The Curinga–Girifalco Line in the framework of the tectonic evolution of the remnant Alpine chain in Calabria (southern Italy)

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Abstract

In the peri-Mediterranean metamorphic belts, the tectonic evolution of the Calabria–Peloritani terrane during the dominant compressive tectonics of the Eocene represents one of the most problematic points in palinspastic restorations. A matter of particular debate is its shortening, which could have occurred during the Alpine or the Apennine subduction. In this regard, a crucial joint is provided by the kinematics of one of the most relevant shear zones such as the Curinga–Girifalco Line, cropping out in central Calabria. This shear zone juxtaposed a nearly complete Hercynian crustal section (i.e. the Sila and Serre Unit) onto the remnants of the Castagna Unit. The data in the available literature on ductile kinematics from the south-eastern branch of the Curinga–Girifalco Line indicate a downward movement of the hanging wall. In the present paper we show new, ductile kinematic data and petrographic evidence from outcrops in the north-western and south-eastern branches of the Curinga–Girifalco Line. Our results highlight the coherent kinematics of the Eocene shortening during the Alpine subduction system, followed by (late Eocene?) Oligocene to early Miocene, dominantly ductile extensional reworking, relating to the Apennines subduction system.

Keywords Curinga–Girifalco Line · Kinematics · Compressional shear zone · Ductile extensional reworking · Eocene Alpine shortening · Oligocene back-arc of Apennines

Introduction

The Curinga–Girifalco Line (CGL) (Schenk 1980) in the Calabria–Peloritani terrane (Bonardi et al. 2001) (Fig. 1, insets top right and left) is characterised by exposures of deep mylonites in the northern Serre Massif (Fig. 1, inset top left). The CGL generally dips towards the south and occurs at the base of a nearly complete Hercynian continental crust (i.e. the Sila and Serre Unit), which, in turn, rests above the Castagna Unit (Fig. 1) (Paglionico and Piccarreta 1976, 1978; Schenk 1980; Spiegel 2003; Langone et al. 2006; Altenberger et al. 2013). This tectonic configuration induced Schenk (1981) to suggest a comparison between the CGL and the Insubric Line, the latter juxtaposing the Ivrea Zone and the Sesia Zone in the western Alps (Fig. 1, inset top right). Hence, in the framework of the dominant compressive Alpine evolution in the Eocene, the CGL was

assumed to have a general top-to-the-European plate realm tectonic transport by Schenk (1984). Subsequently, kinematics framed in the geodynamic reconstruction of the Eocene led Langone et al. (2006) to consider the CGL mylonites to have developed along a top-to-the-Africa thrust, in the south-eastern front of the double-verging Alpine chain. However, in the neighbouring Girifalco village (eastern sector of the structural sketch map of Fig. 1), a downward movement (present-day top-to-the-SE, according to Langone et al. 2006) of the hanging wall can be hypothesised. At first glance this indicates an extensional component of the movement of the CGL during the mylonitic event. Nevertheless, it should be noted that a post-orogenic extensional reworking of the former, dominantly compressive, ductile tectonic contact between the Castagna and the Sila and Serre units, in the Sila Massif and Catena Costiera areas (Fig. 1, inset top left), was invoked by Rossetti et al. (2001, 2004). Thomson (1998) concluded that fission-track data can only account for post-orogenic crustal extension, which probably occurred right along the CGL. Therefore, the main goal of the present research paper was to shed light on the kinematics of the CGL, which represents one of the most relevant regional

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Fig. 1 Structural sketch map of the CGL from Girifalco village (to the East) to the Acconia quarry (to the West), modified after Altenberger et al. (2013) and Langone et al. (2006). The upper right inset represents a sketch of the current position of the Apennines and

Alpine fronts, according to Carminati and Doglioni (2012); the upper left inset represents the geological sketch map of central and northern Calabria–Peloritani terrane, simplified after Festa et al. (2004)

shear zones in the still-debated tectono-metamorphic evolution of the Calabria–Peloritani terrane, controversially related to Apennines (e.g. Knott 1987; Wallis et al. 1993; Rossetti et al. 2001, 2004; Iannace et al. 2007; Shimabukuro et al. 2012; Vitale et al. 2019) vs. Alpine subduction (e.g. Alvarez 1976; Schenk 1984; Cello et al. 1996; Liberi et al. 2006; Carminati and Doglioni 2012).

Geological setting

The Calabria–Peloritani terrane (Bonardi et al. 2001), i.e. the ‘calabro-peloritano arc’ sensu to Amodio-Morelli et al. (1976), is a nappe stack made by three main groups of tectonic units (Fig. 1, inset top left): (i) the Lower Complex, basically consisting of phyllites and the platform to basinal

carbonate rocks of Triassic to middle Miocene age, correlated to lithostratigraphic units cropping out in the Apennines; (ii) the Intermediate Complex, essentially represented by the ophiolite units of Jurassic to Cretaceous Neo-Tethys derivation, recording Eocene high-pressure/low-temperature (HP/LT) metamorphism; (iii) the Upper Complex, made up of continental crust units.

The Upper Complex

In Catena Costiera, Sila and Serre massifs, the Upper Complex (Fig. 1, inset top left) consists of Alpine tectonic nappes, derived from Hercynian continental crust. These record high-pressure overprinting (Piccarreta 1981), including, from the base upward, the Fiume Pomo Unit, the Castagna Unit, and the Sila and Serre Unit (e.g. Festa et al. 2004 and

the references therein). The Castagna Unit mainly consists of orthogneisses and paragneisses, equilibrated under amphibolite facies conditions during the Hercynian orogeny (e.g. Colonna and Piccarreta 1975; Ortolano et al. 2020b). In the footwall of the CGL (Fig. 1), the Hercynian paragenesis of the orthogneisses, derived from the late Precambrian to Early Cambrian granitoids (Micheletti et al. 2007, 2011), is represented by quartz + K-feldspar + muscovite + biotite $\pm$ garnet $\pm$ epidote and $\pm$ plagioclase (Paglionico and Piccarreta 1976, 1978; Spiegel 2003; Langone et al. 2006). The Hercynian fabric is characterised by K-feldspar porphyroclasts, generally wrapped by thin layers of mica and quartz grains, defining an anastomosing foliation (Langone et al. 2006).

The nearly complete Hercynian continental crust constituting the Sila and Serre Unit is approximately 22 to 23 km thick. The lower crustal level consists of metagabbros and granofelses, topped by metapelites equilibrated under granulite facies conditions during the late Hercynian (Fornelli et al. 2011 and the references therein). The metapelites in the hanging wall of the CGL (Fig. 1) are mainly composed of quartz + garnet + sillimanite + biotite $\pm$ cordierite $\pm$ K-feldspar and $\pm$ plagioclase (Spiegel 2003; Langone 2006). The Hercynian fabric is characterised by alternating melanocratic and leucocratic layers (e.g. biotite and sillimanite-rich melanosome and quartz and feldspar-rich leucosome, respectively), defining a migmatitic layering. In general, the foliation wrapping around the different porphyroblasts (garnet, K-feldspar, sillimanite aggregates) follow an anastomosing pattern (Langone et al. 2006). Towards the top, the Hercynian continental crust consists of a thick batholith of granitoids, intruded at mid-crustal levels, and with amphibolite to greenschist facies in the upper crust, represented by paragneisses and phyllites (Schenk 1980; Caggianelli et al. 2000; Langone et al. 2014; Festa et al. 2018; Tursi et al. 2020b). The Sila and Serre Unit ends with upwards of hundreds of metres of a Mesozoic carbonate sedimentary succession lying unconformably on the phyllites (e.g. Festa et al. 2004). Cenozoic exhumation of the Sila and Serre Unit took place from the Oligocene (Thomson 1994), along with an overall crustal tilting of about 40°, which has determined the present-day SE-dip and exposed the Hercynian continental crust in the Serre Massif (Festa et al. 2003).

The Curinga–Girifalco Line

In the northern Serre Massif, ductile deformation along the roughly W–E-striking tectonic contact between the Castagna and the Sila and Serre units (i.e. the CGL (Fig. 1)), produced a 200 to 400 m-thick mylonite belt (estimations by Spiegel 2003; Langone et al. 2006) at the expense of the protoliths of both juxtaposed units (Paglionico and Piccarreta 1976, 1978; Spiegel 2003; Langone et al. 2006). According to Schenk

(1980), the CGL mylonites developed during the middle Eocene, as indicated by Rb–Sr biotite ages of c. 43 Ma. The mylonitic metapelites are characterised by a very limited mineral re-equilibration of the Hercynian protolith, with chloritization of biotite and garnet, and formation of white mica and quartz at the expense of K-feldspar and sillimanite (Spiegel 2003; Langone et al. 2006). According to Langone et al. (2006), the mylonitic orthogneisses are mostly composed of quartz + K-feldspar + muscovite + biotite $\pm$ garnet $\pm$ epidote and $\pm$ plagioclase, which basically represents the Hercynian mineral assemblage; grossular enrichments in the garnet rim, as well as phengite replacement of muscovite, indicate the Alpine overprint. Moreover, retrograde reactions, such as the chloritisation of biotite and sericitisation of K-feldspar, are also locally observed (Langone et al. 2006).

Thermobarometric estimations by Spiegel (2003) revealed that mylonitisation of orthogneisses and metapelites occurred under greenschist facies conditions. According to Langone et al. (2006), petrological evidence, such as the increase of the grossular molar fraction toward the rim of rounded-shaped garnets, indicates that the mylonitic deformation affected the orthogneisses in the epidote–amphibolite facies, at pressures ranging from 0.75 to 0.90 GPa. Similar pressures of deformation are recorded in ultramylonite bands, occasionally present in the mylonitic metapelites involved in the CGL. Accordingly, ultramylonites occurred at the expense of pseudotachylytes during intermittent episodes of brittle deformation within an overall ductile environment (Altenberger et al. 2011, 2013). Thomson (1998) and Langone et al. (2006), suggested that extensional faulting of Oligocene to early Miocene age (30 to 15 Ma) affected the eastern part of the CGL (Fig. 1). This deformation developed at temperature conditions well below 300 °C (Thomson 1998) and promoted the occurrence of cataclasites (Spiegel 2003) and not-mylonitized pseudotachylyte veins, within an overall brittle environment (Langone et al. 2006). Since these brittle structures occur in association with the tectonic contact between the Castagna and Sila and Serre units (e.g. Langone et al. 2006), Miocene shearing was likely restricted only to the portion of the CGL along this tectonic contact.

Material and methods

To achieve the goal of this paper, the CGL has been investigated in its easternmost and westernmost parts, i.e. in the Pesipe Stream valley and in a small quarry near the village of Acconia (hereafter called ‘Acconia quarry’), respectively (Fig. 1).

Detailed geological mapping, together with structural field observations, has been carried out in the Pesipe Stream valley (Fig. 2a), because it is one of the

most promising area, due to some continuity of outcrop exposures from the Castagna Unit to the Sila and Serre Unit (e.g. Spiegel 2003). Further structural data have been measured along the walls of the Acconia quarry (Fig. 2b), where continuous exposures of ‘fresh’ mylonitic

orthogneisses of the Castagna Unit can be observed. The measurement of foliations (about two hundred) and lineations (about eighty) was performed as uniformly distributed as possible in the study areas, avoiding varying data densities between different outcrops.

Fig. 2 **a** Detailed structural-geological map of the Pesipe Stream valley and cross-section through the CGL (samples geographic coordinates: VF77GR 38°48'48.00"N, 16°24'14.00"E; VF80GR 38°49'45.00"N, 16°24'40.00"E; VF78GR 38°49'42.00"N, 16°24'11.00"E; VF79GR 38°49'38.00"N, 16°24'05.00"E; VF88GR 38°49'20.00"N, 16°24'13.00"E; VF86GR 38°49'15.00"N, 16°24'12.00"E; VF87GR 38°49'15.00"N, 16°24'16.00"E; VF85GR 38°49'14.00"N, 16°24'11.00"E; VF84GR 38°49'11.00"N, 16°24'09.00"E; VF83GR 38°49'08.00"N, 16°24'07.00"E; VF82GR 38°48'56.00"N, 16°24'04.00"E; VF81GR 38°48'55.00"N, 16°24'03.00"E). **b** Structural-geological map of the Acconia quarry area and cross-section through the CGL (samples geographic coordinates: VF52AC 38°50'40.39"N, 16°17'13.14"E; VF44AC 38°50'40.18"N, 16°17'13.10"E; VF51AC 38°50'39.84"N, 16°17'13.37"E; VF50ACa&b 38°50'39.31"N, 16°17'13.40"E; VF49AC 38°50'38.97"N, 16°17'13.04"E; VF48AC 38°50'38.66"N, 16°17'12.68"E). The legend refers to both of the structural-geological maps

Oriented samples were collected from both localities: the Pesipe Stream valley (Fig. 2a) and the Acconia quarry (Fig. 2b). The related thin sections (cut parallel to the X and Z axes of the finite strain ellipsoid, i.e. the stretching lineation and its normal towards the top, respectively) were observed under a polarised light microscope and scanning electron microscope (SEM) as well, especially for kinematic purposes. It should be noted that about one hundred and fifty kinematic indicators were observed in thin section. The LEO-EVO50XVP scanning electron microscope of the Department of Earth and Geo-environmental Sciences at the University of Bari Aldo Moro was used for the acquisition of backscattered electron (BSE) images. Quantitative mineral compositions on polished thin sections were obtained using operating conditions of 15 kV acceleration voltage, a working distance of 8.5 mm, beam current of 500 pA and counting times of 50 s.

Results

Field analyses of the CGL and its walls

In the Pesipe Stream valley, the Sila and Serre Unit is basically characterised by high-grade metapelites (Fig. 3a) with interleaved metabasites cropping out in the southern sector of the valley (Fig. 2). It tectonically overlies the Castagna Unit, which is typically represented by orthogneisses (Fig. 3b), cropping out to the north (Fig. 2). Both metapelites and orthogneisses show an older Hercynian S_H main foliation, generally dipping to the SSW, hence WNW–ESE-striking, with a variable dip of up to c. 35° (e.g. Figures 3a, b) near the tectonic contact between the two units. The tectonic contact is sharp, SSW-dipping, and WNW–ESE-striking, with a dip of c. 35–40° (Fig. 2). It consists of a thick ductile shear zone (i.e. the CGL), which is characterised by mylonites formed at the expense of both the metapelites

and the orthogneiss protoliths (Fig. 3c, d). The transition from mylonites to their protoliths takes place within a few metres, with the boundaries of the ductile shear zone being sub-parallel to the tectonic contact (Fig. 2). The mylonitic metapelites at the base of the Sila and Serre Unit (Fig. 2) show a mylonitic S_m main foliation, given by the alternation of fine-grained, biotite-rich layers and coarser-grained felsic layers, generally millimetres and centimetres-thick (Fig. 3c). Up to decimetre-thick quartzo-feldspathic lenses, inherited from the metapelitic protolith, can typically be found stretched parallel to the main mylonitic foliation (Fig. 3c). Locally, very fine-grained layers of ultramylonites are present. Millimetre-sized garnet porphyroclasts are evident in the biotite-rich layers, whereas millimetre-sized feldspar porphyroclasts, embedded in dynamically recrystallised quartz-rich ribbons, characterise the felsic layers (Fig. 3c). Preferentially aligned and stretched quartz, which defines the L_m lineation, primarily occurs along the foliation surfaces of the felsic layers (Fig. 3c).

The mylonitic S_m main foliation in the orthogneisses, at the top of the Castagna Unit (Fig. 2), is basically represented by recrystallised, millimetre- to centimetre-thick, fine-grained, quartz and feldspar layers, including millimetre-sized feldspar porphyroclasts (Fig. 3b). Fine-grained white mica and biotite flakes are preferentially oriented in thin mylonitic layers and small garnets are sometimes recognisable, scattered in the mylonite. The L_m lineation, lying on the mylonitic S_m surfaces, is given by the preferred alignment of stretched quartz (Fig. 3d). Similar structural field features are shown by the mylonitic orthogneisses cropping out in the Acconia quarry.

In the Pesipe Stream valley, the S_m foliation of the mylonitic metapelites shows a mean SSW-dipping azimuth with an average dip of c. 35–40° (Fig. 4a), sub-parallel to the CGL shear zone boundaries and the tectonic contact with the mylonitic orthogneisses (Fig. 2). Moreover, the L_m exhibits a mean SSE dip azimuth and an average plunge of c. 20–25° (Fig. 4a). In the mylonitic orthogneisses, the S_m foliation shows approximately a WNW–ESE strike, however, with opposite SSW or NNE dip azimuth and varying dip (Fig. 4b). In more detail, the S_m foliation with a SSW dipping azimuth exhibits a progressively increasing dip (up to c. 30–35°) approaching the shear zone border with the orthogneiss protolith and the tectonic contact with the mylonitic metapelites (Figs. 2, 4b). Therefore, a sub-parallelism among the steeper SSW-dipping S_m foliations, the CGL shear zone borders and the tectonic contact with the mylonitic metapelites, is observed as well. Towards the central part of the CGL within the mylonitic orthogneisses (in cross-section view), the S_m foliation tends to have a NNE dip azimuth with a mean dip of c. 25° (Figs. 2, 4b), although SSW-dipping layers can also be seen, locally (Fig. 2). A SSE plunge and an average dip of 20–25° is also exhibited by the

Fig. 3 Typical field occurrence of mylonites of the CGL from the Pesipe Stream valley (a–d) and Acconia quarry (e, f). **a** High-grade metapelite (hanging wall), showing S_H layering, as also highlighted in the inset magnification ($38^{\circ}48'56.33''N$, $16^{\circ}24'03.56''E$). **b** Orthogneiss (footwall), showing S_H layering, as highlighted in the inset magnification ($38^{\circ}49'44.02''N$, $16^{\circ}24'40.26''E$). **c** Mylonitic metapelite, showing the millimetre- to centimetre-sized, fine-grained layers that originated the mylonitic foliation S_m ; stretched quartzo-feldspathic lenses defining the main mylonitic foliation S_m and the L_m stretching lineation, are highlighted in the inset magnifications ($38^{\circ}49'10.12''N$, $16^{\circ}24'09.81''E$). **d** Mylonitic orthogneiss, showing millimetre- to centimetre-sized, fine-grained quartz-feldspar S_m layers and stretched quartz defining the L_m lineation, as highlighted in the inset magnifications ($38^{\circ}49'36.55''N$, $16^{\circ}24'17.07''E$). **e** Mylonitic orthogneiss, showing millimetre- to centimetre-sized, fine-grained quartz-feldspar S_m layers ($38^{\circ}50'39.34''N$, $16^{\circ}17'13.82''E$). **f** Stretched quartz defining the L_m lineation on a S_m foliation surface within the mylonitic orthogneiss of **e**. X, Y and Z are the axes of the finite strain ellipsoid (X: stretching lineation L_m ; Z: normal to the foliation S_m and Y: perpendicular to XZ). Mineral abbreviations after Whitney and Evans (2010)

L_m lineation (Fig. 4b), measured especially on the SSW-dipping S_m foliation surfaces, where this lineation is better developed (e.g. Fig. 3d).

As shown in Fig. 4c, the S_m foliation and the L_m stretching lineation of the mylonitic orthogneisses cropping out in the Acconia quarry are clustered, showing a mean SSW dip direction and dips of $35\text{--}40^{\circ}$, with a SSE plunge and dip of $25\text{--}30^{\circ}$, respectively.

The geological profile in Fig. 2a, constructed nearly orthogonal to the mylonitic S_m foliation along the Pesipe Stream valley, allows estimated thicknesses of c. 150 m and c. 750 m for the mylonitic metapelites and the mylonitic orthogneisses, respectively. Thus, a total thickness of c. 900 m for the CGL shear zone can be derived.

The 50 m-thick mylonitic orthogneisses exposed in the Acconia quarry (Fig. 2b) may be correlated to the mylonitic orthogneisses occurring in the neighbouring of the tectonic contact with the mylonitic metapelites of the Pesipe Stream valley (Fig. 2a). A comparable mean dip and dip direction of the SSW-dipping S_m foliation and SSE-plunging L_m lineation can be observed for the mylonitic orthogneisses from the Acconia quarry (Fig. 4c) and the Pesipe Stream valley (Figs. 2, 4b). The distance between the mylonitic orthogneisses of the Acconia quarry and the metapelites that were unaffected by mylonitic deformation of the Sila and Serre Unit (Fig. 2b) also supports the correlation among these mylonitic orthogneisses and those cropping out in the Pesipe Stream valley near the tectonic contact with the mylonitic metapelites (Fig. 2a).

Microscopic analyses and kinematics

Because of the intense deformation affecting the fine-grained mylonites on the CGL, especially the very fine-grained

Fig. 4 a–c Stereographic projections of the main foliation S_m and stretching lineation L_m of the mylonites of the CGL; the dashed, grey plane refers to the shear zone margins, which are sub-parallel to the tectonic contact between the Castagna Unit and the Sila and Serre Unit; the sub-parallelism of the trend between the CGL margins and the S_m foliation can be appreciated. Note in **b** the cluster of the poles of the SSW-dipping S_m foliation, near the tectonic contact between the Castagna and Sila and Serre units and the northern margin of

the CGL, and the cluster of the poles of the NNE-dipping S_m foliation, characterising the central part of the CGL within the mylonitic orthogneisses. The cluster of the poles of the SSW-dipping S_m foliation can be also appreciated in both **c**, regarding the mylonitic orthogneisses near the northern margin of the CGL, and **a**, related to the mylonitic metapelites near the southern margin of the CGL (see the text for further explanation)

Fig. 5 **a** Micrograph of the mylonitic S_m foliation in the metapelite, highlighted by an ultra-mylonitic layer; S–C–C' structures can be observed (crossed-polars; sample VF84GR from the Pesipe Stream valley area; see Fig. 2a for the location). **b** Micrograph of mylonitic metapelite showing σ -type garnet porphyroclasts in the biotite-rich layers, exhibiting kinematics coherent with S–C–C' structures (plane-polarised light; sample VF83GR from the Pesipe Stream valley area; see Fig. 2a for the location). **c** Micrograph of mylonitic orthogneiss, with σ -type K-feldspar porphyroclasts indicating contrasting shear sense; S–C–C' structures are also evident (crossed-polars; sample VF44AC from the Acconia quarry; see Fig. 2b for the location). **d** Micrograph of mylonitic orthogneiss, with a millimetre-sized, dynamically recrystallised σ -type K-feldspar porphyroclast (crossed-polars; sample VF51AC from the Acconia quarry; see Fig. 2b for the location). **e** Micrograph of mylonitic orthogneiss, with a centimetre-

sized K-feldspar domino-type fragmented porphyroclast (crossed-polars; sample VF48AC from the Acconia quarry; see Fig. 2b for the location). **f** Micrograph of mylonitic orthogneiss, with a millimetre-sized garnet shear band type fragmented porphyroclast above a σ -type K-feldspar porphyroclast (plane-polarised light; sample VF48AC from the Acconia quarry; see Fig. 2b for the location). **g** Micrograph of mylonitic orthogneiss, with a millimetre-sized, dynamically recrystallised σ -type K-feldspar porphyroclasts (crossed-polars; sample VF52AC from the Acconia quarry; see Fig. 2b for the location). **h** Micrograph of mylonitic orthogneiss, with a centimetre-sized K-feldspar domino-type fragmented porphyroclast (crossed-polars; sample VF48AC from the Acconia quarry; see Fig. 2b for the location). Oriented thin sections according to X (stretching lineation L_m) and Z (normal to the foliation S_m) axes of the finite strain ellipsoid. Mineral abbreviations after Whitney and Evans (2010)

ultramylonitic layers in the mylonitic metapelites (e.g. Fig. 5a), the best investigation for kinematic purposes has been made at the thin section scale.

In the samples from the Pesipe Stream valley, the main foliation S_m in both mylonitic metapelites and mylonitic orthogneisses is represented by C-type shear bands

that are typically associated with S-planes and C'-type shear bands (Fig. 5a–c). The geometrical relationships between these C'-type shear bands, S-planes and C'-type shear bands indicate a dominant top-to-the-SSE tectonic transport (Figs. 2, 5a–c), according to the stretching lineation L_m trend measured in the field (Figs. 4a, b). The same kinematics is also suggested by most of the observed σ -type porphyroclasts of garnet in the mylonitic metapelites (e.g. Fig. 5b), σ -type porphyroclasts of K-feldspar (e.g. Fig. 5c, d) and K-feldspar domino-type fragmented porphyroclasts in the mylonitic orthogneisses (Fig. 5e). However, contrasting kinematic indicators are present (e.g. σ -type K-feldspar porphyroclasts in Fig. 5c), especially in the samples of mylonitic orthogneisses from the Acconia quarry, where shear band-type fragmented porphyroclasts of garnet (Fig. 5f), σ -type (Fig. 5f, g) and domino-type fragmented porphyroclasts of K-feldspar (Fig. 5h) indicate a top-to-the-NNW tectonic transport (Fig. 5f–h).

The relationship between the blastesis and the deformation event D_m , which gave rise to the mylonitic foliation S_m in both of the sheared protoliths, is summarised in Fig. 6a, b. In all of the mylonites, the syn-kinematic mineral phases are fine-grained, and pre-kinematic quartz and feldspars are, largely, dynamically recrystallised (e.g. Fig. 5d, g). In the mylonitic metapelites quartz, biotite, K-feldspar, plagioclase, garnet, sillimanite and cordierite are mostly pre-kinematic and constitute the typical assemblage of the Hercynian protolith (Fig. 6a). These mylonites exhibit syn-kinematic quartz, biotite, K-feldspar, plagioclase and rare white mica (e.g. Fig. 6c, d). A more conspicuous mineral reworking can be generally observed in the mylonitic orthogneisses, containing syn-kinematic quartz, K-feldspar, plagioclase, biotite and white mica. However, these minerals, together with garnet and ilmenite are also pre-kinematic and inherited from the mineral assemblage of the Hercynian protolith. Furthermore, the syn-kinematic mineral assemblage also comprises epidote, chlorite and titanite (Fig. 6b).

In the mylonitic orthogneisses, garnet remains stable and reveals also its post-kinematic growth (Fig. 6b). More details are shown in Fig. 6c, where almost-euhedral, millimetre-sized garnets with rim growth around the rounded cores can be observed, mostly in the mylonitic orthogneisses from the Acconia quarry (in which smaller euhedral to sub-euhedral garnets frequently occur). These observations support both pre-kinematic and post-kinematic growth for the cores and the rims, respectively, as well as the post-kinematic growth of the smaller euhedral to sub-euhedral garnets.

Chemical analysis of the larger euhedral garnets and smaller euhedral to sub-euhedral ones from the Acconia quarry (Fig. 7a, b) show almandine-rich compositions (Table 1). In particular, the pre-kinematic core of the larger garnets is characterised by the following: (i) high X_{Alm} and X_{Sps} values of 0.69 and 0.23 mol fractions; and (ii) low X_{Gr} , X_{Py} and X_{Andr} values of 0.02, 0.05 and 0.01 mol fractions (Table 1). Instead, their post-kinematic rim shows the following: (i) high X_{Alm} and X_{Gr} values of 0.71 and 0.19 mol fractions; and (ii) low X_{Sps} , X_{Py} and X_{Andr} values of 0.01, 0.07 and 0.02 mol fractions, respectively (Table 1). Within the small, post-kinematic, euhedral garnets, some core–rim variations commonly occur (Table 1). Indeed, they are characterised from core to rim by the following: (i) slightly decreasing X_{Alm} values from 0.73 to 0.69 mol fractions; (ii) increasing X_{Gr} values from 0.11 to 0.23 mol fractions; (iii) decreasing X_{Sps} values from 0.08 to 0.01 mol fractions; and (iv) slightly increasing X_{Py} values from 0.05 and 0.07 mol fractions (Table 1). The almandine-rich composition of both garnet types is also evidenced by a lack of large variations in the iron X-ray map in Fig. 7a. Moreover, the X-ray map of calcium in Fig. 7b clearly shows that the core of the larger garnets is Ca-poor, while the rim is Ca-rich. Similarly, Ca-rich compositions are evidenced in the smaller euhedral garnet grains as well (Fig. 7b). Therefore, the rim growth of the larger garnets, as well as the smaller euhedral ones, is enriched in the grossular end-member. Summing up, the D_m deformation along the CGL in the Acconia quarry area was active later, with respect to the relic Ca-poor garnets and before the growth of the Ca-rich ones.

On the other hand, small, rounded, pre-kinematic Ca-rich garnets (Fig. 7c) occur in the mylonitic orthogneisses cropping out in the Pesipe Stream valley. These garnets are characterised by grossular-rich compositions, showing some core–rim variations (Table 1). In particular, the core compositions of these garnets highlight the following: (i) high X_{Gr} , X_{Alm} and X_{Sps} values of 0.48, 0.29 and 0.20 mol fractions; and (ii) some low X_{Andr} values of 0.02 mol fractions with nearly zero X_{Py} mole fractions (Table 1). The remarkable changes in the rim of these garnets, with respect to the core, are primarily related to (i) an increase in the X_{Gr} mole fraction up to a value of 0.53 and (ii) a decrease in the X_{Sps} mole fraction to a value of 0.14 (Table 1). Therefore, the D_m deformation along the CGL in the Pesipe Stream valley area would have been active later with respect to the Ca-rich garnets.

Fig. 6 Relationships between blastesis and D_m deformation events (**a**) in the mylonitic metapelite and (**b**) in the mylonitic orthogneiss; symbols ($<$ = pre-kinematic, $>$ = post-kinematic, $\leq$ = from pre- to syn-kinematic, $\supset$ = syn-kinematic) after Passchier and Trouw (2005). **c** Micrograph of syn-kinematic white mica in the mylonitic metapelites (plane-polarised light, sample VF87GR; see Fig. 2a for the location). **d** Magnification of the syn-kinematic white mica in **c** (crossed-polars). **e** Micrograph of small euhedral post-kinematic garnets and euhedral garnet overgrowth on its rounded core (white dashed line) in the mylonitic orthogneiss from the Acconia quarry (plane-polarised light; sample VF49AC; see Fig. 2b for the location). Mineral abbreviations after Whitney and Evans (2010); Wm = white mica

Fig. 7 X-ray Fe (a) and Ca (b) maps for the euhedral garnets in Fig. 6c; note the post-kinematic growth of Ca-rich garnets. c Ca X-ray map of a pre-kinematic Ca-rich garnet in mylonitic orthogneiss

from the Pesipe Stream valley (sample VF77GR; see Fig. 2 for the location). Mineral abbreviations after Whitney and Evans (2010)

Table 1. Representative garnet chemical analyses in the samples from Acconia (VF49AC) and Pesipe Stream valley (VF77GR) areas

Sample	VF49AC				VF77GR	
	Large garnets		Small garnets		Core	Rim
	Core	Rim	Core	Rim		
Point analysis						
SiO ₂	36.35	36.93	36.84	37.43	38.57	37.62
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	20.37	20.56	20.40	21.06	21.14	20.75
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00
FeO _{tot}	30.94	32.76	33.05	31.08	14.15	14.97
Fe ₂ O ₃	0.46	0.70	0.72	0.21	0.83	1.02
FeO	30.53	32.13	32.40	30.89	13.40	14.05
MnO	10.13	0.57	3.73	0.50	9.05	6.26
MgO	1.14	1.73	1.36	1.70	0.00	0.00
CaO	1.16	7.35	4.61	8.23	17.96	20.16
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.14	99.98	100.06	100.02	100.95	99.86
O	12.00	12.00	12.00	12.00	12.00	12.00
Si	2.99	2.98	3.00	3.00	3.02	2.98
Al _{tot}	1.97	1.96	1.96	1.99	1.95	1.94
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	0.03	0.04	0.04	0.01	0.05	0.06
Fe ²⁺	2.10	2.17	2.20	2.07	0.88	0.93
Mg	0.14	0.21	0.16	0.20	0.00	0.00
Mn	0.70	0.04	0.26	0.03	0.60	0.42
Ca	0.10	0.64	0.40	0.71	1.51	1.71
Na	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00
Σ _{cations}	8.03	8.04	8.03	8.01	8.00	8.05
X _{Alm}	0.69	0.71	0.73	0.69	0.29	0.30
X _{Sps}	0.23	0.01	0.08	0.01	0.20	0.14
X _{Gr}	0.02	0.19	0.11	0.23	0.48	0.53
X _{Py}	0.05	0.07	0.05	0.07	0.00	0.00
X _{Andr}	0.01	0.02	0.02	0.01	0.02	0.03
X _{Fe}	0.95	0.91	0.94	0.91	1.00	1.00

Discussion

Deformation history of the CGL

The CGL has previously been investigated, especially its eastern part (e.g. Spiegel 2003; Langone et al. 2006; Altenberger et al. 2011, 2013), and the presence of mylonites had never been reported towards the west, as far as Acconia quarry (Figs. 1, 2b).

In agreement with Spiegel (2003), Langone et al. (2006) and Altenberger et al. (2013), the main foliation (S_m) and the stretching lineation (L_m) of the CGL mylonites show mean SSW and SSE dip direction and plunge, respectively. We interpret the SSW-dipping S_m in mylonitic metapelites as map-scale C-type shear bands, because of its near-parallelism with the margins of the CGL ductile shear zone and the tectonic contact between the Castagna and the Sila and Serre units (Figs. 2, 4a). Concerning the mylonitic orthogneiss body: (i) the NNE-dipping foliation towards its central part (in cross-section view); and (ii) the SSW-dipping foliation, with dip progressively increasing approaching the southern and the northern margins, allowed us to interpret the S_m as map-scale S-planes, on the whole, sub-parallel to the margins of the CGL ductile shear zone (Figs. 2, 4b, c).

The observed variations of the foliation attitude in the mylonitic orthogneisses are interpreted to be caused by later folding events, as described by Langone et al. (2006). According to interpretations by these authors, the northern margin of the CGL should dip towards the north; by contrast it dips to the SSW (Fig. 2a). A later folding event is thus not supported by the geological map and foliation attitudes analysis (Figs. 2a, 4). On the basis of our interpretation, in terms of map scale S-planes and C-type shear bands for the S_m , a remarkable total thickness of c. 900 m can be calculated for the mylonites of the CGL (Fig. 2). This is significantly greater than the 400 m estimated by Langone

et al. (2006). Such map-scale S-planes are quite consistent with a top-to-the-SSE shear sense, as also obtained by Langone et al. (2006). In addition, the geometric relationships between the SSW-dipping S_m main mylonitic foliation and the SSE-dipping L_m lineation (Fig. 7a–c) would imply a left-lateral component of movement along the CGL, in a dominantly extensional tectonic context. While this dominant extensional kinematics is the most evident, they are not exclusive, since contrasting kinematic indicators are present in all the mylonites. As a matter of fact, and according to the attitudes of the L_m stretching lineations, the kinematic indicators suggest that a top-to-the-SSE shear sense is generally more widespread than those indicating a top-to-the-NNW tectonic transport. Therefore, a reworking of the CGL passing from top-to-the-NNW to top-to-the-SSE tectonic transport (i.e. switching from thrusting to extensional faulting), is plausible during ductile deformation due to variations in the geodynamic setting (Figs. 8, 9). This interpretation is supported by the growth of the Ca-rich garnet in the mylonitic orthogneisses, which is both (i) post-kinematic in the Acconia quarry area (e.g. Fig. 6b, e and 7b), where the top-to-the-NNW shear sense is dominant (e.g. Fig. 1, 2b), and (ii) pre-kinematic in the Pesipe Stream valley (e.g. Fig. 6b, 7c) (see also Langone et al. 2006), where the top-to-the-SSE tectonic transport predominates (e.g. Fig. 1, 2a). Hence, Ca-rich garnet growth occurred after the NNW-directed thrusting and before the SSE-directed extension.

The syn-kinematic growth, among other mineral phases, of white mica, epidote and titanite in the mylonitic orthogneisses (Fig. 6b–d) and the dynamic recrystallisation of the feldspars (e.g. Fig. 5d, g) are consistent with ductile deformation under epidote–amphibolite facies conditions, at an approximate peak pressure of 0.9 GPa, as obtained by Langone et al. (2006) and Altenberger et al. (2011, 2013). Since Ca in garnet correlates positively with pressure (e.g. Altenberger et al. 2011), our findings regarding Ca-enrichment in the rim of the larger euhedral garnets, as well as the growth

Fig. 8 Cartoon illustrating the deformational history of the CGL mylonites from the Eocene to the present-day; note, in the present-day frame, the overall crustal tilting towards the southern quadrants and the projected cross-section of Fig. 2

Fig. 9 Cartoon illustrating the plan-view geodynamic palinspastic restoration for the central Mediterranean framed in Eocene, early Oligocene, early Miocene and present-day times, modified after Gueguen et al. (1998), according to Langone et al. (2006) and Molli (2008); transfer faults in the northern and southern Serre Massif according to Cirrincione et al. (2015), Festa et al. (2016) and Orto-

lano et al. (2020a); full and empty arrows indicate active and relic tectonic transport, respectively, according to Rossetti et al. (2001, 2004), for the Sila Massif and Catena Costiera areas, and the results of the present study for the CGL; *Si* Sila Massif, *CC* Catena Costiera, *Se* Serre Massif

of the smaller euhedral to sub-euhedral Ca-rich garnets (Fig. 7a, b), support these peak pressure conditions. Partial replacement of the Hercynian mineral assemblages also suggests that the mylonitic orthogneisses of the Castagna Unit were subjected to fluid–rock interaction during shearing, as also observed in several case studies of ductile-sheared felsic rocks (e.g. Tursi et al. 2018 and the references therein). Moreover, considering the syn-kinematic mineral phases in both mylonitic metapelites and mylonitic orthogneisses, the transition from dominantly compressional to extensional kinematics of the CGL occurred under epidote–amphibolite facies conditions, as also suggested by the P–T deformation conditions estimated by Langone et al. (2006) and Altenberger et al. (2011). During the dominantly extensional reworking, the inherited S_m foliation was locally preserved, together with the post-kinematic growth of Ca-rich garnet, or was even still developing, making the Ca-rich garnet pre-kinematic. Ductile deformation was protracted during exhumation and cooling, as indicated by syn-kinematic chlorite (Fig. 6b), which reasonably formed under the greenschist facies conditions estimated by Spiegel (2003).

Our results provide evidence that the CGL mylonites were subjected to a structural reworking during exhumation, which can be correlated to the findings by Rossetti et al. (2001, 2004) that invoked a post-orogenic extensional reworking of the formerly dominantly compressive ductile tectonic contact between the Castagna and the Sila and Serre units, in the Sila Massif and Catena Costiera areas (Fig. 1, inset top left).

According to the dating carried out by Schenk (1980), the dominant compressional activity of the CGL dates to the Lutetian, i.e. c. 43 Ma (Rb–Sr data on biotite). Furthermore, ages of c. 35 Ma (^{40}Ar – ^{39}Ar data on white mica by Rossetti et al. 2001) and of c. 46 Ma (^{40}Ar – ^{39}Ar data on

white mica by Shimabukuro et al. 2012) were obtained for the high-pressure metamorphism (2.0–2.1 GPa) that affected the Intermediate Complex (Fig. 1, inset top left) (Tursi et al. 2020a), which would support the Lutetian–Priabonian dominant compressional kinematics of the CGL. Taking into account the thermal sensitivities of the dating systems, i.e. up to 400 °C for the Rb–Sr in biotite (Jenkin 1997 and the references therein), the age of the dominant compressional activity of the CGL could be reasonably older and, however, framed in the Eocene (Fig. 8), as also suggested by Del Moro et al. (2000).

Other crucial dates exist for the activity of the CGL. In particular, zircon and apatite fission-track dating of c. 30 Ma and c. 20 Ma for the hanging wall and c. 18 Ma and c. 15 Ma for the footwall rocks of the CGL have been related to dominant crustal extension and exhumation by Thomson (1998). Accordingly, the Sila and Serre Unit and the Castagna Unit experienced deformation at temperatures above 300 °C along the CGL, up to 30 Ma and 18 Ma, respectively. Therefore, the CGL mylonites, that had already formed during the previously dominant compressional tectonic event, started to experience ductile structural reworking, at least from the early Oligocene (or even earlier from the late Eocene), i.e. at the transition from dominantly compressional to extensional tectonics (Fig. 8). Furthermore, during the late Oligocene to early Miocene, brittle deformation was superimposed onto the mylonites of the Sila and Serre Unit, whereas the mylonites of the Castagna Unit were still subjected to ductile deformation and structural reworking (Fig. 8), especially through quartz recrystallisation. Since the presence of cataclasites (Spiegel 2003) and non-mylonitised pseudotachylite veins primarily occur along the tectonic contact between the Castagna and the Sila and Serre units (e.g. Langone et al.

2006), the shearing in the early Miocene was there probably restricted (Fig. 8).

Crustal exhumation in the Cenozoic was accompanied by tilting of about 40° (Thomson 1994; Festa et al. 2003), which determined the present-day SW-dipping and exposition of the CGL and its walls (Fig. 8).

Regional implications

The presence of 900 m of thick mylonites at the base of an almost-complete continental crust section (i.e. the Sila and Serre Unit) is indicative that the CGL acted as a crustal-scale thrust, juxtaposing metamorphic rocks of the Hercynian granulite facies above amphibolite facies (Schenk 1981). According to the thermo-barometric estimations by Langone et al. (2006) and Altenberger et al. (2011, 2013), the mylonites of the CGL experienced deformation at a depth of c. 30 km. Crustal-scale thrusting, namely thick-skinned tectonics, is favoured in E-dipping-type subduction contexts (Doglioni 1992), which, in turn, allows the growth of double-verging orogens such as the Alps (e.g. Doglioni et al. 1997; Dal Piaz et al. 2003; Lenci and Doglioni 2007; Gasco et al. 2013; Lacombe and Bellahsen 2016 and the references therein). Therefore, the compressional character of the CGL seems more suitable in an E-dipping-type subduction context rather than in a W-dipping-type (Doglioni 1992), the latter favouring thin-skinned tectonics in the accretionary prism of single-verging orogens such as the Apennines (e.g. Doglioni 1992; Lenci et al. 2004; Lenci and Doglioni 2007). According to the plan-view of the geodynamic, palinspastic restoration for the western Mediterranean (e.g. Gueguen et al. 1998; Langone et al. 2006; Molli 2008), the present-day top-to-the-NNW kinematics of the CGL would indicate dominant compression with top-to-the-European plate realm tectonic transport during the Eocene, as shown in the scenario in the first frame of Fig. 9. As a consequence, the CGL acted as a thrust within the double-verging southern Alpine chain, and was kinematically coherent with the northern front of the orogen (Fig. 9) instead of with the south-eastern back-front, as suggested by Langone et al. (2006). This explains the roughly opposing tectonic transport of the nappes in the Sila Massif and Catena Costiera (Rossetti et al. 2001, 2004) and may relate their proximity to the back-front of the Alpine chain during the Eocene (Fig. 9). As shown in the early Oligocene and early Miocene frames of Fig. 9, the dominant extensional reactivation of the CGL, as well as the tectonic contacts at the base of the nappes in the Sila Massif and Catena Costiera, should be related to the dismembering of the southern Alpine orogen because of their position in the back-arc of the Apennines subduction system (e.g. Gueguen et al. 1998; Rossetti et al. 2004; Carminati and Doglioni 2012). In this dominantly

extensional tectonic setting, the opposite dip of the former thrusts would have determined an opposite tectonic transport during reactivation of the CGL and the tectonic contacts of the nappes of Sila Massif and Catena Costiera (Rossetti et al. 2001, 2004; Ortolano et al. 2020b) (Fig. 9). Finally, the last frame in Fig. 9 shows the result of the (late Eocene?) Oligocene to early Miocene downward top-to-the-SE tectonic transport along the CGL, coherent also with the sole kinematics observed by Langone et al. (2006) and the downward top-to-the-W kinematics constrained by Rossetti et al. (2001, 2004) along the tectonic contacts of the nappes in the Sila Massif and Catena Costiera areas, in the present-day geographic coordinates.

Concluding remarks

This research paper allowed us to shed light on the kinematics of one of the most relevant regional shear zones in the Calabria–Peloritani terrane (i.e. the CGL), in the framework of the evolution of the Alpine to the Apennine subduction systems. The results obtained for the CGL mylonites support the following conclusions:

- (i) In the northern Serre Massif, the CGL can be prolonged to the west, as far as Acconia village;
- (ii) the SSW-dipping S_m foliation of the mylonitic metapelites represents map-scale, C-type shear bands, whereas the NNE and SSW-dipping S_m foliations of the mylonitic orthogneisses give rise overall to map-scale, S-plane structures;
- (iii) the mylonites show a remarkable total thickness of c. 900 m;
- (iv) the mylonites were subjected to a profound ductile reworking during dominantly extensional tectonics. Accordingly, the top-to-the-NNW and the top-to-the-SSE kinematics of the CGL (in the present-day geographic coordinates) reflect a compressional tectonic regime, succeeded by extensional reactivation of the fault zone;
- (v) the dominant compressional activity of the CGL dates back to the Eocene. The transition from dominantly compressional to extensional tectonics happened approximatively at the end of the Eocene, with the ductile reworking of the mylonites continuing up to the early Oligocene. During the late Oligocene to early Miocene, brittle deformation was superimposed onto the mylonites of the Sila and Serre Unit, whereas the mylonites of the Castagna Unit were still subjected to ductile deformation and structural reworking, especially through quartz recrystallisation. During the early Miocene, dominant exten-

sional tectonics and exhumation protracted, with brittle deformation that was restricted to the tectonic contact between the Castagna and the Sila and Serre units;

- (vi) crustal-scale thrusting, namely thick-skinned tectonics, could have been favoured in the easterly dipping-type subduction context of the Alpine orogeny. Thus, the CGL would have acted as a thrust within the double-verging southern Alpine chain, with top-to-the-European plate realm tectonic transport, which is coherent with the kinematics of the northern front of the Alps. The subsequently dominant extensional character of the CGL is related to the dismembering of the southern Alpine orogen, since its position was in the back-arc of the Apennine subduction system;
- (vii) the dominant extensional tectonics in the (late Eocene?) Oligocene to Miocene, together with the migration of the Calabria–Peloritani terrane framed in the Apennine’s evolution, led to the present-day top-to-the-SSE kinematics of the mylonites. Furthermore, tilting was determined, allowing the SE-dipping of the CGL and its walls.

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