Late Hercynian shear zones in northeastern Sardinia (Italy)*

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Les zones de cisaillement tardi-hercyniennes en Sardaigne du Nord-Est (Italie)

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Mots-clés : Zone de cisaillement, Cisaillement ductile, Orogénie hercynienne, Sardaigne.

Abstract

The late-orogenic evolution of the high- to medium-grade metamorphic complexes in the north of the Hercynian belt in Sardinia (Italy) is characterized by a shear pattern divided into two events: an Early Shear Event (ESE) and a Late Shear Event (LSE). The ESE is characterized by high-temperature shear zones with a top-to-the-SE shearing, and is related to a dome structure. The LSE consists of strike-slip ductile shear zones associated with retrogressive metamorphism and commonly with synkinematic plutons. Based on the structural-metamorphic evolution inferred from macro- and microstructural analysis, we consider that the ESE accommodated the exhumation of the basement of the Hercynian belt in Sardinia and that the LSE belongs to the Late Hercynian strike-slip faulting, well known in SW Europe.

Résumé

Dans le Complexe Métamorphique de haut à moyen degré du nord de la chaîne hercynienne de Sardaigne (Italie), l'évolution tardi-orogénique est caractérisée par un vaste réseau de zones de cisaillement qui résulte de deux événements : le cisaillement précoce (ESE) et le cisaillement tardif (LSE). Le cisaillement précoce est caractérisé par des zones de cisaillement ductiles de haute température avec un sens de cisaillement de la partie supérieure vers le sud-est. La disposition spatiale de ces zones de cisaillement suggère une structure en dôme. L'événement cisaillant tardif est formé par des décrochements ductiles associés soit à un métamorphisme rétrograde, soit à des plutons syncinématiques. L'évolution structurale et métamorphique de ces zones de cisaillement permet de conclure que les cisaillements précoces sont les structures qui accomodent l'exhumation du socle de la chaîne hercynienne de Sardaigne. Les zones de cisaillement tardives appartiennent au système des décrochements tardi-hercyniens connus de longue date dans la chaîne hercyniennes du sud-ouest européen.

Introduction

The post-collisional Hercynian evolution in Sardinia is characterized by Late Carboniferous-Permian extensional tectonism that affected the whole belt and was due to gravitational collapse of the previously thickened crust (Carmignani *et al.*, 1993). Evidence for this Late Hercynian extensional tectonism is widespread throughout the basement, and its development is chronologically constrained by radiometric, sedimentary and paleontological data.

In Sardinia, the end of collisional tectonism is marked by the 350-344 Ma ages of the Barrovian metamorphism of the Axial Zone in the northern part of the island (Ferrara *et al.*, 1978; Del Moro *et al.*, 1991) and by the deposition of Visean-Namurian wildflysch in the Nappe and External zones in the central and southwestern parts of the island (Fig. 1). Although these ages could represent the beginning of the extensional tectonism in the Axial Zone, compression was still active in the External Zone as indicated by wildflysch deposits caught up in the outermost thrusts of the belt (Carmignani *et al.*, 1993). The evidence for extensional tectonism is observed at different crustal levels. In the Axial Zone (Fig. 1), the HT/LP metamorphic assemblage (sillimanite-andalusite ± cordierite facies) dated at 303 Ma (Del Moro *et al.*, 1991) overprints the Barrovian amphibolite assemblage (Elter *et al.*, 1986). The former assemblage developed during a late deformation within discrete ductile normal shear belts (Oggiano and Di Pisa, 1987; Elter *et al.*, 1990; Elter and Corsi, 1995; Corsi *et al.*, 1998) and is synkinematic with an extensional crenulation cleavage (Carmignani *et al.*, 1993). The post-collisional evolution led to wide-

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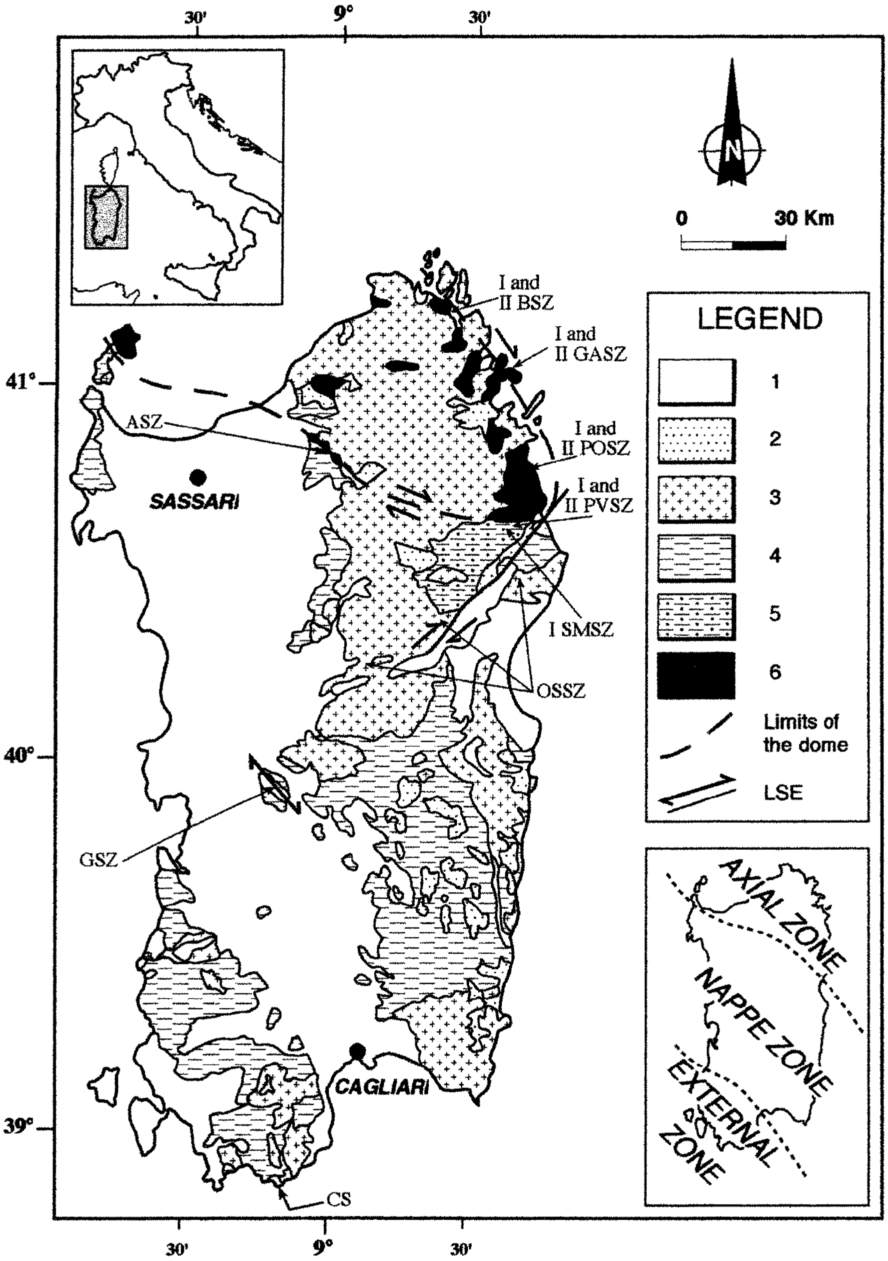

Fig. 1.- Schematic geological sketch of Hercynian Sardinia showing the location of the Early and Late Shear Events (ESE, LSE).
1: Quaternary deposits; 2: Mesozoic deposits; 3: granites s.l., from syn- to late-granitic suites (from 307 ± 6 Ma to 289 ± 1 Ma); 4: mica schists and paragneisses from biotite to garnet+oligoclase zones, granodioritic orthogneiss (458 ± 33 Ma) and augen gneiss (441 ± 33 Ma); 5: mica schists and paragneisses from staurolite+biotite to kyanite+biotite condensed isogrades and amphibolites; 6: High Grade Metamorphic Complex (HGMC) in sillimanite + muscovite and sillimanite + K-feldspar zones (344 ± 7 Ma); I, II BSZ: Barrabisa Shear Zones; I, II GASZ: Golfo Aranci Shear Zones; ASZ: Anglona Shear Zone; I, II POSZ: Porto Ottiolo Shear Zones; I, II PVSZ: Posada Valley Shear Zones; I SMSZ: Siniscola Mamone Shear Zone; OSSZ: Ottana Senes Shear Zone; GSZ: Grighini Shear Zone; CS: Capo Spartivento Gneiss Dome.

Fig. 1.- Carte géologique schématique de la Sardaigne hercynienne montrant la localisation des cisaillements précoces (ESE) et les cisaillements tardifs (LSE).
1 : Quaternaire ; 2 : Mésozoïque ; 3 : Granites s.l., suites syn à tardi-tectoniques (de 307+/- 6 Ma à 289 +/- 1 Ma) ; 4 : Micaschiste et paragneiss (zone à biotite et à grenat+oligoclase), orthogneiss granodioritique (458 +/- 33 Ma) et gneiss oeillé (441 +/- 33 Ma) ; 5 : Micaschiste et paragneiss (zone à staurotide+biotite et à disthène+biotite) ; 6 : Complexe Métamorphique de Haut Grade (HGMC, zones à sillimanite+muscovite et sillimanite+K-feldspath, 344 +/- 7 Ma). I, II BSZ : Barrabisa Shear Zones ; I, II GASZ : Golfo Aranci Shear Zones ; ASZ : Anglona Shear Zone ; I, II POSZ : Porto Ottiolo Shear Zones ; I, II PVSZ : Posada Valley Shear Zones ; ISMSZ : Siniscola Mamone Shear Zone ; OSSZ : Ottana Senes Shear Zone ; GSZ : Grighini Shear Zone ; CS : Dome de gneiss de Capo Spartivento.

spread anatexis through dehydration melting in an active decompressional regime (Ricci, 1992) and to the emplacement of several small bodies of synkinematic peraluminous granites strongly deformed under high-temperature solid-state conditions (Di Vincenzo *et al.*, 1994, 1996).

In the Nappe Zone of central Sardinia (Fig. 1) the evidence for extensional tectonism is particularly common in the Flumendosa antiformal stack that is made up of several tectonic units whose emplacement caused ductile deformation (Carmignani *et al.*, 1993). The sense of shear along low-angle detachments is away from the culmination of the antiform with coeval opposite motion toward both the northeast and southwest. These structures led to the tectonic unroofing and exhumation of mid-crustal metamorphic rocks along the antiform. In the External Zone of southwestern Sardinia, the Capo Spartivento antiform (Fig. 1) comprises orthogneisses derived from Ordovician granites, overlain by weakly metamorphic rocks of Late Precambrian-Early Cambrian age. Granitic gneisses show an amphibolite facies metamorphism dated at 280 Ma (Carmignani *et al.*, 1993) and their secondary foliation evolves progressively into a mylonitic foliation toward the detachement contact with the overlying metasedimentary rocks, where extensional shear bands and low-angle normal faults are conspicuous.

The geometric and kinematic features of the extensional structures reveal the presence of conjugate shear zones with opposite directions of displacement. Carmignani *et al.* (1993) hypothesized an extensional model characterized by conjugate shear zones giving rise to the exhumation of amphibolite facies rocks with the thermal perturbation due to the tectonic unroofing being responsible for HT/LP metamorphism and anatexis. The fast uplift was also responsible for the stability of the amphibolite facies paragenesis at upper crustal levels, where the deformation developed in a brittle fashion (Ricci, 1992; Carmignani *et al.*, 1993). Consequently, some regions across the belt underwent tectonic denudation, unloading and offsetting, whereas others showed relative subsidence and were the sites of clastic sedimentation and volcanism of Late

Carboniferous-Early Permian age. According to Carmignani *et al.* (1993), the extension may have started in the Axial Zone of the chain by underplating, and then propagated toward the External Zone through normal and/or wrench ductile shear zones that evolved into normal faults at upper crustal levels.

Geological setting

The upper part of the Hercynian basement of Sardinia (Fig. 1) consists of SW-verging nappes interposed between the High Grade Metamorphic Complex (HGMC) of northern Sardinia (Figs. 2, 3) and a folded foreland (External Zone) that crops out in the southwestern corner of the island. The geodynamic evolution implies a B-type subduction followed by continent-continent collision with stacking up of the Gondwanian continental margin and finally, at the end of convergence, the gravitational collapse of the Hercynian orogenic wedge (Carmignani *et al.* 1986, 1994). Evidence for collisional structures is preserved in the HGMC, which contains high-pressure rocks and is separated from the Nappe Zone of central Sardinia by the Posada-Asinara Shear Zone (Elter, 1985, 1987; Elter and Sarria, 1989; Elter *et al.*, 1990, 1993; Cappelli *et al.*, 1992; Elter and Corsi, 1995). In the Nappe Zone, a thrust pile is clearly recognizable in the low-grade metamorphic complex (Carmignani *et al.*, 1994). The Rb/Sr and $^{40}Ar/^{39}Ar$ ages of muscovite and amphibole within the Barrovian metamorphic assemblages in the Nappe Zone range around 350 Ma, suggesting a minimum age for the collision (Del Moro *et al.*, 1991), whereas in the HGMC, the 344 ± 7 Ma Rb/Sr-whole rock age of a banded migmatite is ascribed to an early stage of uplift (Ferrara *et al.*, 1978; Elter *et al.*, 1986; Ricci, 1992; Elter and Corsi, 1995).

The Hercynian metamorphism is characterized by a NE-SW regional zonation. The metamorphic grade increases rapidly northeastward from sub-greenschist/greenschist facies in the External and Nappe zones, to amphibolite facies with lenses of retrograde metamorphosed granulite and eclogite within the HGMC (Ghezzo *et al.*, 1982; Elter *et al.*, 1986; Franceschelli *et al.*, 1989, 1998; Ricci, 1992). The basement experienced a polyphase deformation coeval with a P-T-t path evolving from high-pressure to medium-pressure conditions. Different clockwise-P-T-t paths in contiguous segments of the belt suggest that, during the uplift stage, different blocks experienced differential exhumation rates or mechanisms (Ricci, 1992).

Widespread plutonic activity affected the basement during the Late Hercynian tectonic-metamorphic evolution, giving rise to the composite Sardinia-Corsica Batholith. In Sardinia, pluton emplacement occurred over a time span of about 30 Ma (from about 310 to 280 Ma) within an evolving tectonic extensional setting that postdated the thickening stage. The plutonic activity consisted mainly of two associations: a dominant high-K calc-alkaline association and a peraluminous association. The emplacement sequence took place during and after the exhumation stage of the basement and can be divided as follows (Bralia *et al.*, 1981): 1) a syn-tectonic group of strongly foliated intrusions with clear evidence of high-temperature solid-state deformation; 2) a late-tectonic group of large plutons with variably marked magmatic foliation (about 70% of the batholith); 3) a post-tectonic group of intrusions consisting of shallow-level massive leucogranites (about 20% of the batholith). Geochronological data indicate ages ranging from about 310 Ma to about 295 Ma and about 290-280 Ma, for the second and the third groups respectively (Del Moro *et al.*, 1975; Scharbert, 1978; Cocherie, 1984). The emplacement of the peraluminous granites was approximately contemporaneous with the emplacement of the calc-alkaline granites. Available ages are in the range 305-298 Ma (Carmignani *et al.*, 1986; Macera *et al.*, 1989; Di Vincenzo *et al.*, 1994, 1996). From a structural point of view, the older primary-foliated granites generally constitute elongate plutons with a NW-SE foliation parallel to the main structural pattern of the belt, whereas the younger post-tectonic plutons are round or elongate along a NE-SW direction. Some sheet-like intrusions, mainly of peraluminous composition, show clear synkinematic relationships with shear zones; e.g. the Mt. Grighini Complex (Musumeci, 1992) and the S. Basilio Intrusion (Di Vincenzo and Ghezzo, 1992). Isotopic data indicate cooling ages for biotite, both in the metamorphic and intrusive rocks, mainly in the range 295-280 Ma (Del Moro *et al.*, 1975; Di Vincenzo *et al.*, 1994). The post-orogenic sedimentary and volcanic Lower Permian cover sequences rest directly on the migmatitic rocks in the Axial Zone. Thus field and isotopic data suggest that the exhumation processes, particularly pronounced in the Axial Zone, developed mainly before the emplacement of the leucogranite plutons.

The shear pattern

When dealing with the post-collisional evolution of the Sardinian Orogeny, an important role must be attributed to a composite network of shear zones. These shear zones are not coeval and some of them show a complex metamorphic evolution from early HT/LP stages to late MT-LT/LP conditions associated with changes in the sense of movement. Many of the shear zones are still not radiometrically dated, but their relative ages can be deduced from field relationships and through assuming that, in a given area, shear zones characterized by MT-LT/LP ultramylonites are younger than HT/LP shear zones. Two shearing events are recognized: namely an Early Shear Event (ESE) and a Late Shear Event (LSE).

Five shear zones associated with a synkinematic HT-LP metamorphism are related to the ESE (Figs. 1, 2). Three of these crop out in the HGMC: the I Barrabisa Shear Zone (I BSZ), the I Golfo Aranci Shear Zone (I GASZ) and the I Porto Ottiolo Shear Zone (I POSZ). Of the other two, the I Siniscola Mamone Shear Zone (I SMSZ) is recognizable in the northern part of the Inner Nappe Zone, and the I Posada Valley Shear Zone (I PVSZ) crops out between the HGMC and the I SMSZ. The LSE, which reworks the ESE (Fig. 4 A), consists of strike-slip faults divided into two sub-systems: a first group with synkinematic intrusions and a second group with a synkinematic retrograde metamorphism. From south to north, the LSE structures are: i) the Mt. Grighini Shear Zone (GSZ); ii) the Ottana - Mt. Senes Shear Zone (OSSZ); iii) the II Posada Valley Shear Zone (II PVSZ), the Anglona Shear Zone (ASZ), and the II Porto Ottiolo Shear Zone (II POS); iv) the II Golfo Aranci Shear Zone (II GASZ); and v) the II Barrabisa Shear Zone (IIBSZ) (Figs 1, 2).

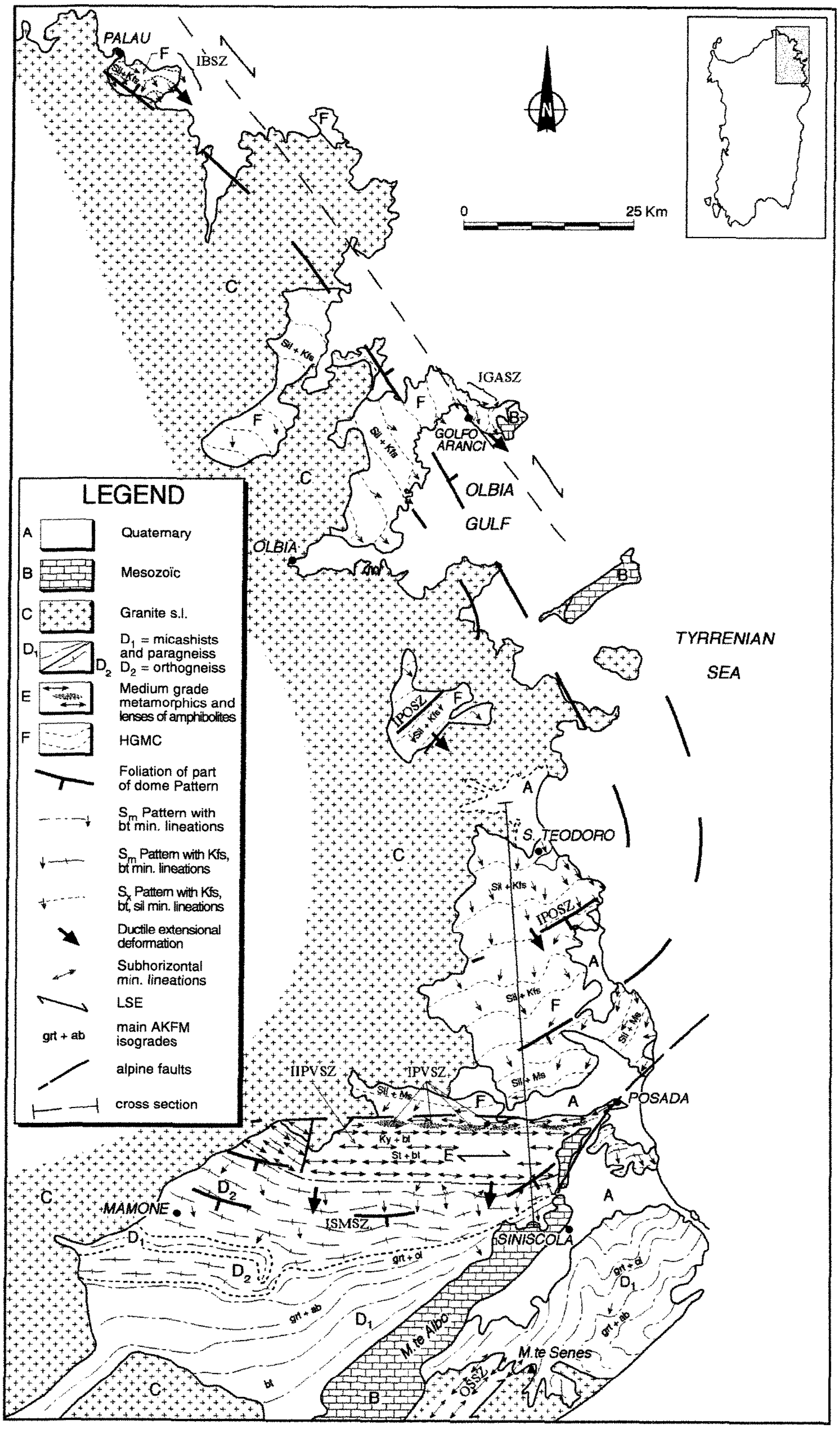

Fig. 2.- Schematic geological map of the northeastern coast of Sardinia showing the location of ESE shear zones. The shear zones outline a domal pattern (bt = biotite; ms = muscovite; Kfs = K-feldspar; sil = sillimanite; grt = garnet; ab = albite; ol = oligoclase; ky = kyanite; st = staurolite). Only a few Alpine faults are shown.

Fig. 2.- Carte géologique schématique de la côte nord-est de la Sardaigne avec la localisation des zones de cisaillement précoces. Ces zones de cisaillement définissent une structure en dôme. (bt : biotite ; ms : muscovite ; Kfs : K-feldspath ; sil : sillimanite ; grt : grenat ; ab : albite ; ol : oligoclase ; ky : disthène ; st : staurotide). Seulement quelques failles Alpines sont reportées.

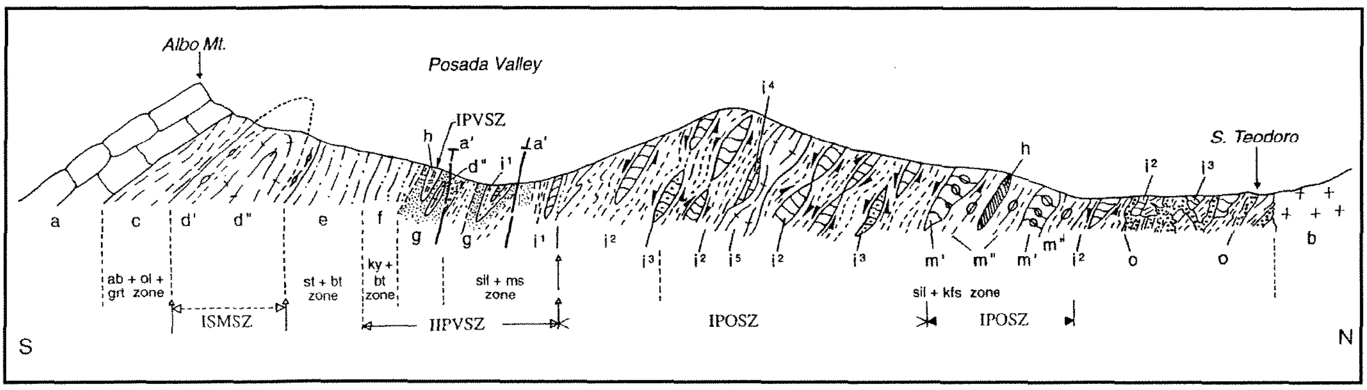

Fig. 3.- Schematic cross section of NE Sardinia (not to scale).
a: Jurassic-Cretaceous limestones; a′: Alpine faults; b: late- to post-granitic suites; c: mica schist and paragneiss of the albite+oligoclase+garnet zone; d′: Lodé-Mamone augen gneiss (441 ± 31 Ma); d″: Lodé-Mamone granodioritic orthogneiss (458 ± 31 Ma); e: mica schist and paragneiss of the staurolite+biotite zone; f: mica schist and paragneiss of the kyanite+biotite zone; g: ultramylonites related to II PVSZ; h: Torpé amphibolites with relics of I PVSZ; i-m-o: HGMC: i1: sillimanite gneiss (sillimanite+muscovite zone); i2: stromatitic migmatites and gneisses s.l. (sillimanite+K-feldspar zone, 344 ± 7 Ma); i3: P.ta dell' Ainu sillimanite dictyonites; i4: Tamarispa calc-silicate rocks (Elter and Palmeri, 1992); i5: Tanaunella-San Lorenzo granodioritic orthogneiss (458 ± 31 Ma); m′: P.ta de Li Tulchi granodioritic augen gneiss; m: P.ta de Li Tulchi eclogites and amphibolites; o: S.Teodoro nebulites and stromatitic migmatites (sillimanite+K-feldspar zone).

Fig. 3.- Coupe schématique du nord-est de la Sardaigne (échelle non respectée).
a : calcaires du Jurassique-Cretacé, a′ : failles Alpines ; b : Suites granitiques tardi ou post tectoniques ; c : Micaschiste et paragneiss (zone à albite+oligoclase+grenat) ; d′ : Gneiss oeillé de Lodé-Mamone (441+/- 31 Ma) ; d″: orthogneiss granodioritique de Lode-Mamone (458+/- 31 Ma) ; e : Micaschiste et paragneiss (zone à staurotide+biotite) ; f : Micaschiste et paragneiss (zone à disthène+biotite) ; g : Ultramylonites associées à II PVSZ ; h : amphibolites de Torpé contenant des reliques de I PVSZ ; i-m-o) : HGCM : i1 : gneiss à sillimanite (zone à sillimanite+muscovite) ; i2 : migmatites stromatitiques et gneiss s.l. (zone à sillimanite +K-feldspath, 344 +/- 7 Ma) ; i3 : dictionites à sillimanite de la P.ta dell' Ainu ; i4 : gneiss à silicates calciques de Tamarispa (Elter and Palmeri, 1992) ; i5 : orthogneiss granodioritiques ; m′ : gneiss oeillé granodioritique; m″ : éclogites et amphibolites de La P.ta de Li Tulchi ; o: nébulites et migmatites stromatitiques de S.Teodoro (zone à sillimanite+K-feldspath).

Kinematic indicators and microstructures in the ESE and LSE

Many types of well-preserved kinematic indicator are associated, at both macroscopic and microscopic scale, with mylonitic foliation (XY plane) in all the shear zones, with C′- and C-type shear bands being the common mylonitic planar morphologies (Fig. 4 B). Polymineral down-dip lineations (Fig. 4 C,D) are recognized in the ESE, whereas poly- to mono-mineral slickenlines are widespread in the LSE.

The XZ plane shows shear sense criteria such as sigmoidal porphyroclasts (Fig. 4 E), domino-like K-feldspar porphyroclasts (Fig. 4 F), shear bands (Fig. 4 B), sheath folds, shear folds and tension gashes. At microscopic scale, the kinematic indicators are: i) biotite-muscovite mica fish (Fig. 4 G); ii) kyanite fish (Fig. 4 H); iii) stretched and boudinaged staurolites or garnets; iv) deformed hornblende porphyroclasts (only recognizable in the ESE shear zones); v) "V"-shaped pull-apart microstructures in K-feldspar porphyroclasts (Hippert, 1993).

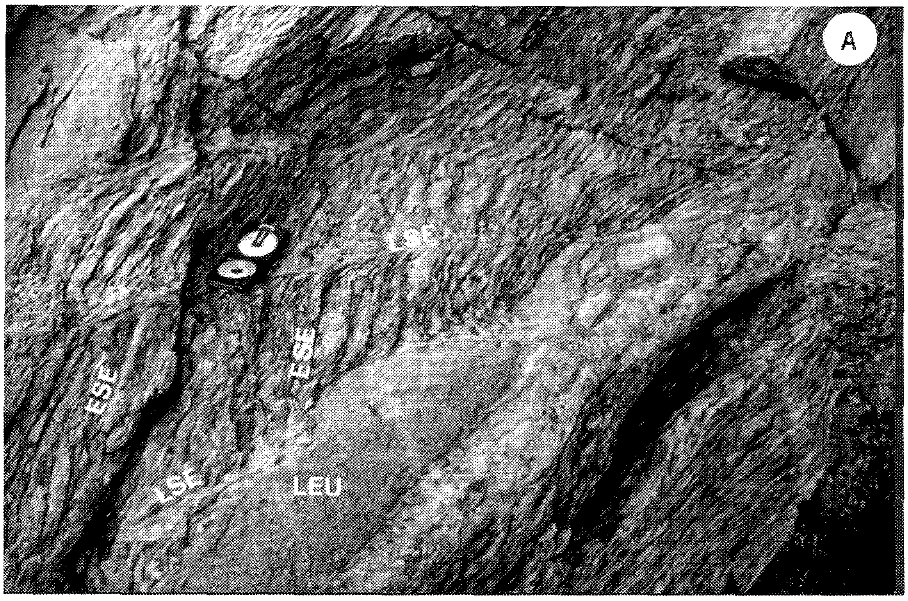

Fig. 4A.- Relationships between the Early Shear Event (ESE) and Late Shear Event (LSE) in the Porto Ottiolo Shear Zone (I POSZ). Note the intrusion of late granite (LEU - leucogranites) cutting both ESE shear bands and LSE shear bands.

Fig. 4A.- Relations entre ESE et LSE dans la Zone de cisaillement de Porto Ottiolo (I POSZ). Noter l'intrusion de granite tardif (LEU= Leucogranites) qui coupe les zones de cisaillement ESE et LSE.

In agreement with many authors (e.g. Boullier and Bouchez, 1978; Simpson, 1985; Vernon, 1991; Kruhl, 1996; Mackinnon *et al.*, 1997; Bozkurt and Park, 1997) we recognize many types of microstructure synkinematic with the mylonitic foliation. A common texture in the ESE is platten-quartz in large quartz ribbons with branching-grain patterns, typical of amphibolite facies (Fig. 4 I). Also, although rarely found, a chessboard-subgrain pattern in quartz (formed by basal and prismatic boundaries of nearly equal size) allows us to

Fig. 4B.- ESE shear bands in the banded migmatite of the Porto Ottiolo Shear Zone (I POSZ). The sense of shear is top-to-the-SE.

Fig. 4B.- Bandes de cisaillement ESE dans les migmatites de Porto Ottiolo (I POSZ). Le sens de cisaillement est vers le sud-est.

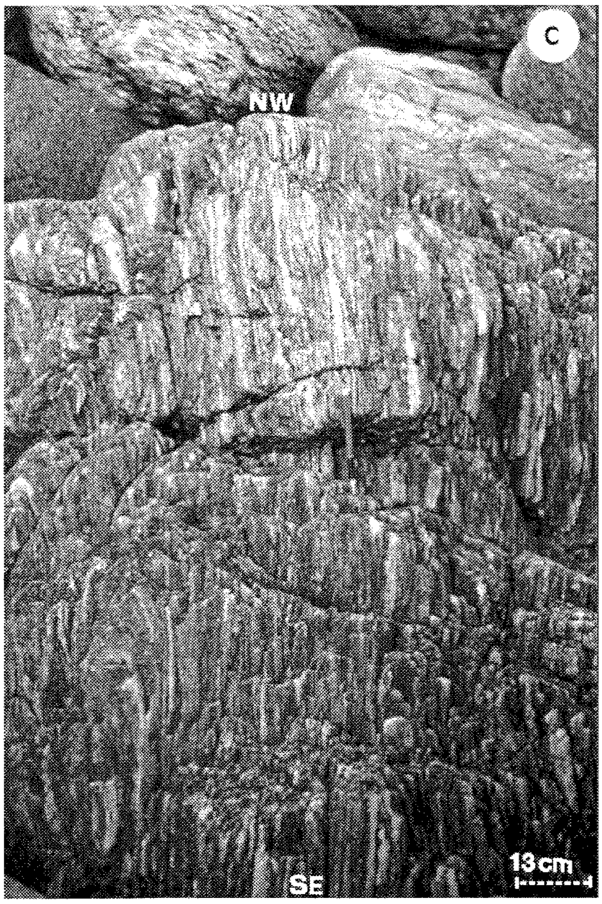

Fig. 4C.- K-feldspars and quartz rods in the ESE mylonitic foliation of the Golfo Aranci Shear Zone (I GASZ) orthogneiss. This lineation dips 30°- 40° to the SE.

Fig. 4C.- Rods de feldspath potassique et quartz sur la foliation mylonitique des orthogneiss de Golfo Aranci (I GASZ). Ces linéations pendent de 30 ° à 40° vers le sud-est.

presume a composite metamorphic evolution from granulitic facies to amphibolitic facies. Typical quartz textures in the LSE are: 1) ribbons with diffuse subgrain domains; 2) ribbons with an elongate granoblastic texture; 3) ribbons with large elongate grains of irregular size; 4) local ribbons with large elongate and irregular grains together with cordierite. Myrmekites are also observed along micro shear bands in the ESE.

Metamorphic patterns

Shear zones of the Early Shear Event (ESE)

All shear zones belonging to the ESE show an amphibolite facies metamorphic evolution, with K-feldspar + prismatic sillimanite + fibrous sillimanite + garnet + intermediate plagioclase + biotite + muscovite + quartz being the common minerals recognized along the mylonitic foliation. The synkinematic mineral assemblage allows us to determine the P-T conditions as P >4 kb and T >650° to <<850 °C (Fig. 5). The presence of platten quartz, large to branching ribbon-type quartz, parallel to the mylonitic foliation is indicative of synkinematic recrystallization of quartz under amphibolite facies conditions (Boullier and Bouchez, 1978; Mackinnon *et al.*, 1997). Furthermore, the presence of ductile deformation fabrics in the intermediate plagioclase shows that deformation was firstly accommodated by intracrystalline slip and secondly by twinning at T greater than 550 °C (Olsen and Kohlstedt, 1985; Jensen and Starkey, 1985; Ji and Mainprice, 1988; Bozkurt and Park, 1997). The growth and the concentration of fibrous sillimanite in the foliation plane was coeval with mylonitization. According to Vernon (1987) the main factor controlling the location of fibrous sillimanite in folia is the ability of fibrous aggregates to undergo a strong non-coaxial deformation by grain boundary sliding (i.e. fibre-sliding) without an appreciable build-up of dislocations. Relict K-feldspar porphyroclasts show strain-related myrmekites formed during the mylonitization. The myrmekite formation could be related to the diffusion creep-exsolution process (Simpson, 1985; Hippert, 1993; Bozkurt and Park, 1997).

Shear zones of the Late Shear Event (LSE)

The metamorphic evolution of the LSE shear zones is more complicated than that of the ESE shear zones. Those associated with synkinematic intrusions are characterized by high-temperature textures. The presence of plagioclase deformation fabrics in the magmatic bodies indicates a deformation T > 550 °C (Olsen and Kohlstedt, 1985; Jensen and Starkey, 1985; Ji and Mainprice, 1988; Bozkurt and Park, 1997).

The LSE shear zones associated with retrograde metamorphism show two different patterns. The II PVSZ is characterized by a synkinematic greenschist facies metamorphism (Elter, 1985; Elter 1987; Elter *et al.*, 1990), whereas in the II BSZ, II GASZ and II POSZ the ductile deformation was coeval with a metamorphic event represented by a K-feldspar + intermediate plagioclase + biotite + muscovite mineralogical assemblage (Elter and Corsi, 1995). In the OSSZ, the presence of cordierite-quartz ribbons parallel to the foliation, plus rare stretched andalusite crystals, indicates that the shearing was coeval with the emplacement of the Mt. E-Senes granodiorite and peraluminous leucogranite bodies. In the GSZ, the metamorphic evolution was clearly influenced by the huge volume of synkinematic intrusions.

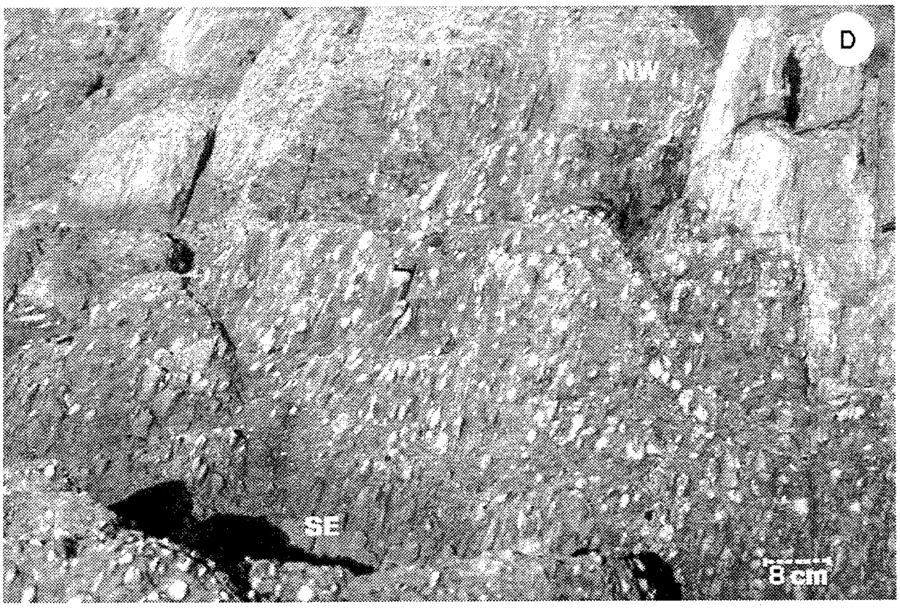

Fig. 4D.- Fibrolitic sillimanite and quartz lineations in ESE mylonitic foliation of the biotite - sillimanite gneisses in the Porto Ottiolo Shear Zone (I POSZ). They dip SE at about 20°- 30°.

Fig. 4D.- Linéation de sillimanite fibreuse et quartz sur la foliation mylonitique à biotite et sillimanite des gneiss de Porto Ottiolo (I POSZ). Leur pendage est de 20°- 30° vers le sud-est.

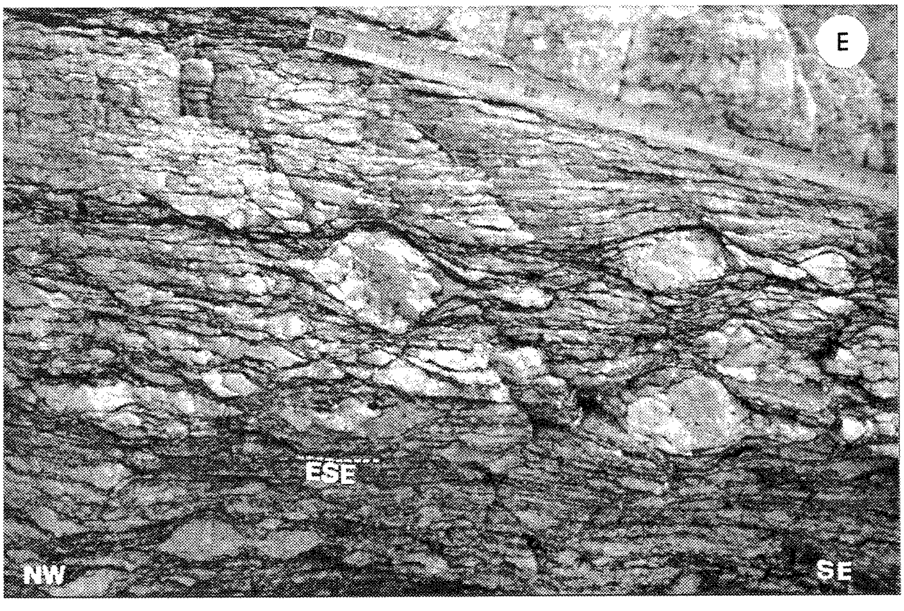

Fig. 4E.- Sigmoidal porphyroclasts of K-feldspar in the XZ plane of the augen gneiss in the Barrabisa Shear Zone (I BSZ). The sense of shear is top-to-the-SE.

Fig. 4E.- Porphyroclastes sigmoïdes de feldpath potassique dans le plan XZ des orthogneiss de Barrabisa (I BSZ). Le sens de cisaillement est vers le SE.

Structural analysis of the shear zones

Structural pattern of the Early Shear Event (ESE)

I Barrabisa Shear Zone (I BSZ). The I BSZ, in the northern part of Sardinia (Figs. 1, 2; Elter *et al.*, 1993), is a WNW-ESE-trending ductile shear zone, about 0.5 km thick, generated in the sillimanite + muscovite stability field. The sheared rocks are migmatites and rarely metagranites of the HGMC. Two ductile shear events are recognized. An earlier event of scattered deformation characterized by shear bands with a rare NW-SE down-dip mineral lineation (K-feldspar + quartz rod lineations) with a top-to-NW shear sense. A later event related to a major penetrative shear zone that also shows down-dip biotite + muscovite ± K-feldspar mineral lineations, but with top-to-the-SE shearing.

I Golfo Aranci Shear Zone (I GASZ). The I GASZ, confined to the HGMC, is exposed near the village of Golfo Aranci (Figs. 1, 2). Elter and Ghezzo (1995) have shown the extensional characters of this shear zone. It is a NW-SE-trending ductile shear zone, about 1 km thick, in the sillimanite - K-feldspar stability field. The sheared rocks are augen metagranite with "septa" of migmatites and granite and aplite-pegmatite dikes. Several pods of unsheared migmatite are recognized, in which kyanite inclusions in plagioclase are the most common metamorphic relics. There were two ductile

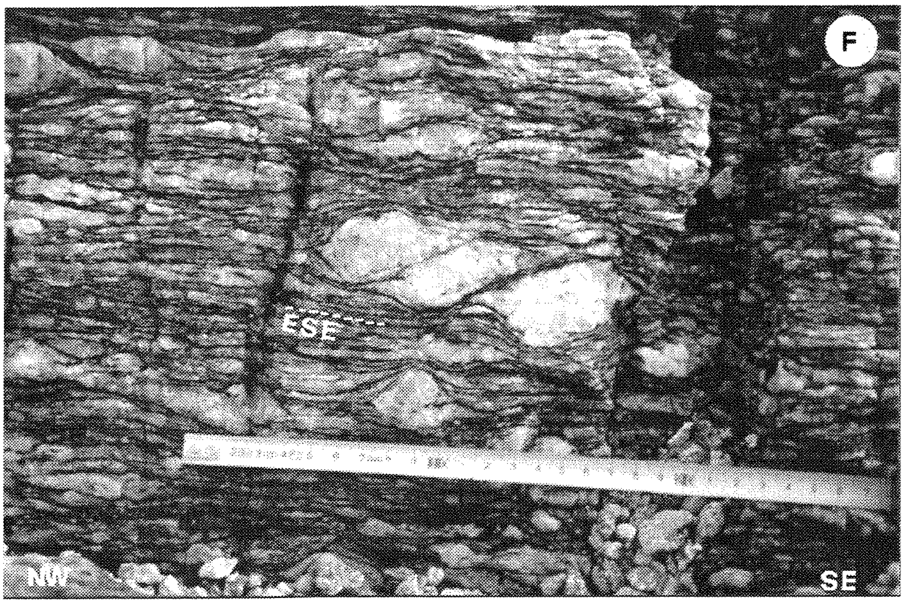

Fig. 4F.- Domino-like K-feldspar in the XZ plane of the orthogneiss in the Golfo Aranci Shear Zone (I GASZ). The sense of shear is top-to-the-southeast.

Fig. 4F.- Feldspath potassique en domino dans le plan XZ de l'orthogneiss de Golfo Aranci (I GASZ). Le sens de cisaillement est vers le sud-est.

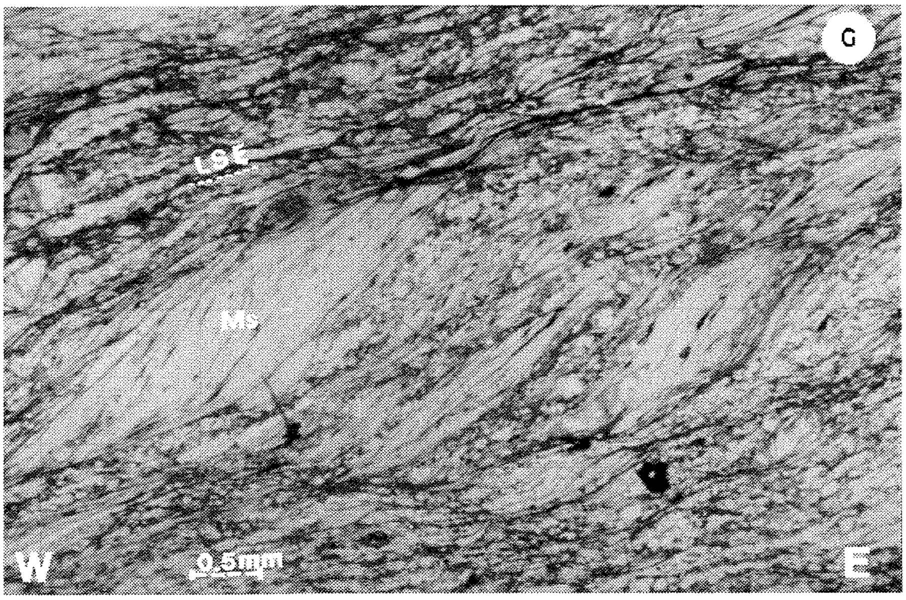

Fig. 4G.- Microphotograph of LSE sigmoidal mica in the kyanite+staurolite+garnet-bearing mica schists - paragneisses in the Posada Valley Shear Zone (II PVSZ). The sense of shear is dextral (Ms: muscovite, crossed nicols, XZ plane).

Fig. 4G.- Microphotographie de mica sigmoïde dans les micaschistess et paragneiss à disthène + staurotide + grenat de la Vallée de Posada (II PVSZ). Le sens de cisaillement est dextre (Ms : muscovite, nicols croisés, plan XZ).

shearing events. The first is generally associated with ultramylonitic rocks and is characterized by a NE-SW down-dip stretching lineation of elongated K-feldspar and quartz on the mylonitic foliation and a top-to-NE movement in the XZ plane. The second event is revealed by shear bands, coeval with the recrystallization of biotite, muscovite and K-feldspar, oriented along a NW-SE lineation and with a top-to-the-SE shear sense.

I Porto Ottiolo Shear Zone (I POSZ). The I POSZ crops out along the coast between Olbia and Porto Ottiolo and affects the migmatites and augen metagranites (Figs. 1, 2, 3; Elter and Corsi, 1995). Pods of unsheared migmatite contain rare kyanite inclusions in plagioclase. With a thickness varying from 1 to 10 m, the I POSZ is a composite, NE-SW-trending, 20-60° SE dipping, ductile shear zone generated in the sillimanite - K-feldspar stability field. Three ductile deformations are identified. The first is only recognizable in the amphibolitized eclogitic bodies (Ghezzo *et al.*, 1982); it consists of a NW-SE mineral lineation of elongated garnet and top-to-the-NW shear bands (Elter and Corsi, 1995). The second shear event was coeval with new shear bands showing a NE-SW down-dip mineral lineation (K-feldspar + quartz) and a top-to-the-SW sense of shear. The third event also shows shear bands and a new NW-SE mineral lineation of biotite + muscovite + fibrolitic sillimanite ± K-feldspar, but the shearing is top-to-the-SE.

I Posada Valley Shear Zone (I PVSZ). The I PVSZ (Carosi and Elter, 1989) is only recognizable in the scattered amphibolite lenses of Torpé along the Posada Valley (Figs 1, 2, 3, Memmi *et al.*, 1983). The amphibolitic bodies are enclosed in a greenschist facies ultramylonite derived from ortho- and paragneiss. The shear event is characterized by a NWW-SEE vertical foliation and a subhorizontal hornblende lineation. A detailed study of the optical characteristics of the deformation of the intermediate plagioclase and of their chemical composition allowed Carosi and Elter (1989) to define HT/LP synkinematic conditions. The I PVSZ subhorizontal lineation is not comparable with the other ESE shear zones and, together with the metamorphic evolution, such a geometry suggests that the I PVSZ may be a dextral transcurrent shear zone.

I Siniscola Mamone Shear Zone (I SMSZ). The I SMSZ crops out along the Siniscola - Mamone ridge (Figs 1, 2, 3; Elter and Nardelli, 1997; Corsi *et al.*, 1998) and affects a granodioritic augen orthogneiss dated at 458±33 Ma and 441±33 Ma (Rb/Sr, whole rock, Ferrara *et al.*, 1978). It is a thick (about 10 km), composite, WNW-ESE-trending ductile shear zone dipping towards the SSE and was generated under amphibolite facies conditions. The deformation is characterized by a down-dip NNW-SSE mineral and stretching lineation of feldspars and quartz rods. Shear bands show that the SSE part is moving down.

Structural pattern of the Late Shear Event (LSE)

LSE shear zones associated with synkinematic intrusions

Mt. Grighini Shear Zone (GSZ). The GSZ outcrops in western central Sardinia (Fig. 1). It is a NW-SE-trending ductile dextral wrench shear zone (Elter *et al.*, 1990, 1993; Musumeci, 1992). Synkinematic intrusive rocks within the shear zone have yielded radiometric ages of 305-300 Ma (Rb/Sr method on whole rock, Laurenzi *et al.*, 1991). Shearing gave rise to low-temperature S-C mylonites and retrogressive ultramylonites with a subhorizontal NW-SE stretching lineation. Kinematic analysis points to a dextral sense of shear with an amount of ductile displacement of about 7 km (Elter *et al.*, 1990). Low-angle N-S- and E-W-trending brittle-normal faults, originated during a late evolution of the shear zone, show a progressive change of deformation regime from ductile wrenching to brittle normal faulting (Musumeci, 1992).

Ottana - Mt. Senes Shear Zone (OSSZ). The OSSZ crops out along the Ottana-Nuoro-Mt. Senes line (Fig. 1; Elter *et al.*,1993; Di Vincenzo *et al.*, 1994). It is a SW-NE-trending dextral ductile strike slip and, with a length of about 95 km and an average thickness of 2-6 km, constitutes the longest shear zone known in Sardinia. The sheared rocks are granodioritic-tonalitic granites with a NW-SE magmatic foliation. Synkinematic two-mica granites (dated at 298 ± 7 Ma, $^{40}Ar/^{39}Ar$; Di Vincenzo *et al.*, 1994) also crop out along the OSSZ and in the Mt. Senes area. A high-temperature solid-state deformation with a SW-NE foliation and subhorizontal SW-NE biotite lineation is recognized. Near Mt. E-Senes, hornfelses are also sheared. The OSSZ is partly dislocated by the sinistral Tertiary Nuoro Fault.

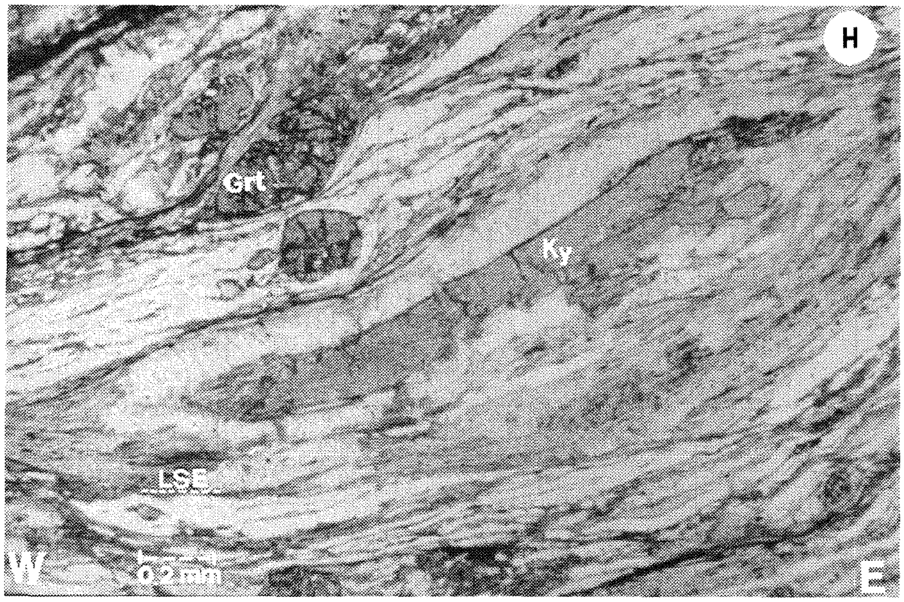

Fig. 4H.- Microphotograph of LSE sigmoidal kyanite in the kyanite+staurolite+garnet-bearing mica schists - paragneisses of the Posada Valley Shear Zone (II PVSZ). The sense of shear is dextral (Ky: kyanite, Grt: garnet, crossed nicols, XZ plane).

Fig. 4H.- Microphotographie de disthène sigmoïde dans les micaschistess et paragneiss à disthène + staurotide + grenat de la Vallée de Posada (II PVSZ). Le sens de cisaillement est dextre (Ky : disthène ; Gt : grenat, nicols croisés, plan XZ).

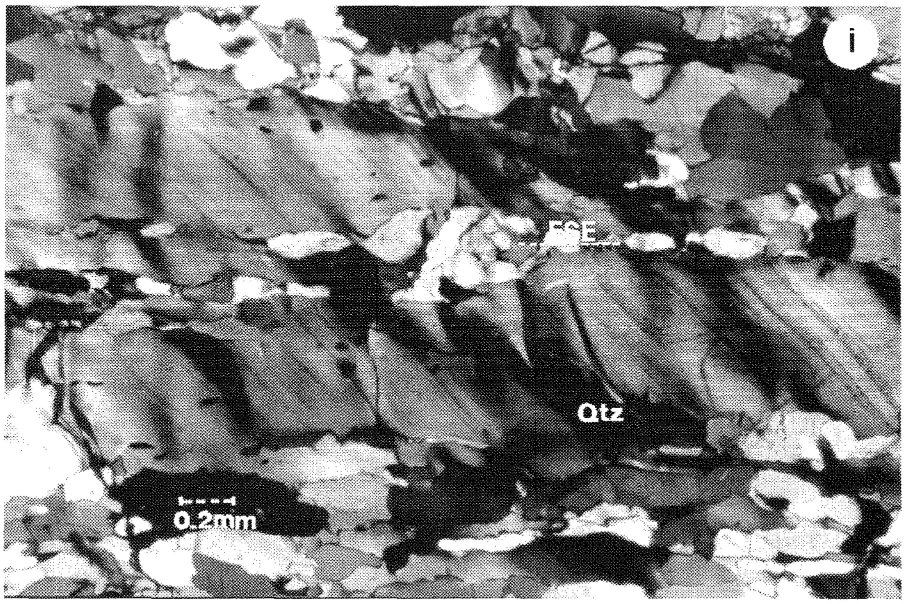

Fig. 4I.- Microphotograph of high-temperature ribbon quartz parallel to ESE mylonitic foliation in the banded migmatite of the Porto Ottiolo Shear Zone (IPOSZ) (Qtz - quartz, crossed nicols, XZ plane).

Fig. 4I.- Microphotographie de ruban de quartz de haute température parallèle à la foliation mylonitique précoce dans les migmatites rubanées de Porto Ottiolo (I POSZ). (Qtz - quartz, crossed polars, XZ plane).

Anglona Shear Zone (ASZ). The ASZ (Oggiano and Di Pisa, 1992), which crops out in northwestern Sardinia (Fig. 1), is a NW-SE-trending dextral ductile shear zone associated with ultramylonites that are between migmatites and ky+st+ol-bearing mica schists and paragneisses. The Badesi tonalite-granodiorite bodies, which show a solid-state flow foliation, are probably also related to this shear zone. A few kilometres to the north of the shear zone, two-mica granites, dated at 300 Ma ($^{40}Ar/^{39}Ar$ method on biotite; Macera *et al.*, 1989; Del Moro *et al.*, 1991), crop out in the migmatites. The ASZ is considered to be the northwestward prolongation of the II PVSZ (Cappelli *et al.*, 1992).

II Barrabisa Shear Zone (II BSZ). The II BSZ (Elter *et al.*, 1993; Fig. 1), is a branched system of NW-SE-trending

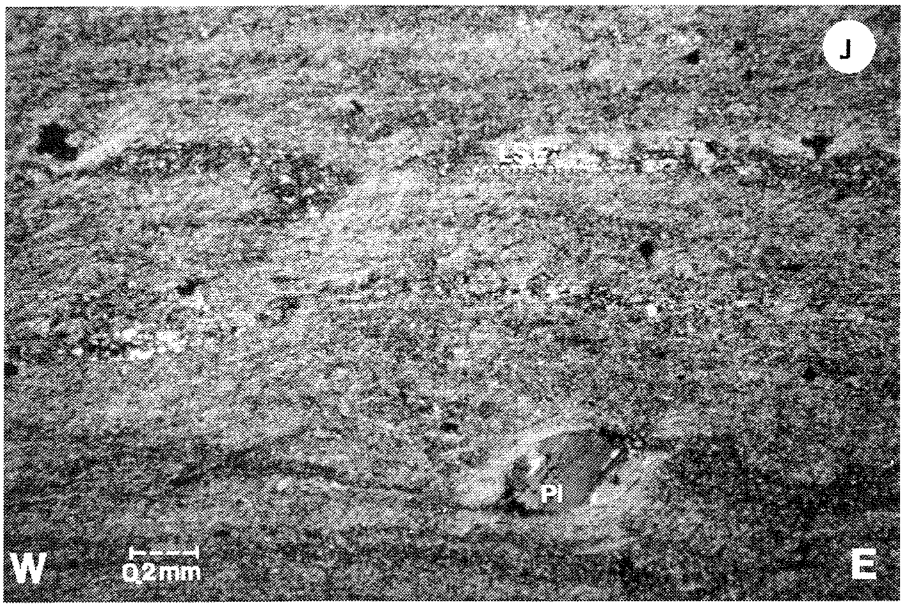

Fig. 4J.- Microphotograph of LSE ultramylonite in the Posada Valley Shear Zone (II PVSZ). The dextral sense of shear is defined by sigmoidal plagioclase porphyroclast (Pl) (crossed nicols, XZ plane).

Fig. 4J : Microphotographie d'ultramylonite dans la zone de cisaillement tardive de la Vallée de Posada (II PVSZ). Le sens de cisaillement dextre est défini par des porphyroclastes sigmoïdes de plagioclase (Pl). (nicols croisés, plan XZ).

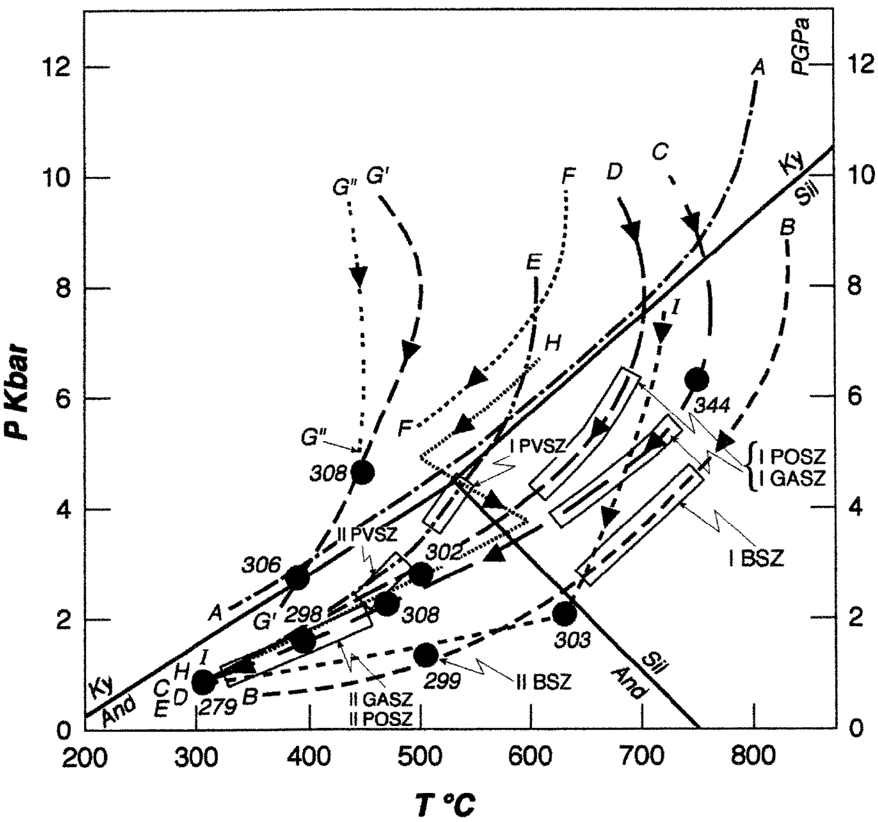

Fig. 5.- P-T-t paths for some metamorphic zones of the Hercynian basement (modified from Franceschelli et al., 1989, 1998; Musumeci, 1992; Ricci, 1992; Ghiribelli, 1992). A-A: P-T-t path of the granulites from NE Sardinia; B-B: P-T-t path of the sil + Kfs zone in the Barrabisa area; C-C: P-T-t path of the sil + Kfs zone in the Golfo Aranci and Porto Ottiolo areas; D-D: P-T-t path of the sil + ms zone in the Porto Ottiolo area; E-E, F-F: P-T-t paths of the ky + st + bt zone in the Posada Valley area; G'-G', G''-G'': P-T-t paths of the gt + bt zone; H-H: P-T-t path of the Grighini area; I-I: P-T-t path of the Anglona area.

subvertical and narrow (about 10 cm to 1 m thick) shear zones. A NW-SE subhorizontal biotite-muscovite lineation is recognized. A synkinematic two-mica granite dated at 300 Ma (40Ar/39Ar method on muscovite; Del Moro *et al.*, 1991) crops out in the western part of the shear zone. At the microscopic scale, biotite and muscovite are statistically subparallel to the new mylonitic foliation; the asymmetric mica shape indicates a dextral sense of shear.

LSE shear zones associated with synkinematic retrograde metamorphism

II Posada Valley Shear Zone (II PVSZ). The II PVSZ (Elter, 1985, 1987; Elter *et al.*, 1990, 1993) is an E-W-trending ductile dextral strike-slip fault exposed in the Posada Valley (Figs. 1, 2, 3). Its thickness reaches about 10 km and it is regarded as the boundary between the HGMC and the Nappe Zone (Elter and Corsi, 1995). Shear deformation gave rise to greenschist facies S-C mylonites. A subhorizontal E-W mineral lineation of biotite and chloritized biotite is clearly recognizable in all lithotypes. The mica schist and paragneiss show a condensed isograde succession (staurolite + biotite and kyanite + biotite). The kinematic analysis indicates a dextral sense of shear with a ductile displacement of about 6.5 km (Elter *et al.*, 1990). The II PVSZ shows many types of mylonitic rock, from protomylonites to ultramylonites. The mylonitic foliation is the only planar anisotropy observed in the ultramylonitic rocks (Fig. 4J). In the western part of the shear zone, the II PVSZ is affected by a HT metamorphism represented by a static biotite crystallization on the C plane and annealing of ribbon quartz. This thermal event was related to the emplacement of

Fig. 5.- Trajets P-T-t pour quelques zones métamorphiques du socle hercynien (modifié de Franceschelli et al., 1989, 1998; Musumeci, 1992 ; Ricci, 1992; Ghiribelli, 1992). A-A : trajet P-T-t pour les granulites du nord-est de la Sardaigne; B-B : trajet P-T-t de la zone à sil + Kfs pour Barrabisa ; C-C : trajet P-T-t de la zone à sil+kfs pour Golfo Aranci et Porto Ottiolo ; D-D : trajet P-T-t de la zone à sil+ms pour Porto Ottiolo ; E-E, F-F : trajets P-T-t des zones à st+ky+bt pour la Vallée de Posada ; G'-G', G''-G'' : trajets P-T-t des micaschistes et paragneiss de la zone à gt+bt ; H-H : trajet P-T-t pour Grighini ; I-I : trajet P-T-t pour Anglona.

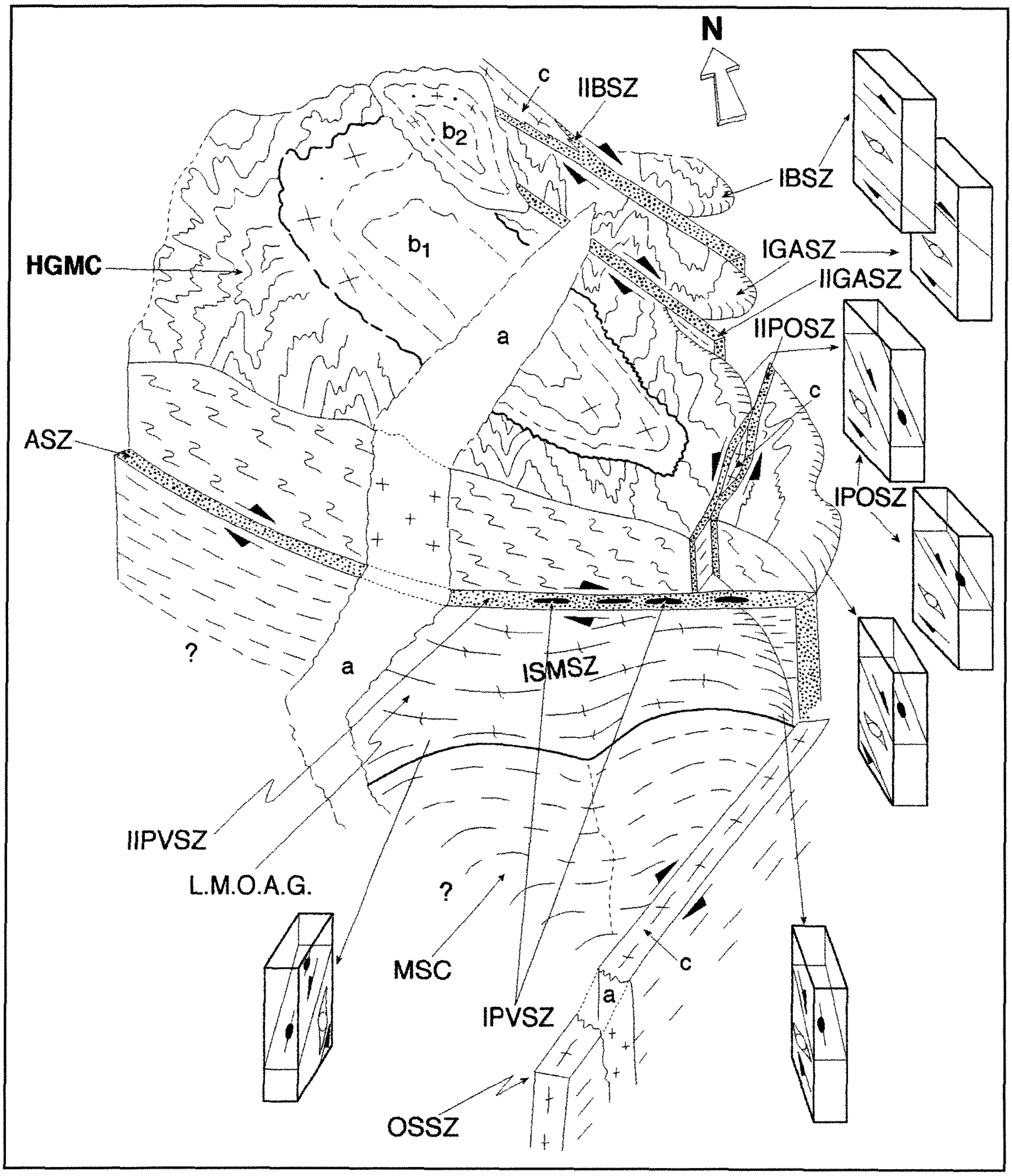

Fig. 6.- Schematic block diagram of NE Sardinia (modified from Elter and Corsi, 1995). a: post-tectonic leucogranites; b1: syn-tectonic granodioritic suite; b2: late-tectonic monzogranitic suite; c: syn-kinematic granitic suite (Barrabisa and Ottana intrusions); M.S.C.: mica schist and paragneiss of ab+ol+gt zone; L.M.O.A.G.: Lodé-Mamone augen-orthogneiss; black lenses: Torpé amphibolites; HGMC: High Grade Metamorphic Complex. ESE: I BSZ, I GASZ, I POSZ, I PVSZ, I SMSZ; LSE with synkinematic retrograde metamorphism: II GASZ, II POSZ, II PVSZ; LSE with synkinematic granitic intrusions: ASZ, OSSZ, II BSZ.

Fig. 6.- Bloc diagramme schématique du nord-est de la Sardaigne (modifié de Elter et Corsi, 1995). a) : granite post-tectonique (leucogranites); b1 : suite granitique syn-tectonique (suite granodioritique) ; b2 : suite granitique tardi-tectonique (monzogranitique) ; c : granite syn-cinématique (intrusions de Barrabisa et Ottana); M.S.C.: micaschiste et paragneiss de la zone albite+oligoclase+grenat ; L.M.O.A.G. : orthogneiss oeillé de Lodé-Mamone ; lentilles noires : amphibolites de Torpé ; HGMC : Complexe Metamorphique de haut grade. Zones de cisaillement (ESE) : I BSZ, I GASZ, I POSZ, I PVSZ, I SMSZ ; zones de cisaillement tardives avec un métamorphisme retrograde syn-cinématique : II GASZ, II POSZ, II PVSZ; zones de cisaillement avec des intrusions granitiques syn-cinématiques : ASZ, OSSZ, II BSZ.

large leucogranitic bodies dated about 290 Ma (Rb/Sr; Bralia *et al.*, 1981).

II Porto Ottiolo Shear Zone (II POSZ). The II POSZ (Elter and Corsi, 1995) is a branched system of narrow, NNE-SSW-trending subvertical shear zones (about 5 cm to 1 m thick), that transposes the earlier shear zones. Subhorizontal NE-SW biotite and muscovite lineations are clearly recognizable along the mylonitic foliation. Well-preserved kinematic indicators show a sinistral sense of shear. This narrow shear zone is also characterized by elongate bodies of foliated granite or granodiorite and by aplitic/pegmatitic dykes.

II Golfo Aranci Shear Zone (II GASZ). The II GASZ (Elter *et al.*, 1993; Elter and Ghezzo, 1995) is an anastomosing system of narrow NNW-SSE-trending subvertical shear zones (about 10 cm to 5 m thick) with NNW-SSE subhorizontal lineations of biotite and muscovite. These narrow shear zones are characterized by the presence of foliated granitic bodies as in the II POSZ. The NW-SE foliation, the subhorizontal lineation and shear criteria indicate a dextral motion.

Discussion and implications concerning the exhumation of the Sardinian basement

As presently known from the literature (Bralia *et al.*, 1981; Ricci, 1992; Carmignani *et al*, 1994), the Sardinian Belt of the Hercynian Orogeny underwent contrasted metamorphic-structural evolutions from the External Zone to the Axial Zone. The Permian-Triassic volcanic-sedimentary basins exhibit different rates of extension from south to north (Fontana *et al.*, 1982). In the Nappe Zone, the Permian-Triassic basins rest on a greenschist facies metamorphic sequence, whereas in the HGMC they overlie migmatites. The P-T-t path of the HGMC (Fig. 5) suggests a depth about 30 to 15 km for the migmatization process related to a fast decompression connected with the uplift (Ricci, 1992). Extension was induced by gravity collapse of the previously thickened Hercynian crust (Carmignani *et al.*, 1993) as suggested in other domains of the Hercynian Belt (e.g. Faure, 1995).

For Sardinia, we propose, a geodynamic evolutionary model whereby the exhumation was tectonically assisted by the shear zones of the Early Shear Event (ESE). All these shear zones exhibit the following features: i) pervasive HT-LP metamorphism coeval with shearing; ii) variably trending foliation planes; iii) consistent NW-SE mineral and stretching lineations; iv) consistent top-to-the-SE shearing. Due to their areal arrangement, these shear zones allow us to recognize the presence of a gneissic-migmatitic dome in the HGMC (Fig. 6). Therefore the ESE can be globally interpreted as related to an extensional doming.

This early period was followed by a second ductile deformation (LSE) characterized by dominantly dextral strike-slip wrenching (only the II POSZ is sinistral). Some of these late shear zones are associated with synkinematic granites for which the age of emplacement is confined between *ca.* 305 Ma and 295 Ma. Due to the main horizontal component of displacement, these faults did not play a significant role in the exhumation of the Sardinian basement. The network of the shear zones related to the LSE is not restricted to Sardinia, but is also found in Corsica and the Maures Massif (Vauchez and Bufalo, 1988; Corsi *et al.*, 1998, Onezime *et al.*, 1999; Elter *et al.*, 1990) and clearly belongs to the Late Carboniferous-Permian shear pattern recognized throughout the Hercynian belt (Arthaud and Matte, 1975).

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