallized bands in the quartz porphyroclasts (Fig. 5h). At low strain, porphyroclasts preserve their globular aspect, even though they are now formed by smaller disconnected quartz crystals (Fig. 5i). At this stage of deformation, syntectonic recrystallization in quartz porphyroclasts does not accommodate most of the strain in the rock. The small quartz grains deriving from larger porphyroclasts do not suffer any rigid body rotation, and all the grains still show the same original crystallographic orientation (Fig. 5i). This requires that most of the strain is accommodated in the fine-grained matrix. The quartz-phyllosilicate matrix is now fully recrystallized, and thin pure quartz ribbons are present throughout the rocks. It is very likely that strain localized in these plastically deformed quartz layers, leaving the rest of the rock where porphyroclasts survive, mostly undeformed.

At higher strains, dynamic recrystallization significantly affects the quartz porphyroclasts, and the undeformed parts of the crystal are now subordinate with respect to the areas where rotation recrystallization has occurred. The final product of this process is the disappearance of the large quartz porphyroclasts, replaced by elongated aggregates of dynamically recrystallized quartz grains. Coalescence of quartz aggregates leads to ribbons of recrystallized quartz grains (Fig. 5l), which form interconnected weak layers (Handy, 1994). At this stage, strain localizes in plastically deformed quartz layers, not in the matrix, and the rocks have a typical mylonitic microstructure, with alternating thick pure quartz layers and phyllosilicate-rich layers: rotation recrystallization in quartz is the main deformation mechanism operating. Feldspar grains are enveloped by quartz layers and exhibit only brittle behaviour.

Although quartz-mylonites with well-developed dynamically recrystallized quartz layers are widespread in the Baccu Locci mylonites, they are not typical of the high-strain zones. Levels where strain localizes are characterized by black fine-grained mylonites, where continuous ribbons of plastically deformed quartz layers are more difficult to observe. Zones of higher strain in the Baccu Locci mylonites are recognized during field work by the occurrence of quartz veins that are progressively deflected and boudinaged along the regional mylonitic foliation, by the presence of ubiquitous elongated porphyroclasts and shear bands, and by a penetrative foliation at all scales. The microstructures of these zones are characterized by widespread fine-grained black matrix, also in thin section.

In the fine-grained Baccu Locci mylonites, dynamically recrystallized quartz ribbons are boudinaged (Fig. 5m) and found only as elongate lenses in a fine phyllosilicate-rich matrix; this implies that crystal plasticity in quartz is not the main deformation mechanism in these rocks. Plastically deformed quartz layers boudinaged along the mylonitic foliation suggest that: (a) the fine-grained matrix is now weaker than quartz; and (b) most of deformation is again localized in the matrix. The process that led to such diffuse phyllosilicate development in the matrix, and the mechanism that replaces crystal plasticity in quartz as the dominant deformation mechanism in the rock remain to be investigated.

Mica growth is common in fractured feldspar, and its growth during all stages of deformation is indicated by undeformed muscovite grains along the mylonitic foliation and in pressure shadows near feldspars. This implies that metamorphic reactions occur between feldspar and muscovite during deformation. This is also supported by the observation that muscovite content increases with decreasing feldspar grain size in the high strain zones of the Baccu Locci mylonites. Syntectonic metamorphic reactions led therefore to diffuse phyllosilicate formation at the expenses of feldspar (Knipe and Wintsch, 1985; Janecke and Evans, 1988; O'Hara, 1988; Wintsch *et al.*, 1995). Breakdown of feldspar produces very fine mica grains (average long axes of crystals, 15–30 μm) perfectly aligned along the mylonitic foliation. The extremely small grain size of mica made diffusive mass transfer processes competitive with respect to crystal plasticity, to accommodate most of the strain in the rock. Grain-size reduction due to production of mica by feldspar breakdown therefore causes a change in the main deformation mechanism operating, from dislocation creep in quartz to viscous grain-boundary sliding in muscovite-rich levels. Plastically recrystallized quartz ribbons are consequently boudinaged. Strain localizes in muscovite levels and muscovite-rich levels develop where deformation and syntectonic reactions occur. Reaction-enhanced ductility (White and Knipe, 1978) accounts for the field evidence that fine-grained mylonites and high-strain shear zones mostly develop in the Ordovician metavolcanic rocks, where feldspar porphyroclasts are present. Reaction weakening due to mica formation is frequently reported from deformed granitoids (Evans, 1988; Janecke and Evans, 1988; O'Hara, 1988; Gapais, 1989; Evans, 1990; Wintsch *et al.*, 1995) and is here inferred to be important also during the deformation of volcanic rocks. Since feldspar contents are not very high in these rocks, reaction softening and the change in deformation mechanism occur only at later stages of mylonitic deformation, after crystal plasticity in quartz. A schematic overview of the microstructural development of the Baccu Locci mylonites is reported in Fig. 10.

A characteristic of the Baccu Locci mylonites at outcrop and hand specimen scale is the black colour of the phyllosilicate-rich layers, which gives a fine, laminated appearance to the rock (Fig. 5n). The black colour

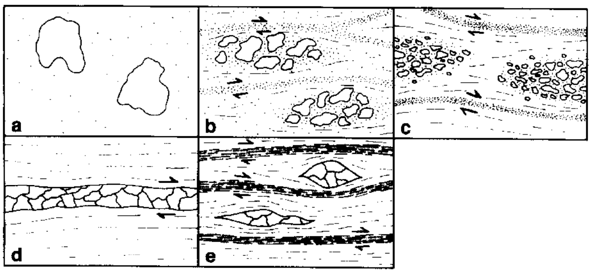

Fig. 10. Evolution of microstructures in the Baccu Locci mylonites. Strain and recrystallization increase from (a) to (e). (a) Undeformed acid volcanic rocks with large quartz crystals in a fine grained quartz-rich matrix. (b) Strain and plastic deformation occurred in narrow quartz layers in the matrix, and porphyroclasts are only locally recrystallized. (c) Porphyroclasts are now fully recrystallized, but strain still localized in the matrix. (d) Coalescence of totally recrystallized porphyroclasts led to quartz-rich layers, that then accommodated most of strain. (e) Increasing mica content due to feldspar breakdown led to viscous flow localization in phyllosilicate-rich levels and to boudinage of dynamically recrystallized quartz ribbons.

is due not to graphite or organic matter, but to diffuse oxides enrichment (rutile, ilmenite, etc.), not present in the undeformed rocks and hence linked with the mylonitization. Oxides appear as fine-grained aggregates ($< 10\ \mu m$) of irregular rounded shapes, mostly concentrated along the mylonitic foliation in the mica-rich layers, but also dispersed throughout the rock. The observation that Fe-oxides are not only found along the main foliation makes it unlikely that they originated as insoluble residues along pressure solution surfaces, but favours the interpretation of a hydrothermal material, deposited during deformation.

Hydrothermal deposition and breakdown of feldspar involving hydration suggests that fluid-assisted deformation mechanisms were important during development of the Baccu Locci mylonites. Feldspar breakdown and reaction softening are more efficient with a high water content in the system. Replacement of feldspar by muscovite led, at the same time, to a negative volume change, increasing porosity and permeability and hence allowing more fluid infiltration (Rumble and Spear, 1983; Wintsch *et al.*, 1995). This sheds new light on the origin of the Baccu Locci ore deposits. Mylonites of the Baccu Locci area host conspicuous As–Pb–Fe sulphide deposits, exploited since the last century for arsenic and lead, with minor occurrences of native gold and silver. This mineralization has been regarded as being of sedimentary origin ('stratabound syngenetic'), with mobilization and concentration occurring during the Hercynian metamorphism (Zucchetti, 1958; Schneider, 1972; Bakos *et al.*, 1990; Bakos *et al.*, 1991). The interpretation is based on the assumption that ore lenses are concordantly interbedded within Silurian black shales. Since we consider that the black phyllites of the Baccu Locci area are mylonites derived from Ordovician volcanic rocks and Cambrian sandstones, and because undeformed ore deposits occur along the mylonitic foliation (Zucchetti, 1958; Bakos *et al.*, 1990), part of this mineralization may have a metamorphic origin, contemporaneous with mylonitization.

DEFORMATION AND MYLONITES IN THE RIU GRUPPA UNIT

The Riu Gruppa unit is the deepest tectonic unit in the nappe stack of South-East Sardinia and outcrops below the Baccu Locci mylonites in two separate tectonic windows within the study area: along the Riu Gruppa river and southeast of Baccu Locci (Fig. 7). Investigations in the Riu Gruppa unit have been carried out previously by several workers (Carmignani *et al.*, 1978; Carosi *et al.*, 1990a; Gattiglio and Oggiano, 1992), and following Franceschelli *et al.* (1992), temperature during greenschist facies metamorphism was here slightly higher that in the Gerrei unit.

Inferences about the relationships between deformation and metamorphism during the D_1 phase can be proposed for the Riu Gruppa unit. Ordovician volcanic rocks below the Baccu Locci mylonites show the growth of syntectonic albite porphyroblasts during D_1 foliation development (Fig. 5o). Porphyroblasts first overgrew an older foliation and afterwards grew progressively during non-coaxial deformation, contemporaneous with the development of the main foliation. The main foliation in thin section and in the field corresponds to the mylonitic foliation in the Baccu Locci mylonites. Since in the field and in thin section, an older foliation is recognizable, porphyroblast growth postdates the early thrusting and folding stage, and is contemporaneous with the main nappe emplacement stage (Figs 3 & 4).

In the hinge zone of the Riu Gruppa antiform, the lowermost levels of the Riu Gruppa unit occur. Lithologically Silurian black shales and phyllites are exposed, as well as Devonian carbonate rocks now metamorphosed into marbles and dolomitic marbles and lower Carboniferous metaconglomerates, quartzites and phyllites. Due to the strong internal deformation suffered by these rocks, we mapped this part of the Riu Gruppa unit as a distinct lithostratigraphic unit, the Sa Lilla complex (Fig. 7).

In the Sa Lilla complex, marbles show a pervasive foliation, resulting from alternating white and grey levels on a fine scale (Fig. 5p), which completely obliterates bedding and any primary structures within the rock. Dolomitic layers are strongly deformed and now occur only as scattered rounded or lens-shaped boudins along the S_1 fabric. Rounded dolomite boudins range in size from centimetres to metres and are flanked by fine-grained dolomite aggregates, developing tails with stair-stepping geometry (Lister and Snoke, 1984; Passchier *et al.*, 1993). Folds are not very common in marbles, and are usually restricted to small-scale, intrafolial, isoclinal folds, strongly non-cylindrical, with fold axes almost parallel to the stretching lineations (Fig. 9h). All these features indicate extensive shear deformation together with plastic recrystallization. Adjacent quartzites and phyllites do not show such an intense deformation, though a well developed foliation is present. We therefore regard the Sa Lilla complex as a large volume of rock affected by non-coaxial deformation, with mylonitic deformation mostly confined to the carbonate levels.

Microstructures in the marbles of the Sa Lilla complex do not show any evidence of intense plastic deformation due to static recrystallization. A fully annealed fabric occurs (Fig. 5q), with polygonal microstructures (granoblastic). D_1 foliation and isoclinal folds are not recognizable in thin section, as the grains show no shape-preferred orientation. Calcite crystals generally have diameters of 150–200 μm. Local post-annealing deformation in the marbles is observed only in thin section along small-scale shear-zones (Fig. 5r), leading to development of a new foliation, dynamic recrystallization and shape-preferred orientation of calcite crystals (mean long axes 50–100 μm). Since D_2 and D_3 phases are not very intense in the area, we consider these shear zones as having developed during D_1 phase (early thrusting and folding or main nappe emplacement stage, Fig. 3). This again supports what we inferred earlier that the main crystal growth occurred during the crustal thickening phases, and experienced D_1 late stage deformation (Fig. 3c).

CONCLUSIONS

Field work and microstructural investigations indicate that mylonitic deformation during continental shortening prevailed in many tectonic units of the Hercynian basement of Sardinia, together with top-to-south-southeast thrusting, strong non-coaxial deformation, plastic deformation in calcite-, feldspar- and quartz-rich rocks, and more or less complete obliteration of earlier folding structures. During earlier phases of thrusting (Fig. 3a), polyphase deformation and mylonite development occurred in the Riu Gruppa and Barbagia units, and at the same time, folding affected the Meana Sardo and the Gerrei units. Ongoing deformation produced main nappe emplacement and regional mylonitic foliation development in the Meana Sardo and Barbagia units (Fig. 3b). In both these units, in addition to the main foliation, relics of older foliation are preserved, related to earlier thrusting and folding stages. As we do not recognize mappable overprinting relationships over large areas between early thusting and main nappe emplacement structures (foliation, lineations, folds, etc.), but only a main foliation with relics of an older foliation, we regard all these features as D_1; i.e. developed during continuous progressive continental shortening. Overprinting relationships on a map scale are observed only in the Gerrei and Riu Gruppa units, where mylonitic deformation during main nappe emplacement is less intense and only locally developed below the Meana Sardo and Gerrei thrusts. This allows us to observe isoclinal folding later overprinted by a flat-lying foliation in the Gerrei nappe, and small-scale shear zones deforming annealed microstructures in the marbles of the Riu Gruppa unit. Shortening during the main nappe emplacement event therefore decreases from the Barbagia unit to foreland areas.

Deformation of annealed microstructures (Fig. 5r) and porphyroblasts containing inclusion patterns (Fig. 5o) testify that crystal growth occurred after D_1 early thrusting and before the main nappe emplacement event. Main grain growth is hence not related to extensional tectonics or granite emplacement, but occurred during crustal shortening, possibly linked to the relaxation of isotherms with ongoing deformation. Greenschist facies conditions are recorded throughout D_1, and estimations based on the deformation mechanisms operating in quartz mylonites along thrusts (subgrain rotation recrystallization) indicate that the temperatures did not exceed 400°C during deformation.

Investigations in the Baccu Locci mylonites document the progressive development during D_1 of fine-grained quartz mylonites from Ordovician volcanic rocks and Cambrian sandstones. At low strain, plastic deformation (dislocation creep) occurred only in the fine grained quartz matrix of volcanics and sandstones where the strain localized, whilst larger quartz porphyroclasts show only dislocation glide features (undulose extinction and deformation bands) (Fig. 10b & c). Porphyroclasts underwent rotation recrystallization only at larger strains, and their coalescence formed dynamically recrystallized quartz ribbons that then accommodated most of the strain (Fig. 10d). Ongoing deformation and syntectonic breakdown of feldspar producing mica led to mineral change and grain-size reduction with reaction softening and strain localization in the phyllosilicate-rich matrix (Fig. 10e). Therefore in the Baccu Locci mylonites, an initial change of the dominant deformation mechanism from crystal plasticity in the matrix to dynamic recrystallization in pure quartz layers is recorded, followed by a transition from dislocation creep in quartz to viscous grain-boundary sliding in muscovite-rich levels. Fluid-assisted deformation occurred in the Baccu Locci mylonites, and this can provide an explanation for some of the occurrences of ore deposits in the area.

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