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ScienceDirect
Journal of Geodynamics 42 (2006) 140–158
JOURNAL OF GEODYNAMICS
http://www.elsevier.com/locate/jog

The Curinga-Girifalco fault zone (northern Serre, Calabria) and its significance within the Alpine tectonic evolution of the western Mediterranean

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Received 25 January 2006; received in revised form 26 June 2006; accepted 27 June 2006

Abstract

Hercynian basement rocks and Mesozoic ophiolites of the Calabria-Peloritani terrane drifted in the present position during the opening of western Mediterranean basins (namely Liguro-Provençal and Tyrrhenian basins) since the Oligocene. Basement rocks were partly involved by Alpine (late Cretaceous—Eocene) deformation and metamorphism before the onset of the drifting process. Even though the kinematics of the Alpine deformation in Calabria has been already defined, restoration of structural and kinematic data to the original position and orientation before the opening of the western Mediterranean has never been performed. In this work we present new structural and petrological data on a major tectonic contact of Alpine age exposed in central Calabria (Serre Massif). Structural and kinematic data are then restored at the original orientation in the early Oligocene time, to allow a correct tectonic interpretation.

In the Serre Massif the Hercynian basement is sliced into three nappes emplaced during the Alpine orogeny. The upper nappe is formed by a nearly continuous section of the Hercynian crust, consisting of medium- to high-grade metamorphic rocks in the lower portion. The intermediate nappe mainly consists of orthogneisses, whereas the lower nappe is chiefly composed of phyllites. The contacts between the Alpine nappes are outlined by well developed mylonitic and cataclastic rocks. The Curinga-Girifalco Line is a well exposed shear zone that overprints mainly metapelitic rocks of the upper nappe and granitoid orthogneisses of the intermediate nappe. Mylonites of the intermediate nappe typically show overgrowths on garnet and hornblende with grossular-rich and tschermakitic composition, respectively. The Alpine mineral assemblage indicates that deformation took place in epidote-amphibolite facies at pressures ranging from 0.75 to 0.9 GPa.

In the investigated area mylonites strike roughly WNW–ESE, with shallow dips towards SSW. Kinematic indicators in mylonites are mostly consistent with a top-to-the-SE shear sense in the present geographic coordinates. The mylonitic belt is affected by later extensional faults outlined by South-dipping cataclasite horizons. Published geochronological data indicate that mylonites and cataclasites developed in Eocene and early Miocene times, respectively.

Considering rotational parameters coming from paleomagnetic studies and large-scale palinspastic reconstructions, the shear sense of the Curinga-Girifalco Line has been restored to the early Oligocene position and orientation. Through restoration a top-to-the-S shear sense is obtained. This result is in striking agreement with the convergence direction between Africa and W-Europe/Iberia during Eocene, computed from the North Atlantic magnetic anomalies. Our geodynamic reconstruction, combined with structural

DOI of the original article:10.1016/j.jog.2006.06.003
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doi:10.1016/j.jog.2006.06.004

and petrological evidence, allows to relate the Curinga-Girifalco mylonites to a thrust related to the southeastern front of the double-verging Alpine chain. The adopted method could be used also for other exotic terranes, such as the Kabylie or the Corsica-Sardinia, to better constrain geometry and evolution of the southern Alpine belt.

Keywords: Western Mediterranean evolution; Calabria-Peloritani terrane; Alpine metamorphic overprint; Shear zone; Palinspastic reconstruction

1. Introduction

The Calabria-Peloritani terrane is an exotic fragment, mainly consisting of Hercynian basement rocks, located between the Sicilian Maghrebides and the Southern Apennines (Fig. 1a). According to classical interpretations (e.g., Alvarez et al., 1974), the Hercynian basement, together with ophiolite-bearing nappes, underwent deformation and metamorphism during Paleogene (Borsi and Dubois, 1968; Rossetti et al., 2001) within the southern branch of the Alpine chain (Southern Alpine belt in Fig. 1b). Southeastward drifting of the Calabria-Peloritani terrane to the present position took place during the opening of western Mediterranean basins (or Liguro-Provençal and Tyrrhenian basins), since the Oligocene. Plate kinematics reconstructions in the Mediterranean area have always been very controversial due to the lack of well-defined oceanic magnetic anomalies and to complex tectonic history. Large scale Africa–Europe plate kinematics is usually reconstructed by using North Atlantic magnetic anomalies providing a regional framework in which more local marine and land geological information need to be placed. The interferences between orogenic and extensional processes leading to tectonic inversion make difficult to correlate land geology information and fairly complicates our understanding of the western Mediterranean evolution. Consequently, most of the reconstructions are based on marine geophysics and geology data. However, these models have to be confirmed by the structural and stratigraphical evidences derived from land survey. This is usually done by placing stratigraphic and sedimentary information on a paleogeographic sketch, structural data being used only for shortening or extension directions (D'Argenio et al., 1973; Mostardini and Merlini, 1986; Dercourt et al., 1986).

This paper aims to discuss new structural, kinematic and petrological data recently collected in central Calabria (northern Serre area) along a major Alpine shear zone (Schenk, 1980). This shear zone is located at the base of the main crystalline nappe of Calabria making this a key area to reconstruct the kinematics of the Alpine deformation. Structural and microstructural analyses are used to constrain kinematics, whereas petrology indicates depth and thermal conditions during shear zone development. Structural and kinematic data are then restored to the original position

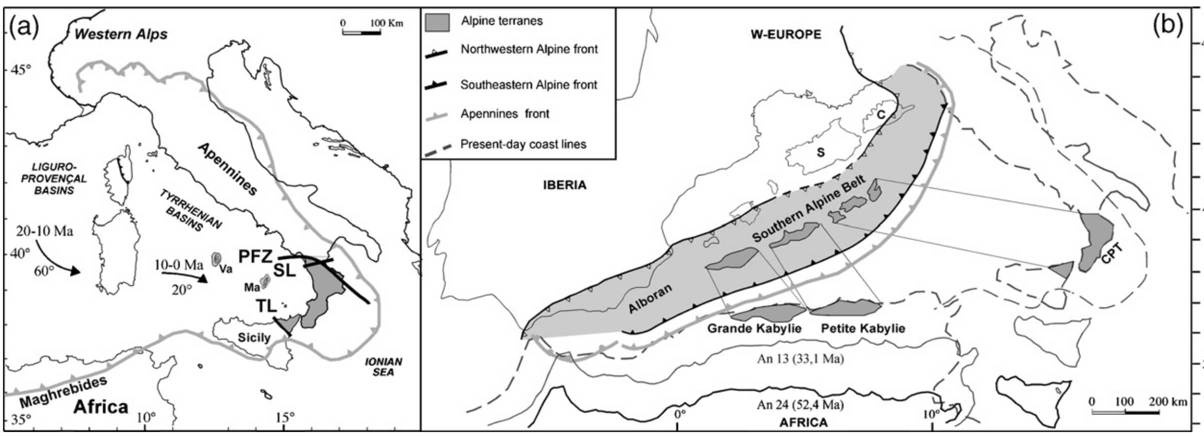

Fig. 1. (a) Tectonic sketch map of the Apennines and the Tyrrhenian Sea (modified after Gueguen et al., 2001). The major strike-slip faults that bound the Calabria-Peloritani terrane and the main rotational phases experienced by this area during the opening of Liguro-Provençal Basin (60° counterclockwise) and Tyrrhenian sea (20° clockwise) are also represented. The counterclockwise rotation is the same for the entire Calabria-Peloritani terrane; the clockwise rotation is referred only to the central–southern Calabria. *Abbreviations:* SL, Sangineto Line; PFZ, Pollino Fault Zone; TL, Taormina Line; Va, Vavilon basin; Ma, Marsili basin. (b) Pre–rift framework of the western Mediterranean showing the final position of the Calabria-Peloritani and Kabylie terranes after post-Oligocene migration, according to Alvarez et al. (1974) and Gueguen et al. (1998). In the reconstruction are also reported paleoposition of Africa at An 24 and An 13. *Abbreviations:* CPT, Calabria-Peloritani terrane; S, Sardinia; C, Corsica; An, Magnetic anomaly.

and orientation; distances and angles are derived from regional palinspastic reconstructions computed following a quantitative approach (Gueguen et al., 1998). This reconstruction, mainly based on structural and kinematic data, is then used to verify consistency of plate tectonics models of the Mediterranean area, with particular emphasis on the convergence direction between Africa and W-Europe/Iberia during Eocene.

2. Geological setting

Due to its long and complex geological history, the western Mediterranean area has always been an intricate puzzle in geodynamic reconstructions. In fact, this area has been involved in all the major geodynamic and tectonic events since the Hercynian times. As a consequence, the origin and position of the Calabria crystalline terrains has been thoroughly discussed in the literature (Argand, 1916; Ogniben, 1969; Dubois, 1970; Alvarez et al., 1974; Amodio-Morelli et al., 1976; Vai, 1992; Cello et al., 1996; Bonardi et al., 2001; Rossetti et al., 2001). Hereafter, we will briefly review the geodynamics of the Liguro-Provençal and Tyrrhenian basins that is closely connected to the evolution of the Calabria-Peloritani terrane.

2.1. Regional outline of the central–western Mediterranean

The evolution of the southern Alpine belt, now dismembered around the western Mediterranean basins (Fig. 1b), is still very controversial. The most debated topic is the dip of the subduction during the late Cretaceous-Paleogene in the double-verging Alpine chain. Some authors (Alvarez, 1976; Réhault et al., 1984; Doglioni, 1991; Doglioni et al., 1999; Guerrera et al., 2005) argue in favour of a SE-dipping Alpine type subduction and main norhwestward vergence of the chain (Haccard et al., 1972; Amodio-Morelli et al., 1976; Bonardi et al., 1994; Cello et al., 1996). Other authors (Dercourt et al., 1986; Séranne, 1999) think that the subduction already started in the southern Alpine belt with a NW-dipping Apennine polarity, with a main vergence towards the southeast (Rossetti et al., 2001; Faccenna et al., 2001).

However, starting from late Eocene the geodynamical framework of the western Mediterranean area underwent dramatic changes when the European continental lithosphere began to be involved in the subduction in the western Alps (Stampfli et al., 2002 and references therein). As a consequence, the northwestern front of the Alpine system reached the stage of continental collision (Fig. 1b). In this stage the subduction rate of European lithosphere decreased while the Africa–Europe plate convergence rate, linked to the opening of the Atlantic ocean, remained almost steady. This led to a progressive increase of deformation along the southeastern front of the southern Alpine belt, giving rise to the Apennines front during the Oligocene (Fig. 1b). Therefore, the Neogene and Quaternary geodynamics of the western Mediterranean was dominated by the roughly eastward migration of the Apennines–Maghrebides arc in the general frame of slow convergence between Africa and Europe. Coevally, extension propagated towards the southeast in the hangingwall of the retreating west-dipping subduction zone (Réhault et al., 1984; Malinverno and Ryan, 1986; Doglioni, 1991; Gueguen et al., 1997, 1998). The evidences for the subduction of the Adriatic plate underneath Italy have been deeply reinforced through time by geophysical and geochemical data (Mongelli et al., 1975; Peccerillo, 1985; Finetti and Del Ben, 1986; Beccaluva et al., 1989; Spakman, 1989; Amato et al., 1993; Serri et al., 1993; Selvaggi and Chiarabba, 1995). More recently, Lucente et al. (1999) clearly imaged a high-velocity anomaly that flattens at the lower-upper mantle discontinuity beneath the Tyrrhenian sea, consistently with the presence of a long subducted slab. The presence of a still active subduction under the Apennine chain is questioned by some authors (i.e., Carminati et al., 1998; Wortel and Spakman, 2000) that envisage slab breakoff episodes during the late Miocene-Pliocene.

Starting from 118 Ma the relative motion of Africa with respect to Europe followed a counterclockwise path with orientations varying from SW–NE to S–N. However, the convergence direction for the last 10 Ma is still controversial: northwestwards (Dewey et al., 1989; Mazzoli and Helman, 1994; Rosenbaum et al., 2002); northwards (Srivastava et al., 1990); northeastwards (Albarello et al., 1995). The amount of shortening during the whole Tertiary is estimated to about 150 km in the western Alboran area (Fig. 1b) and increases significantly further East (Tunisia), up to 250 km (Campan, 1995) or 300 km (Dewey et al., 1989).

The West-directed subduction retreated eastward up the present position underneath the Apennines and Maghrebides (Fig. 1b). In the hangingwall of the subduction back-arc extension opened irregular troughs as the Liguro-Provençal and Tyrrhenian basins (Réhault et al., 1984; Malinverno and Ryan, 1986; Royden et al., 1987; Doglioni, 1991). Lithospheric swells, sort of boudins, were isolated between those basins, such as the Corsica-Sardinia microplate

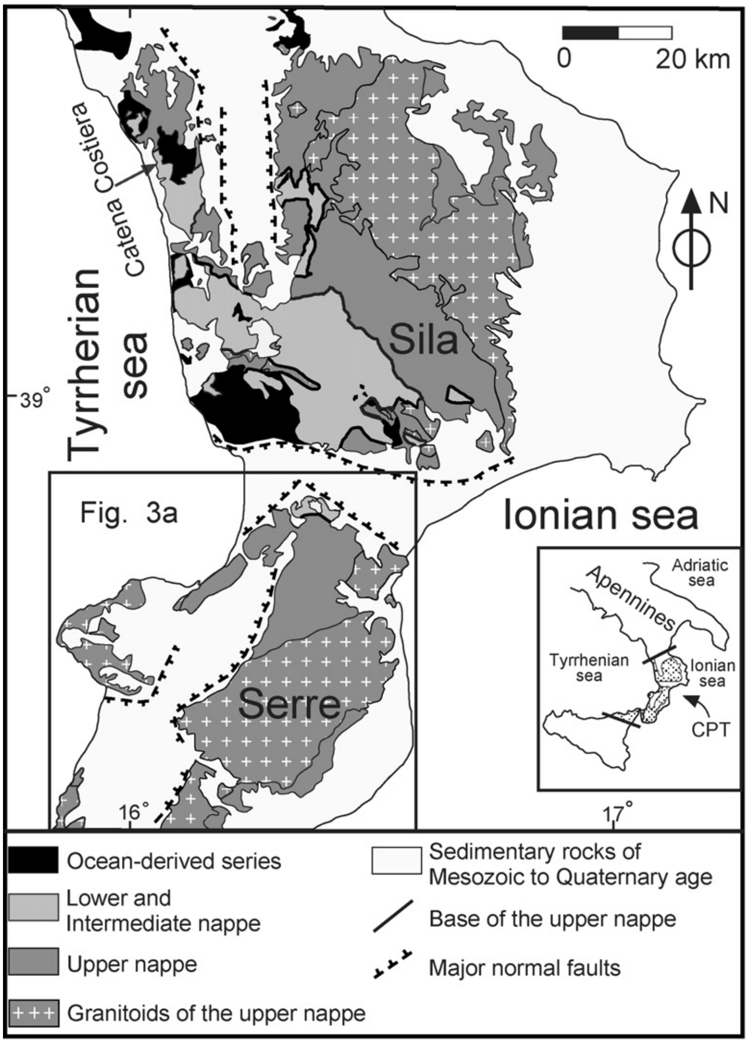

Fig. 2. Geological sketch map of the northern–central Calabria, inspired to Amodio-Morelli et al. (1976), Schenk (1990) and Bonardi et al. (2001).

and the Balearic promontory (Gueguen et al., 1997). Coevally, the Alpine-Betic orogen was dismembered in several fragments, like the Kabylian and Calabria-Peloritani terranes, that migrated southeastward and overthrusted the Apennine–Maghrebide chain (Alvarez et al., 1974; Réhault et al., 1984; Gueguen et al., 1997). These fragments are well recognisable since consist mostly of metamorphic and igneous rocks, that differ from the sedimentary rocks typical of the Apennine–Maghrebide orogeny. The Calabria-Peloritani crystalline fragment represents an exotic terrane located between the Sicilian Maghrebides and the southern Apennines. This block is bounded by important strike-slip faults of regional importance (Fig. 1a), namely the Sangineto Line (Amodio-Morelli et al., 1976) or Pollino Fault Zone (Van Dijk and Scheepers, 1995; Perrone, 1996) to the North and the Taormina Line to the South (Ghisetti and Vezzani, 1981). In the following section, we will describe the regional geology of northern–central Calabria, addressing in particular the Alpine deformation in the northern Serre area (Figs. 2 and 3a).

2.2. Geology of northern Serre

The northern Serre area (central Calabria, Figs. 2 and 3a) is mainly characterized by outcrops of the Hercynian continental crust, locally overprinted by Alpine deformation and retrograde metamorphism (Paglionico and Piccarreta, 1976). In northern Calabria (Sila and Catena Costiera; Fig. 2) tectonic units derived from the Hercynian continental crust overlie oceanic-derived series related to the Jurassic rifting (Dietrich, 1976), whereas these series are not observed

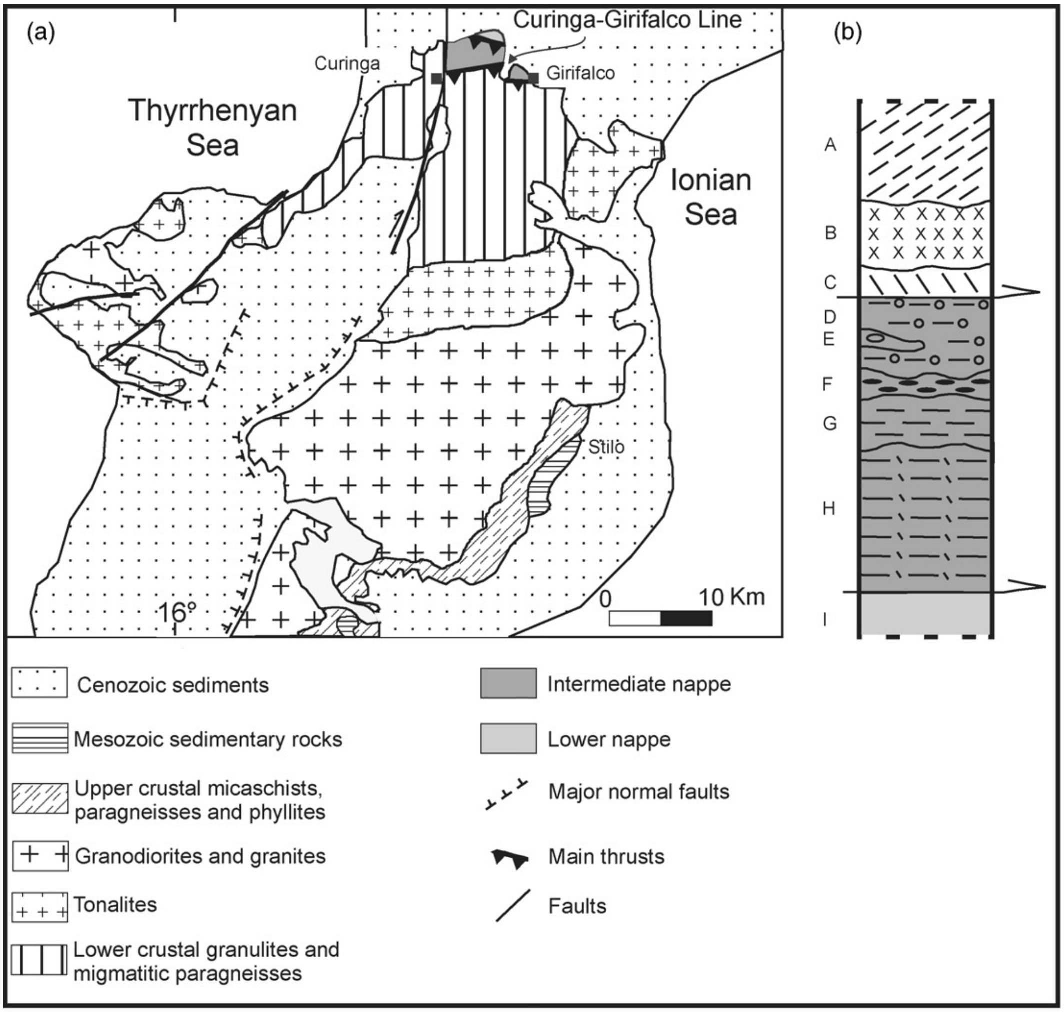

Fig. 3. (a) Schematic geology of the Serre Massif (modified after Schenk, 1990; Rottura et al., 1991; Bonardi et al., 2001); (b) lithological and tectonic sketch across the nappe pile, inspired to Amodio-Morelli et al. (1976) and Paglionico and Piccarreta (1976): (A) fine-grained to coarse-grained fels; (B) metabasic rocks; (C) migmatitic paragneisses; (D) granitoid orthogneisses; (E) amphibolite lenses; (F) augen gneisses; (G) leucocratic orthogneisses; (H) paragneisses and micaschists; (I) phyllites.

in central and southern Calabria (Amodio-Morelli et al., 1976; Bonardi et al., 2001). The continental crust mainly consists of three nappes (Dubois, 1970) that can be distinguished on the basis of the different Hercynian and Alpine overprints.

The upper nappe has a considerable thickness and represents a nearly continuous section of the Hercynian crust (Schenk, 1980) well recognizable both in northern and in central Calabria (Serre; Fig. 3a). It is composed of granulite facies metamorphic rocks, overlain by thick granitoid sheets in the intermediate level, followed upwards by medium- to low-grade metamorphic rocks. The main metamorphism, responsible also for partial melting in the lower crust, was synchronous to intrusion of granitoids and took place during the late stages of the Hercynian orogeny (Graessner et al., 2000).

The intermediate and lower nappes have a minor thicknesses and are composed of Hercynian medium to low-grade metamorphic rocks. The Alpine metamorphic overprint locally affected both nappes along some shear zones. In the northern Serre area the intermediate nappe mainly consists of orthogneisses with some paragneisses and micaschists (Paglionico and Piccarreta, 1976), whereas the lower nappe is chiefly composed of phyllites (Fig. 3b), locally overlain by Mesozoic sediments in the Catena Costiera area (Dietrich, 1976; Fig. 2). A Rb–Sr age on white mica of 268 ± 4 Ma has been obtained by Schenk (1980) on a mylonitic orthogneiss of the intermediate nappe. This age resulted from a sample containing both tiny Alpine white mica and larger Hercynian mica fishes. For this reason it was considered by Schenk (1980) as a mixed age.

The nappe pile has been built up during the Alpine orogeny and all tectonic contacts are outlined by well-developed mylonites and cataclastic rocks. The contact between the upper and intermediate nappes (Fig. 2) separates the base of the thick crustal section from amphibolite-facies gneisses and shows the best developed Alpine overprint. In the northern Serre area this contact is known as the Curinga-Girifalco Line (Fig. 3a). Schenk (1981) compared this structure to a segment of the Insubric Line that in the western Alps separates the crustal section of the Ivrea zone to the South, unaffected by the Alpine event, from the Sesia zone to the North, overprinted by intense Alpine metamorphism. Rb–Sr method on biotite yielded an Eocene age (43 ± 1 Ma) on a mylonitic orthogneiss from the intermediate nappe (Schenk, 1980). Using the fission track method on zircon and apatite Thomson (1994, 1998) proposed that the low temperature history of the Curinga-Girifalco Line developed during crustal extensional movements between 18 and 15 Ma.

3. The Curinga-Girifalco Line

The Curinga-Girifalco Line is characterized by cataclastic and mylonitic rocks arranged in a 400 m thick belt (Fig. 4a and b). The deformation zone mainly consists of mylonites that generally overprint migmatitic paragneisses of the upper nappe and granitoid orthogneisses of the intermediate nappe (Fig. 4b). Mylonites derived from the migmatitic paragneisses have been identified as the mylonites of the Curinga-Girifalco Line by Spiegel (2003). Thin bands of incohesive grey cataclasites, produced at lower T conditions, are found chiefly near the contact between the upper and the intermediate nappe with a thickness of some meters.

3.1. Field and structural data

In the analysed area the Curinga-Girifalco Line is roughly oriented WNW–ESE and the main contact dips of 37° to the SSW (197°N; Fig. 4a). The shear zone is offset by younger faults showing strike-slip or extensional kinematics. Migmatitic paragneisses of the upper nappe are present in the hangingwall, whereas orthogneisses and paragneisses of the intermediate nappe are mostly located in the footwall. A minor sheet of migmatitic paragneisses is enclosed within the lithologies of the intermediate nappe along the Pilla stream and South of the Iacurso village (Fig. 4a).

The aim of the field work was to reconstruct the deformation history and sense of shear of the Curinga-Girifalco Line. A detailed mapping of the tectonites and of their relationships with the less deformed host rocks has been performed. Furthermore, in order to better constrain the geometry of the shear zone, particular attention has been dedicated to measurements of lineation and foliation both in the migmatitic paragneisses and in the granitoid orthogneisses. Even if outcropping conditions are quite good over the entire area, two localities, close to the Girifalco psychiatric hospital and the hydroelectric central (Fig. 4a), resulted of particular interest showing the entire deformed belt. In fact, weakly deformed rocks of both footwall and hangingwall as well as highly deformed rocks of the shear zone can be observed there.

In the studied area foliation presents a variable attitude due to late folding events. The main foliation in the migmatitic paragneisses is mostly defined by a compositional layering inherited from the Hercynian fabric. The Alpine event reworked this original fabric that now appears strongly flattened and sheared. A prevailing South-dipping attitude of the foliation was widely recognized (Fig. 5a). Lineations on foliation planes plunge at low angle towards 104°N and 150°N (Fig. 5a). These are outlined by both stretched quartz crystals and aligned biotite flakes. The main foliation of granitoid orthogneisses gently dips towards East and South (Fig. 5b). The lineations are defined by elongated quartz grains, aligned biotite flakes and feldspar porphyroclasts. Their orientation is broadly northwest–southeast, but a wide scatter in the southeast quadrant is observed (Fig. 5b). Close to the Addolorata church in Girifalco village (Fig. 4a), granitoid orthogneiss display two distinct lineations, plunging to 140°N and 280°N on the same mylonitic foliation. This suggests a polyphase deformation history of the intermediate nappe. Summing up, lineations with slightly different orientations (about 140–150°N and 105–110°N) are observed in both hangingwall and footwall rocks of the Curinga-Girifalco Line. As shown above, all lineations display similar features and thus can be referred to the Alpine deformation. The Hercynian fabric is well preserved in the upper nappe South of the Curinga-Girifalco Line where foliations and variably oriented stretching lineations are related to granulite facies metamorphism (Kruhl and Huntemann, 1991).

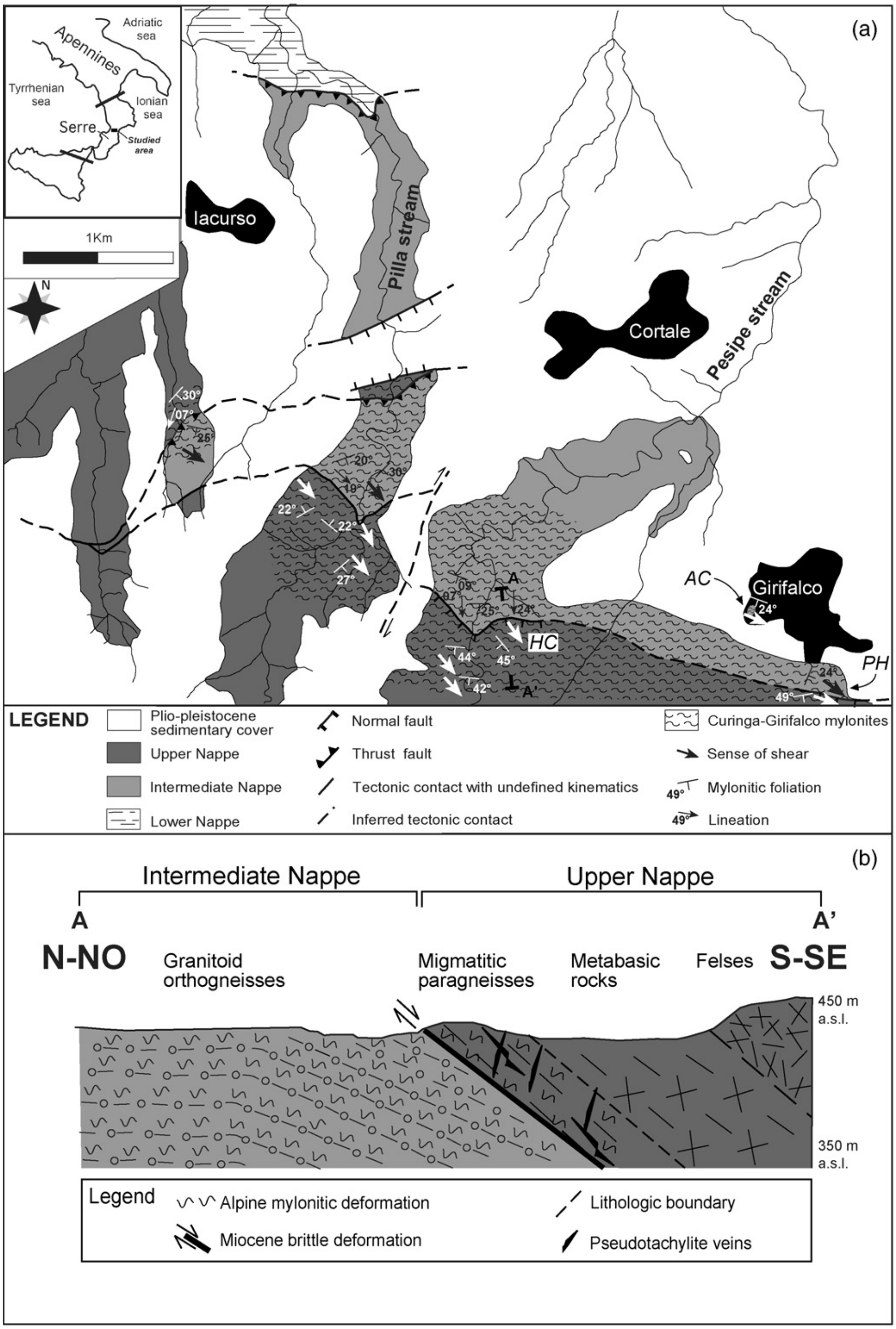

Fig. 4. (a) Geological map of the studied area (northern Serre), based on original 1:5000 mapping, showing the Curinga-Girifalco mylonites and the distribution of the kinematics and structural data. *Abbreviations:* HC, hydroelectric central; AC, Addolorata church; PH, psychiatric hospital; (b) cross-section showing the main features of the Curinga-Girifalco Line at the hydroelectric central (A–A′ in the geological map).

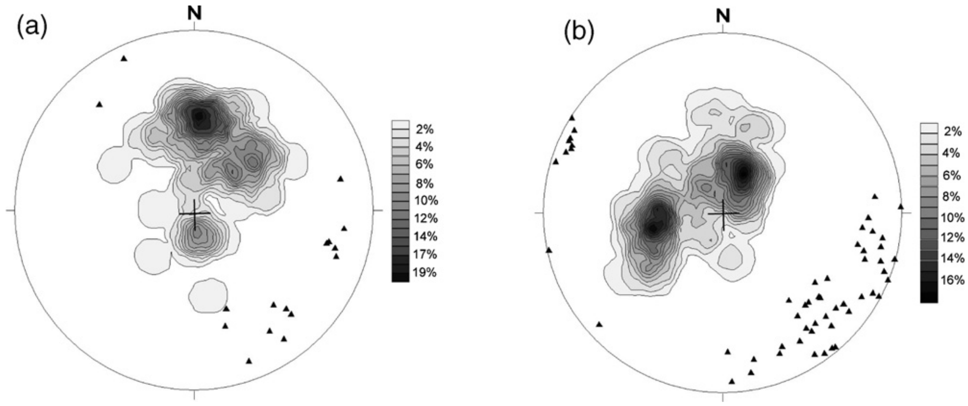

Fig. 5. Structural data from the Curinga-Girifalco mylonites. Stereoplots show contour line of the poles to the mylonitic foliation of migmatitic paragneisses (a: 90 data) and granitoid orthogneisses (b: 134 data). Equal-area projection, lower hemisphere, search area 1.0%; peak 20% in paragneisses, 18.66% in orthogneisses. Small triangles represent stretching and mineral lineation of migmatitic paragneisses (a, 17 data) and granitoid orthogneisses (b, 55 data).

3.2. Petrography and microstructures of the Curinga-Girifalco mylonites

The Hercynian mineral paragenesis of migmatitic paragneisses mainly consists of quartz + garnet + sillimanite + biotite ± K-feldspar and ± plagioclase defining amphibolite/granulite facies conditions. Cordierite has been locally recognized by Spiegel (2003). During the late-Hercynian evolution (300–290 Ma) high grade metapelites experienced peak metamorphic conditions in a *T* range of 680–800 °C and *P* range of 0.55–0.75 GPa (Schenk, 1984, 1990). In the migmatitic paragneisses two main fabrics related to the Hercynian and Alpine deformations, respectively, can be recognized. The Hercynian fabric is characterized by alternating leucocratic and melanocratic layers, e.g., quartz- and feldspar-rich leucosome and biotite- and sillimanite-rich melanosome, respectively, that define a migmatitic layering of stromatic type (Ashworth, 1985). Generally, the foliation wraps around different porphyroblasts (garnet, K-feldspar, sillimanite aggregates) of variable size (0.5–4.5 mm), following an anastomosing pattern.

During the Alpine orogenesis, migmatitic paragneisses experienced a metamorphic overprint and deformation at lower temperature conditions (Fig. 6a). The Alpine metamorphic event caused a partial mineral reequilibration. Chloritization of biotite and garnet, formation of white mica and quartz at the expense of K-feldspar and sillimanite are locally observed. Sillimanite breakdown is very incomplete, as documented by well recognisable prismatic crystals that are commonly boudinaged with precipitation of white mica, biotite and oxides in necks and extensional fractures.

Widespread pseudotachylite veins, with thickness ranging from few cm to 1 m, are generally parallel or at low angles to the mylonitic foliation and often display an ultramylonitic fabric (Fig. 6b). Matrix mainly contains biotite, whereas clasts are represented by sillimanite, quartz and feldspar, both in single crystals and in aggregates. The presence of ductilely deformed pseudotachylites in the mylonites is indicative of *T* conditions typical of the brittle–ductile transition, where pseudotachylite-forming events are intermittent in an overall ductile regime (Passchier, 1982, 1985; Swanson, 1992). Incomplete retrograde reactions and abundance of pseudotachylite veins indicate that deformation took place in water-deficient conditions (Passchier, 1985). As pointed out by Spiegel (2003), this is a consequence of the low water content in the fluid phase of the metapelitic protolith.

Orthogneisses of the intermediate nappe are the main lithology affected by shearing in the footwall of the Curinga-Girifalco Line. These are metagranitoid rocks mostly composed of quartz + K-feldspar + muscovite + biotite ± garnet ± epidote and ± plagioclase. Amphibolite lenses, consisting of hornblende + plagioclase + quartz + epidote + phengite ± biotite, chlorite and sphene, are closely associated with the orthogneisses. The Hercynian fabric, locally observed in migmatitic paragneisses, is here not recognizable and the main fabric is related to the Alpine metamorphic event. In the orthogneisses K-feldspar porphyroclasts are generally wrapped by thin layers of mica and quartz grains defining an anastomosing foliation (Fig. 6c). The ductile Alpine event determined the formation of a mylonitic foliation, reduction of porphyroclast size and development of rare pseudotachylite veins. Mylonitization is accompanied by crystallization of small grains of biotite, white mica and epidote along the foliation planes. Retrograde reactions, such as chloritization of biotite and sericitization of K-feldspar, are locally observed.

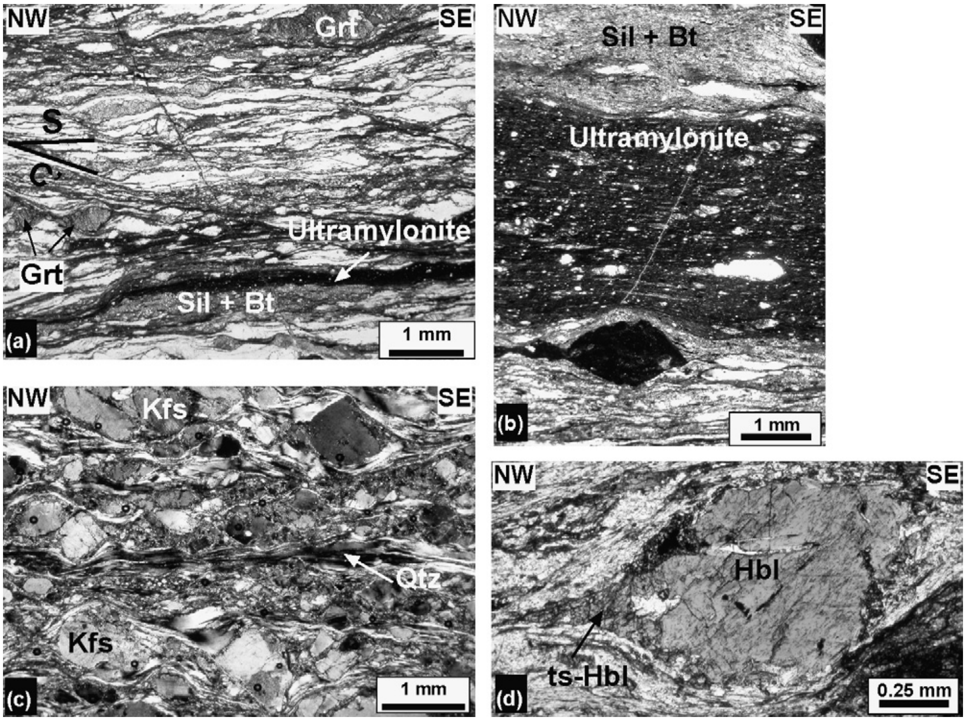

Fig. 6. Micrographs of the Curinga-Girifalco mylonites. (a) Typical fabric characters of a mylonite derived from migmatitic paragneisses (plane polarized light); (b) pseudotachylites showing an ultramylonitic fabric in the migmatitic paragneisses (crossed polars); (c) mylonites derived from granitoid orthogneisses (crossed polars); (d) sigmoidal hornblende porphyroclasts with tails of bluish tschermakitic hornblende. Mineral symbols according to Kretz (1983).

The presence of stable biotite on the foliation planes in almost all the examined mylonites indicates temperatures higher than 400 °C. Both in the migmatitic paragneisses and in the granitoid orthogneisses mylonitization promoted different intracrystalline deformation mechanisms. Effects of these mechanisms are mostly visible in quartz that is generally present as stretched crystals. This phase shows deformation bands and subgrain boundaries as a consequence of recovery, combined with dynamic recrystallization by bulge nucleation and subgrain rotation (White, 1977; Urai et al., 1986). The latter recrystallization mechanism is outlined by the gradual transition of aggregates of subgrains to aggregates of new grains. The widespread evidence of dynamic recrystallization by subgrain rotation in quartz is consistent with deformation taking place at intermediate temperatures (about 400–500 °C) according to Stipp et al. (2002). Other mineral phases such as feldspar, mica, garnet and sillimanite show mainly microfaulting, kinking and boudinage. Incipient intracrystalline deformation is locally observed in K-feldspars. In amphibolite lenses hornblende makes up porphyroclasts with a sigmoidal shape (Fig. 6d), wrapped by mica flakes and epidote grains.

3.3. *P–T* conditions of deformation

P–T conditions during mylonitization favoured formation of rare overgrowths around some minerals. These are observed in the lithologies of the intermediate nappe. We recognized overgrowths of garnet in granitoid orthogneisses and overgrowths of bluish tschermakitic hornblende around green hornblende porphyroclasts in metabasic rocks. The orthogneisses (Qtz + Kfs + Pl + Phe ± Grt) show a mylonitic fabric characterized by the presence of K-feldspar porphyroclasts surrounded by a quartz–mica-rich fine-grained matrix. Here are dispersed small subhedral garnets (<1 mm) fractured and surrounded by tiny grains frequently concentrated along tails (Fig. 7a). By using a scanning electron microscope and back scattered electron (BSE) images (Fig. 7b) we have seen that the tails consist of very small garnet clasts partially welded by overgrowths. The latter show strong compositional contrast with respect to the former grains, appearing darker in BSE images. SEM/EDS analyses (Table 1) reveal that the main compositional difference resides in the proportion of the grossular molecule. In particular, average grossular content in garnet overgrowths is

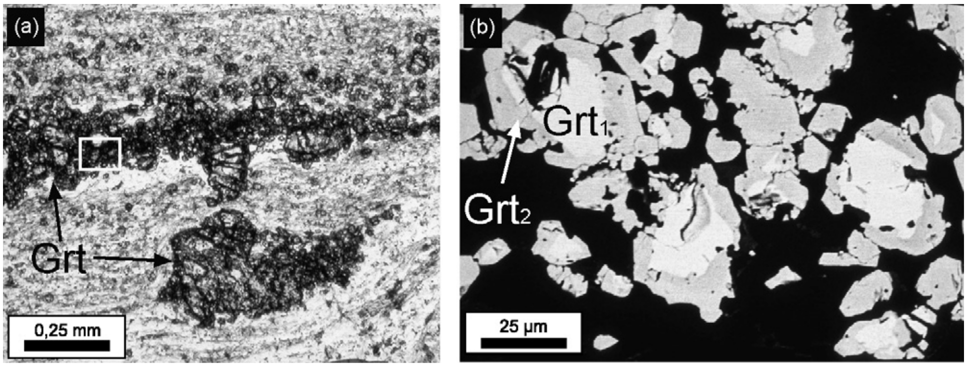

Fig. 7. (a) Small garnets with tail composed of tiny garnet grains in a mylonitic orthogneiss; (b) SEM–BSE image showing a detail (white box in (a)) of the tiny garnet grains: grossular-rich overgrowths developed during the Alpine event appear in a darker grey tone.

Table 1
Selected mineral compositions by SEM–EDS analyses in orthogneiss and amphibolite from the intermediate nappe

	Orthogneiss					Amphibolite			
	Grt core	Grt overgrowth	Phe	Phe	P1	Hb1 core	Hb1 overgrowth	Phe	P1
SiO_2	36.10	37.13	50.80	48.18	64.19	44.43	42.45	48.63	67.52
TiO_2						0.78	0.30	0.47	
Al_2O_3	20.96	21.11	30.22	28.16	21.82	10.86	15.23	30.31	19.91
FeO	30.01	19.81	3.18	6.74		17.09	18.01	3.05	0.18
MnO	9.70	7.07		0.44		0.20	0.25	0.13	
MgO	0.96	0.38	1.17	1.65		9.90	7.74	2.19	
CaO	1.44	14.06			2.39	11.11	10.15		0.55
Na_2O			0.60	0.27	10.35	2.13	2.62	0.24	11.54
K_2O			10.66	10.67	0.14	0.42	0.61	10.54	0.04
tot.	99.17	99.57	96.63	96.11	98.89	96.93	97.36	95.56	99.74
$\sum$O	12	12	22	22	8	23	23	22	8
Si	2.98	2.97	6.70	6.55	2.86	6.69	6.39	6.50	2.96
Ti						0.09	0.03	0.05	
Al	2.04	2.00	4.70	4.52	1.15	1.93	2.70	4.78	1.03
Fe	2.07	1.33	0.35	0.77		2.15	2.26	0.34	0.01
Mn	0.68	0.48		0.05		0.03	0.03	0.01	
Mg	0.12	0.05	0.23	0.33		2.22	1.74	0.44	
Ca	0.13	1.21			0.11	1.79	1.63		0.03
Na			0.15	0.07	0.89	0.62	0.76	0.06	0.98
K			1.79	1.85	0.01	0.08	0.12	1.80	
$\sum$cat	8.01	8.03	13.93	14.15	5.02	15.61	15.67	13.99	5.01
Alm%	69	41							
Pyr%	4	2							
Sps%	23	16							
Grs%	4	41							
Ab%					88				97
An%					11				3
Or%					1				

Mineral symbols according to Kretz (1983), analyses were performed at Dipartimento Geomineralogico (University of Bari) by a Cambridge S360 SEM equipped with a LINK AN 10,000 ED detector. Operating conditions were: 15 kV accelerating potential, 1 nA probe current, 25 mm working distance, standards by Microanalysis Consultants Ltd.

around 44% whereas it amounts to about 3% in the original fragments. Notable differences exist also for proportions in almandine (39% versus 70%), pyrope (1% versus 6%) and spessartine (16% versus 23%). To estimate *P–T* conditions of deformation we assumed that garnet overgrowths were in equilibrium with phases present in the fine-grained matrix. Garnet-phengite thermometer (calibration of Green and Hellman, 1982) and garnet–plagioclase–white mica–quartz barometer (calibration of Hodges and Crowley, 1985) have been adopted. Results indicate a temperature of 525 ± 50 °C and a pressure of 0.9 ± 0.1 GPa during deformation.

Amphibolite lenses (Hbl + Pl + Qtz + Ep + Phe ± Bt ± Chl ± Spn) show overgrowth textures such as rims and tails of bluish-tschermakitic hornblende around porphyroclasts of green-hornblende. Other small crystals of bluish-amphibole are recognizable throughout foliation planes. Composition of main phases in amphibolite lenses by SEM/EDS analyses is given in Table 1. In comparing cores and overgrowths of amphiboles, wide compositional differences can be observed. The overgrowths are decidedly richer in Al (average values of 2.64 versus 1.98, atoms p.f.u.) and poorer in Si with respect to cores of porphyroclasts. In addition, overgrowths are characterized by a higher Fe/(Fe + Mg) ratio (0.570 versus 0.493). Negligible or minor differences can be observed for the other elements. The Al content in amphibole is influenced both by tschermak ($[Mg,Fe]Si^{IV} = Al^{VI}Al^{IV}$) and edenite ($Si = NaAl^{IV}$) exchange, sensible to *P* and *T*, respectively. Therefore, the observed notable contrast in Al content, together with the negligible difference in Na content between core and overgrowths, point to a major role of the tschermak exchange.

In order to obtain additional information we have also tried to determine *P–T* conditions of deformation by applying amphibole-plagioclase thermometry (calibration of Holland and Blundy, 1994) and phengite barometry (calibration of Massone and Schreyer, 1987). Owing to the low anorthite content detected in plagioclase, only the thermometer A by Holland and Blundy (1994) was used. Results indicate *P–T* conditions for deformation of 570 ± 40 °C and 0.75 ± 0.1 GPa.

In synthesis, thermobarometrical estimates on orthogneisses and amphibolites of the intermediate nappe suggest that deformation took place in the epidote-amphibolite facies at *P* ranging between 0.75 and 0.9 GPa.

3.4. Shear sense indicators

Radiometric ages indicate that the tectonic evolution of the Curinga-Girifalco Line includes two main deformation events. An early Eocene mylonitic event is indicated by Rb/Sr ages on biotite (Schenk, 1980), whereas a subsequent early Miocene cataclastic event is suggested by contrasting thermal histories in the footwall and hangingwall of the Curinga-Girifalco Line obtained by zircon and apatite fission track analyses (Thomson, 1994). Various shear sense indicators, observed mainly in thin section, have been used to determine the kinematics of the Curinga-Girifalco mylonites. In mylonites derived from migmatitic paragneisses kinematic indicators are mostly C′-type shear bands (Berthé et al., 1979; Fig. 6a). Winged porphyroclasts, of δ- and σ-type (Passchier and Simpson, 1986), are present only in ultramylonitic bands (Fig. 8a). In the granitoid orthogneisses the best developed kinematic indicators are represented by synthetic and antithetic microfaults crosscutting K-feldspar porphyroclasts and, in minor extent, C′-type shear bands and δ/σ-type winged porphyroclasts (Fig. 8b and c). Ribbons formed by quartz aggregates are characterized by both lattice and shape preferred orientations in migmatitic paragneisses and in granitoid orthogneisses (Fig. 8c). The results of the kinematic analysis indicate mainly SE-directed shearing for the examined mylonites (Figs. 4a and 9). In particular, this shear sense is observed in granitoid orthogneisses at the Addolorata church (Girifalco village), along the 285°N plunging stretching lineation. Grey inchoesive fine-grained cataclasites with thickness of about some meters are localized mainly between migmatitic paragneisses and granitoid orthogneisses. Kinematics of the later cataclastic deformation is top-to-the-SW, as documented by C-type shear bands (Fig. 10). In the present-day coordinates this is consistent with extensional movements along the Curinga-Girifalco Line, with synchronous tectonic exhumation of the footwall block. This extensional brittle deformation is coherent with the contrasting footwall and hangingwall thermal histories reconstructed by Thomson (1994, 1998) using fission track thermochronology.

4. Discussion

The structural data related to ductile deformation along the Curinga-Girifalco Line can be referred to Alpine deformation, since Eocene ages (43 ± 1 Ma) have been obtained (Schenk, 1980). Therefore, the present-day orientation of the lineation data doesn't describe anymore the original deformation field and has to be restored to the initial position to be interpreted in terms of Alpine deformation.

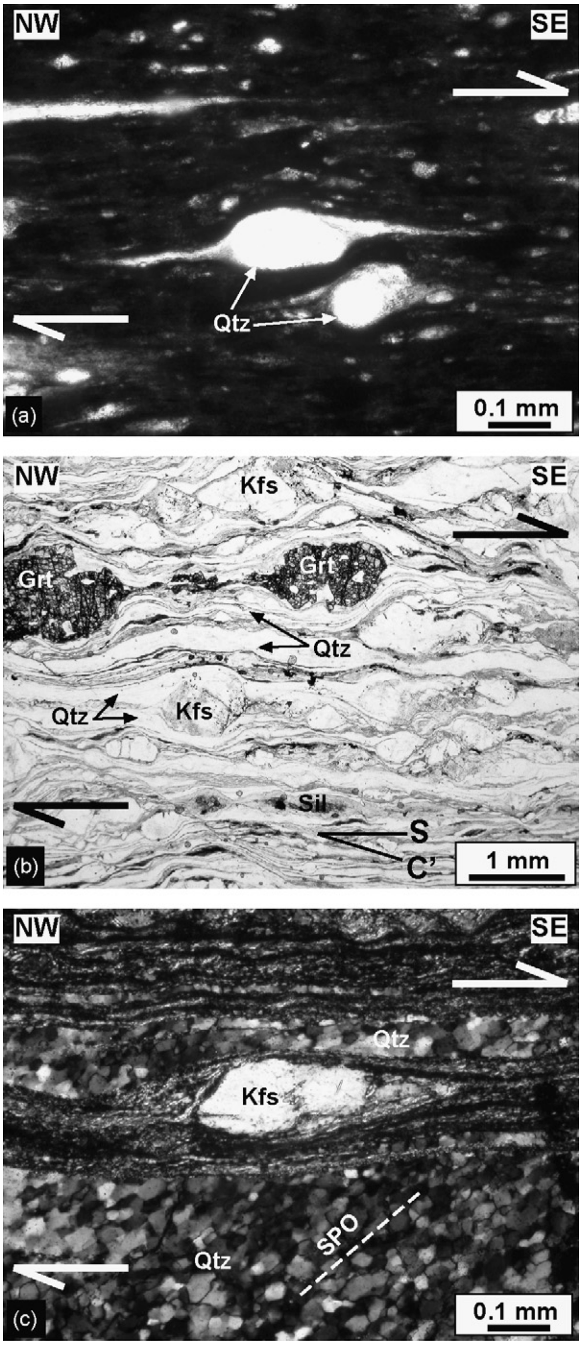

Fig. 8. Micrographs showing shear sense indicators in the Curinga-Girifalco mylonites; (a) σ-type winged porphyroclast of quartz in ultramylonitic layer of a migmatitic paragneiss (plane polarized light); (b) S–C′ type shear bands in mylonitic granitoid orthogneiss (plane polarized light); (c) σ-type winged porphyroclast and SPO (shape preferred orientations) of quartz crystals in fine-grained layers in a granitoid orthogneiss (crossed polars). All kinematic indicators show a dextral shear sense.

During the Oligo-Miocene evolution of the western Mediterranean, the Calabria-Peloritani terrane experienced two main rotational phases (Fig. 1a and b).

The first phase is related to the opening of the Liguro-Provençal basin that led to a counterclockwise rotation of the Corsica-Sardinia microplate of about 60° around a pole located at 42.7°N and 9.6°E (Gueguen, 1995; Gueguen et al., 1997). This is in good agreement with geophysical modeling (Chamot-Rooke et al., 1999) and with paleomagnetic

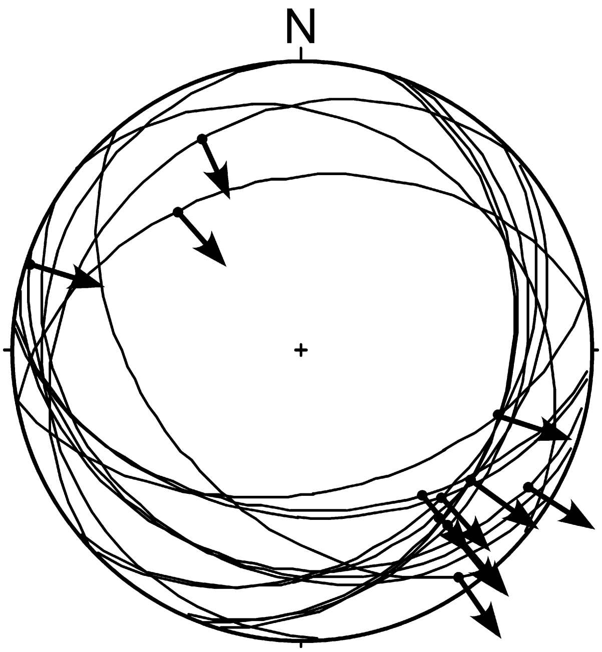

Fig. 9. Kinematic data for the Curinga-Girifalco mylonites. Stereoplot shows equal-area projection (lower hemisphere) of 11 tectonic transport directions (arrows) with the related mylonitic foliation planes (great circles).

estimates on volcanic rocks of Sardinia (Edel, 1979; Montigny et al., 1981) and on Tertiary sediments of Corsica (Vigliotti and Kent, 1990). During this first rotation, the Calabria-Peloritani terrane rotated together with the Corsica-Sardinia microplate as a single block (Auzende et al., 1973; Séranne, 1999 and references therein).

The second rotational phase started from the late Miocene, when extension migrated towards southeast, stepping over the Corsica-Sardinia microplate. This led to the opening of Tyrrhenian Sea and to the coeval separation of the Calabria-Peloritani terrane from the Corsica-Sardinia microplate (Gueguen et al., 1998). The Tyrrhenian Sea opened in two phases with firstly the rifting and seafloor spreading of the Vavilov basin (~8–6 Ma) and then the opening of the Marsili basin (~1.9–1.5 Ma; Fig. 1a; Savelli, 2005). This caused successive rotations in different sectors of the Calabrian block. Paleomagnetic studies on Pliocene sedimentary cover allowed Scheepers et al. (1994) to estimate a clockwise rotation of about 20° (Fig. 1a) in the northern sector of the Serre massif. Mylonites of the Curinga-Girifalco Line rotated together with the Calabria-Peloritani terrane, since their formation predates the two rotational phases.

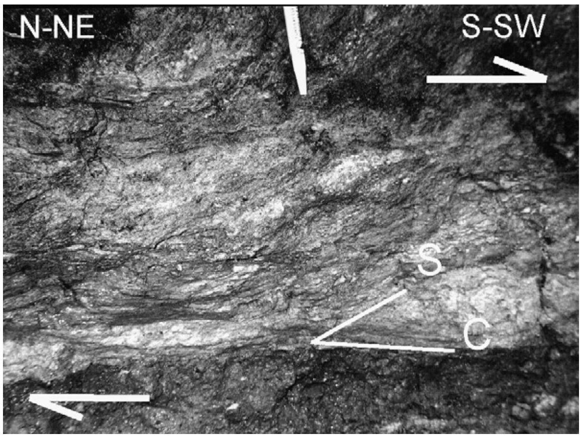

Fig. 10. S–C fabric with a top-to-the-SW shear sense in a cataclasite from the Curinga-Girifalco Line near the hydroelectric central outcrop. Pencil for scale (about 7 cm).

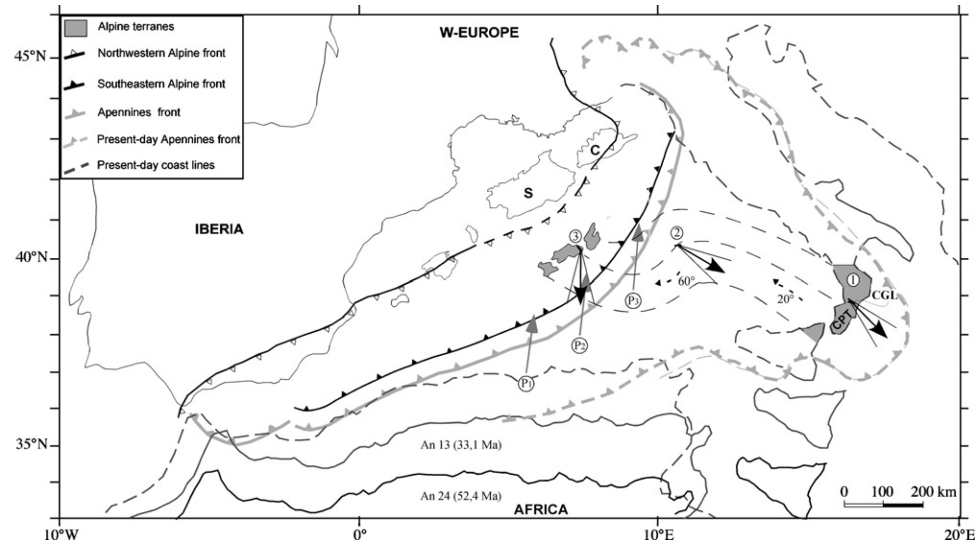

Fig. 11. Palinspastic reconstruction of the Calabria-Peloritani terrane at the Oligo-Miocene time (modified after Gueguen et al., 1998) with paleoposition of Africa at An 24 and An 13. Black arrows represent the shear transport direction with 95% confidence values of the Curinga-Girifalco Line. These lineations (135 ± 14°N) have been carried back in the original position and orientation: 1 = present-day; 2 = after the opening of the Liguro-Provençal basin; 3 = initial position. After restoration shear sense becomes top-to-the-S. Black dashed flow lines depict the post-Eocene migration of the Calabria-Peloritani terrane and black dashed arrows show rotations applied to lineations. Grey arrows represent the convergence direction between Africa and W-Europe/Iberia computed at three points (P_1, P_2, P_3) located in the vicinity of the paleoposition of the Calabria-Peloritani terrane (see text for explanations). Direction of convergence is in good agreement with restored kinematics.

To draw a palinspastic reconstruction of the Alpine fabric elements, the western Mediterranean basins have been restored to the pre-rift situation reversing the rotation path. After restoration, the linear fabric elements of the Curinga-Girifalco mylonites assume a nearly North–South direction (Fig. 11) with a South-directed tectonic transport. This orientation corresponds to the original deformation field in this segment of the Alpine chain during the Eocene.

To understand the significance of the restored kinematic data and to give a better interpretation of the palinspastic reconstruction, the orientation of linear fabric elements has been compared with regional tectonic regimes active during the Eocene–Oligocene times (Fig. 11).

Unfortunately, due to the lack of oceanic-type magnetic anomalies between Africa and Europe, it is not possible to reconstruct directly the relative motion of the two plates. Thus the kinematics of the Africa versus W-Europe/Iberia system has to be determined indirectly through a more complex circuit that considers the motion of both W-Europe/Iberia and Africa plates referred to North America.

Since ductile deformation has been dated at 43 ± 1 Ma (Schenk, 1980) we need to compare the restored direction of tectonic transport obtained along the Curinga-Girifalco Line with the coeval relative motion between Africa and W-Europe/Iberia. This can be obtained by computing the relative intermediate Euler pole for the period between magnetic anomalies An 24 and An 13, dated at 52.4 and 33.1 Ma using the magnetostratigraphic time scale by Cande and Kent (1995) and Huestis and Acton (1997), respectively. In the present study, we used the parameters of Müller et al. (1990) for relative motion of Africa versus North America and Srivastava et al. (1990) for relative motion of W-Europe/Iberia versus North America (Table 2). The results are shown in Table 3. Using these finite Euler poles we computed the following intermediate rotation parameters: pole located at 36.68°N and 26.19°W with counterclockwise rotation of 3.69°.

Table 2
Euler poles for relative motion of Africa vs. North America and of W-Europe/Iberia vs. North America

Finite poles	Lat.	Lon.	Rot.	References
AFR/NAM$_{0–24}$	78.33	−2.64	−16.91	Müller et al. (1990)
AFR/NAM$_{0–13}$	75.37	1.12	−10.04	Müller et al. (1990)
IBE/NAM$_{0–24}$	72.98	133.28	−12.94	Srivastava et al. (1990)
IBE/NAM$_{0–13}$	76.34	117.33	−7.98	Srivastava et al. (1990)

Table 3
Finite Euler poles obtained from rotational parameters in Table 2

Finite poles	Lat.	Lon.	Rot.	References
AFR/IBE$_{0–24}$	31.45	−18.58	−7.87	Müller et al. (1990), Srivastava et al. (1990)
AFR/IBE$_{0–13}$	26.94	−12.27	−4.24	Müller et al. (1990), Srivastava et al. (1990)

Table 4
Coordinates of three points (P_1, P_2, P_3) located in the vicinity of the paleoposition of the Calabria-Peloritani terrane (see Fig. 11)

Points	Lat.	Lon.
P_1	37.00	5.50
P_2	37.50	7.30
P_3	39.20	9.10

These parameters have been applied to three points (Table 4) located close to the restored position of the Calabria-Peloritani terrane (Fig. 11) in order to compute their motion during the An 24-An 13 period. Following this approach the local convergence direction between Africa and W-Europe/Iberia has been computed.

As shown on the palinspastic map (Fig. 11), the mean orientation of the restored lineations is in very good agreement with the regional tectonic regime. In particular lineations are sub-parallel to the convergence direction between Africa and the W-Europe/Iberia system. The reconstructed convergence direction together with the pressure increase recorded in the footwall of the Curinga-Girifalco Line indicate that the tectonic transport direction is connected to thrusting in an overall ductile deformation regime. Instead, the development of brittle extensional faults is related to the opening of the western Mediterranean basins and exhumation of the Calabria-Peloritani terrane, as confirmed by the zircon fission track ages (Thomson, 1994, 1998).

Summarizing, the post-Paleocene tectonic evolution of the northern Serre includes two main tectonic events. During the Eocene part of the basement of Calabria was affected by Alpine deformation. In this scenario several shear zones, such as the Curinga-Girifalco Line, were activated. In particular, the South-directed tectonic transport of the Curinga-Girifalco mylonites could be related to thrusting at the southeastern front of the Alpine chain (Fig. 11). After continental collision the Alpine chain experienced a post-collisional extension recorded by brittle fault-rocks of the Curinga-Girifalco Line.

5. Conclusions

Field and microscopic observations of the fault rocks from the Curinga-Girifalco Line provide new information on the tectono-metamorphic evolution of the Calabria-Peloritani terrane after the Paleocene. Two main events characterized the long-lived deformation history of the examined shear zone. An early ductile event of Eocene age was followed during Miocene by a localized brittle deformation along the previous shear zone. Structural and microstructural analysis of the fault rocks revealed a top-to-the-SE shear sense for mylonitic deformation and top-to-the-SW movement during the brittle event. Petrological investigations of different overgrowth textures in mylonitic granitoid orthogneisses and amphibolites indicate that deformation took place in the epidote-amphibolite facies at pressure ranging from 0.75 to 0.9 GPa. This is in agreement with the high-pressure overprint documented in continent-derived units and with the blueschist facies metamorphism experienced by ocean-derived rocks in various areas of the Calabria-Peloritani terrane (De Roever et al., 1974; Amodio-Morelli et al., 1976; Piccarreta, 1981; Platt and Compagnoni, 1990; Rossetti et al., 2001). Deformation and metamorphic events can be linked to a significant Eocene tectonic episode highlighted by geochronological methods (Borsi and Dubois, 1968; Schenk, 1980; Beccaluva et al., 1981; Prosser et al., 2003).

Interpretation of earlier fabric elements in the Calabria-Peloritani terrane and in other exotic terranes, based on present-day coordinates, is however misleading. Therefore, structural, petrological and metamorphic data have to be restored in the original coordinates. This kind of paleotectonic reconstruction allows a correct interpretation of the mylonitic and cataclastic fabrics associated to the Curinga-Girifalco Line. For the paleotectonic reconstruction we considered that during the evolution of the central–western Mediterranean basins the Calabria-Peloritani terrane and thus the Curinga-Girifalco Line migrated towards SE–SSE and experienced simultaneously rotation and tilting. In our restored paleotectonic scenario kinematics of deformation is top-to-the-S. This direction is in good agreement with regional plate tectonic regime during Eocene time. In the original setting barometrical estimates and structural data of mylonites indicate thickening above the Curinga-Girifalco Line, coherently with a contractional tectonic regime. Therefore, we interpret this important shear zone as a thrust of the southeastern front of the Alpine chain acting during Eocene time. The method adopted in this paper can be applied to the other Alpine fragments dispersed in peri-Mediterranean area (e.g., Corsica, Kabylie) in order to improve our understanding of the southern Alpine belt.

Acknowledgments

This paper benefited from careful review by K. Ben, L. Jolivet and an anonymous referee. Financial support from PRIN 2004 project (D. Liotta) and from Ateneo funding from Bari and Potenza Universities are acknowledged. Special thanks to Ascone family for their hospitality during field work.

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