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Field
Trips

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From the upper to the lower continental crust exposed in Calabria

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From the upper to the lower continental crust exposed in Calabria

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Riassunto

In Calabria sono esposte sezioni del basamento pre-Mesozoico che rappresentano un profilo completo della crosta continentale strutturata durante il ciclo orogenico ercinico. Questa circostanza particolare è stata causata dalla tettonica terziaria che ha determinato l'esumazione dei diversi livelli di crosta. L'escursione mira a fornire un quadro generale della crosta continentale che si spera possa essere utile per tarare modelli geochimici, reologici e geofisici. L'itinerario si snoda nella parte centro-meridionale della Calabria e principalmente attraverso il Massiccio delle Serre ed i promontori di Capo Vaticano e di Monte Sant'Elia. Durante i tre giorni di escursione è possibile esaminare le caratteristiche compositive e strutturali dei diversi livelli di crosta, a partire da quella superiore verso quella inferiore. Si possono osservare rocce metamorfiche dal basso grado sino alla facies granulitica ed apprezzare le caratteristiche distintive dei granitoidi intrusi a diversa profondità. Gli effetti dell'intensa perturbazione termica causata dalla messa in posto dei granitoidi sono osservabili sia nella crosta superiore che in quella inferiore, ovvero nella netta aureola di contatto e nella zona migmatitica di bordo, rispettivamente. L'itinerario prevede anche la visita di zone ove risultano ben visibili gli effetti della deformazione localizzata, prodotta dalla tettonica terziaria sulle rocce paleozoiche sia in condizioni fragili che duttili.

Parole chiave: *Calabria, crosta continentale, orogenesi ercinica, granitoidi, metamorfismo di contatto, granuliti*

Abstract

Outcrops of the pre-Mesozoic basement, representative of the whole Hercynian continental crust are exposed in Calabria. This is the result of Tertiary geological evolution that brought to the surface different crustal levels. This geological field trip aims to provide a general picture of the continental crust that hopefully may represent a reference frame for geochemical, rheological and geophysical models. The itinerary develops in central and southern parts of Calabria, namely in the Serre massif and in the promontories of Capo Vaticano and Monte Sant'Elia. In three days it is possible to examine compositional and structural features across an entire crust section. Thus rocks affected by very low-grade to granulite facies metamor-

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phism and distinctive features of granitoids emplaced at different structural levels will be examined. The effects of the intense thermal perturbation produced by granitoid emplacement are visible both in the upper and in the lower crust, in a sharp metamorphic aureole and in a migmatitic border zone, respectively. Finally, some cases of Paleozoic rocks with strongly partitioned deformation, produced by Tertiary tectonics in the brittle and the ductile domains, can be observed.

Key words: *Calabria, continental crust, Hercynian orogeny, granitoids, contact metamorphism, granulites*

General info

Calabria is one of the few sites where cross-sections of the Paleozoic continental crust are exposed from the upper to the lower levels. The venue of the 2012 Congress of the Italian Geological Society in Cosenza was the ideal opportunity to take this field trip and to visit some of the most interesting sections.
The field trip lasts three days focussed on the upper, intermediate and lower crust across the Serre massif, the Capo Vaticano and Mt. Sant’Elia promontories.
Granulite facies rocks and migmatites of the lower crust, granitoids emplaced in the intermediate crust and Paleozoic sequences affected by contact metamorphism in the upper crust are examined in the three days. The goal of the field trip is to outline a general picture of the Calabria continental crustal section and to provide a reference frame for geochemical, structural and geophysical models. Although the main theme of the excursion is the Hercynian continental crust, the selected Stops include also some outcrops with notable examples of Alpine deformation.
Petrographic and structural features of the rocks belonging to different crustal levels can be observed in six selected areas (Fig. 1), following this sequence:
Stilo area (Stops 1.1 and 1.2) and Pietragrande – Squillace area (Stops 1.3 and 1.4), during the whole first day;
Capo Vaticano area (Stop 2.1) and Palmi area (Stops 2.2 - 2.4), during the whole second day;
Curinga area (Stop 3.1) and Girifalco area (Stops 3.2 and 3.3), during the first half of the third day.
The field trip starts from Stilo (RC), a historical village famous for the nice byzantine church “Cattolica”. It is suggested to reach Stilo the day before the start of the field trip and to stay the first night there. For the next two nights the suggested locality is the village of Ricadi (VV) and neighbourhood (Fig. 1), offering a wide range

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of accommodation options. From the last Stop of the field trip it is possible to reach in about 45 minutes Lamezia Sant'Eufemia, the location of the main airport and railway station in Calabria (Fig. 1).
In the field trip short and easy trails are foreseen for each Stop and the maximum elevation will be of about 900 m above see level. It is not required a particular equipment, except for the essential hiking boots and rain jacket or poncho.

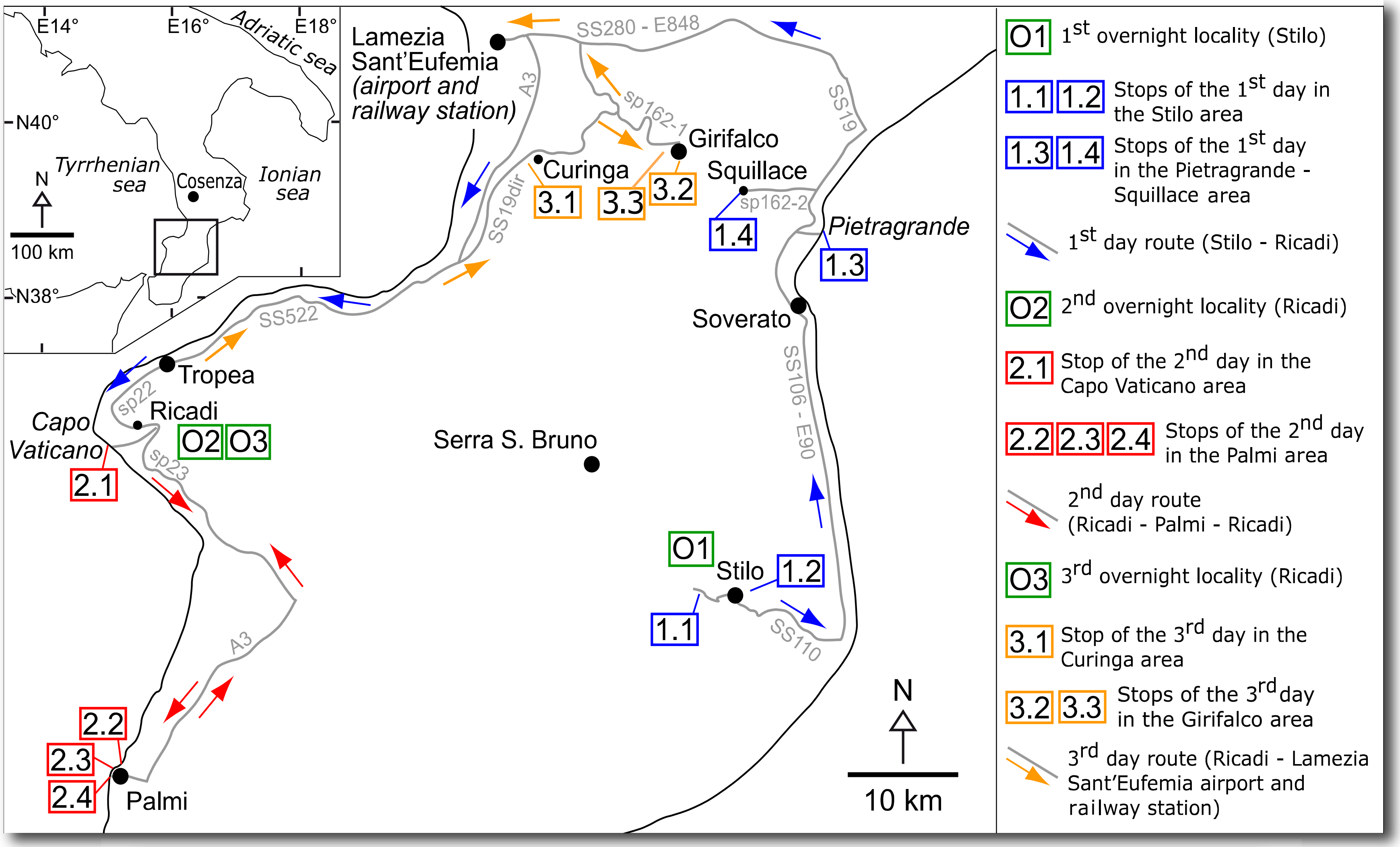

Fig. 1 - An outline of the itinerary followed in the three days of the field trip.

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1 - Introduction

Continental crust sections across the Calabria massifs represent a distinctive feature in the geological frame of the region. Examining the plentiful scientific literature related to Calabria (see Amodio Morelli et al., 1976 and Bonardi et al., 2001 for a review), a role of precursor in drafting continuous sections of the pre-Mesozoic basement should be ascribed to Roland Dubois (e.g., Dubois, 1970, 1971, 1976). Afterwards, Volker Schenk and co-workers, starting from the eighties, detailed in several studies (e.g., Schenk, 1980, 1981, 1984, 1989, 1990; Grässner & Schenk, 1999, 2001; Grässener et al., 2000) continental crustal sections in the Serre, Aspromonte and Sila massifs and made them well known to a worldwide scientific community.

Merit of these scientists was fundamental in providing an integral vision of the Palaeozoic basement exposed in Calabria, obscured when numberless tectonic domains and units, sometimes with different suggested provenance, have been proposed.

Cross-sections, provided by Dubois (1971) and Schenk (1980) for the Sila and Serre massifs, respectively, are shown in Fig. 2.

2 - Crust composition

The Serre crustal section is best known, owing to the weaker disturb produced on the Palaeozoic structure by Tertiary tectonics and to significant exposures of the lower crust detailed by researchers of Bari University under the guidance of Giuseppe Piccarreta (e.g., Amodio Morelli et al., 1973; Moresi et al., 1978; Paglionico & Piccarreta, 1978; Caggianelli et al., 1991; Fornelli et al., 2002) and by Schenk (see references cited in the Introduction).

The continental crust exposed in the Serre Massif can be simplified as follows, from the top to the bottom:

<u>Upper crust</u>:
1) phyllites and slates with intercalations of metavolcanics and marbles;
2) micaschists and paragneisses.
<u>Intermediate crust</u>:
3) isotropic to weakly foliated granodiorites;

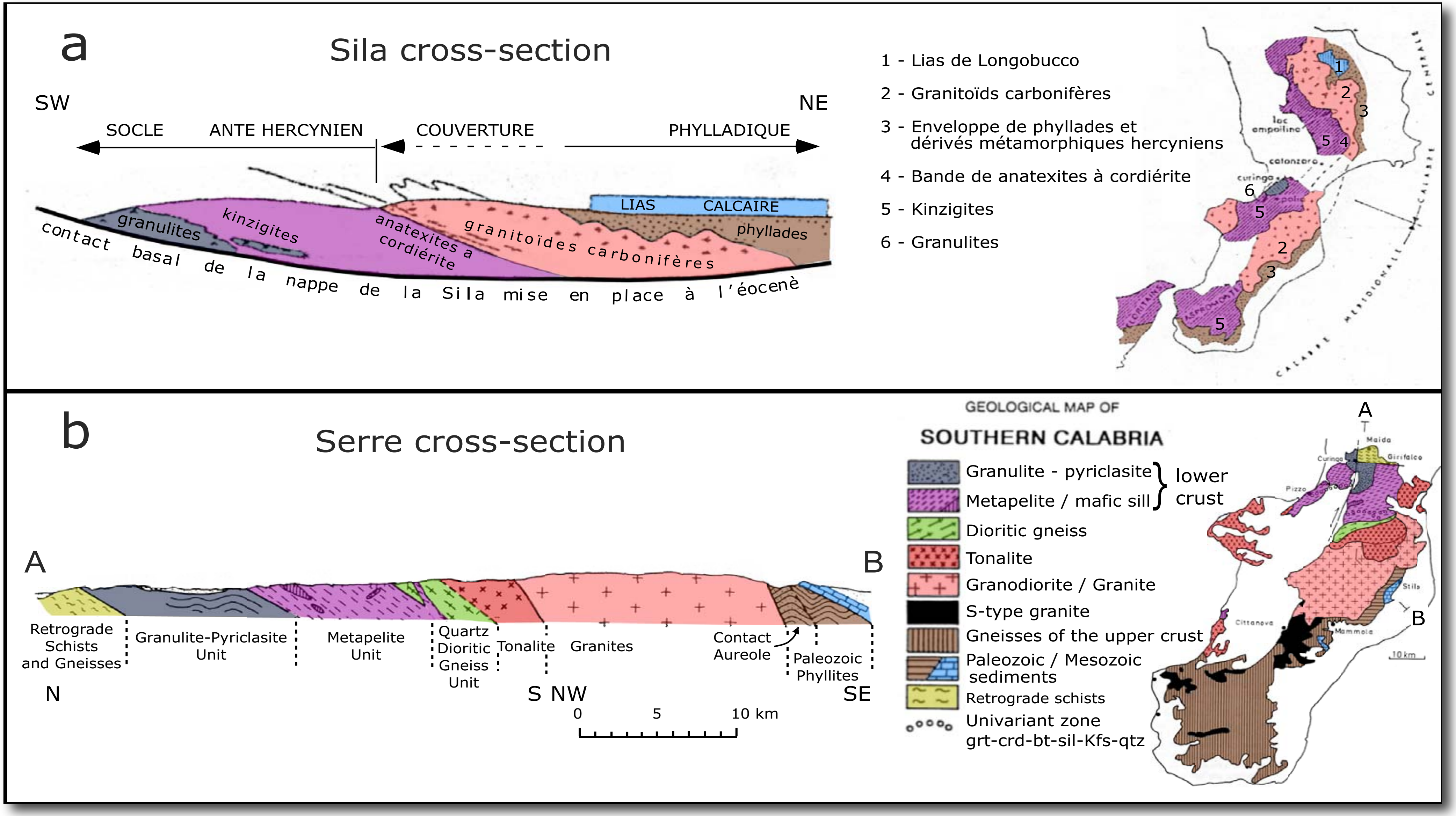

Fig. 2 - Cross-sections by Dubois and Schenk for the Sila (**a**) and Serre (**b**) massifs, respectively (modified after Dubois, 1971 and Schenk, 1980). The geological map of Southern Calabria in (**B**) is modified after Grässner & Schenk, 1999.

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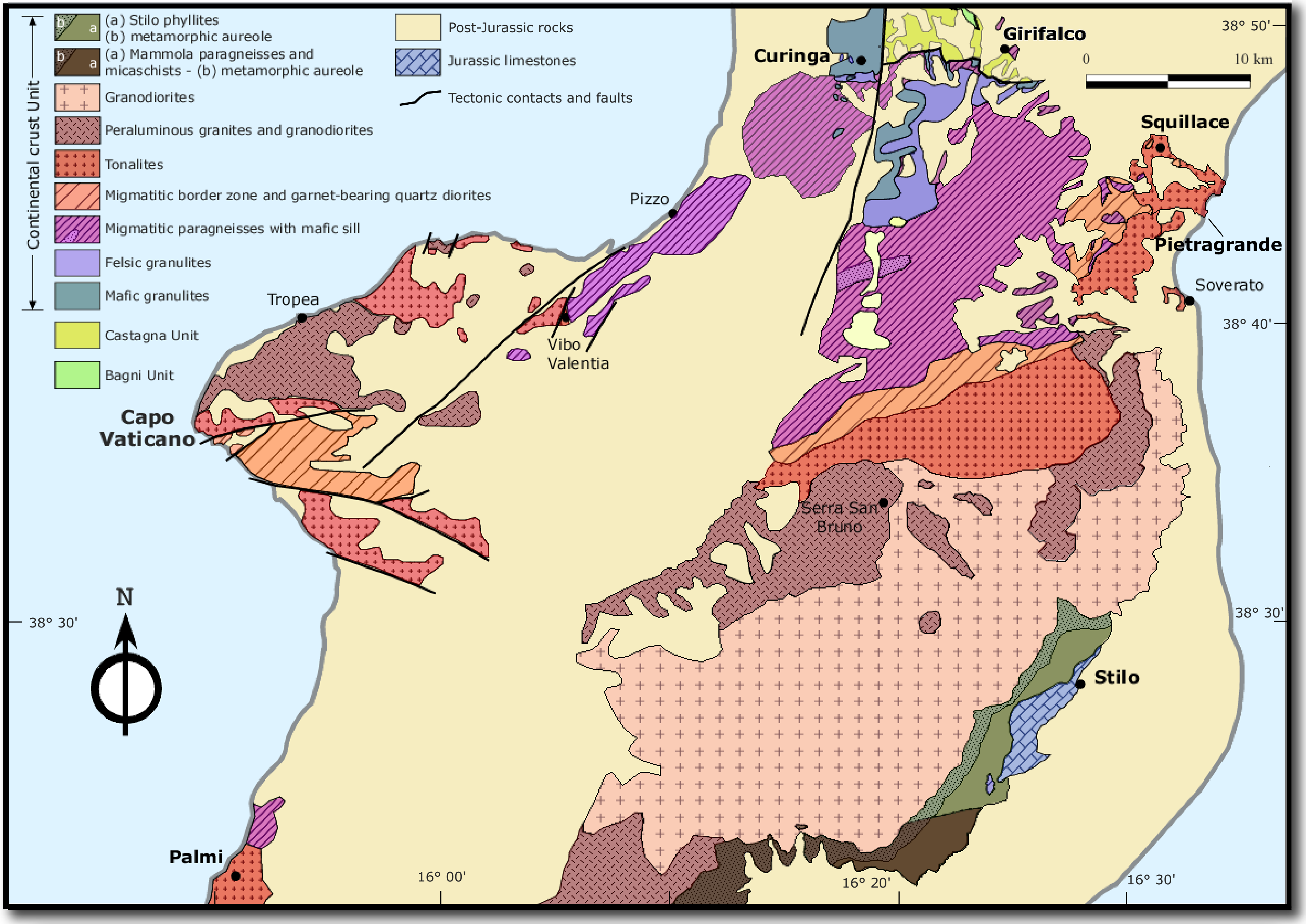
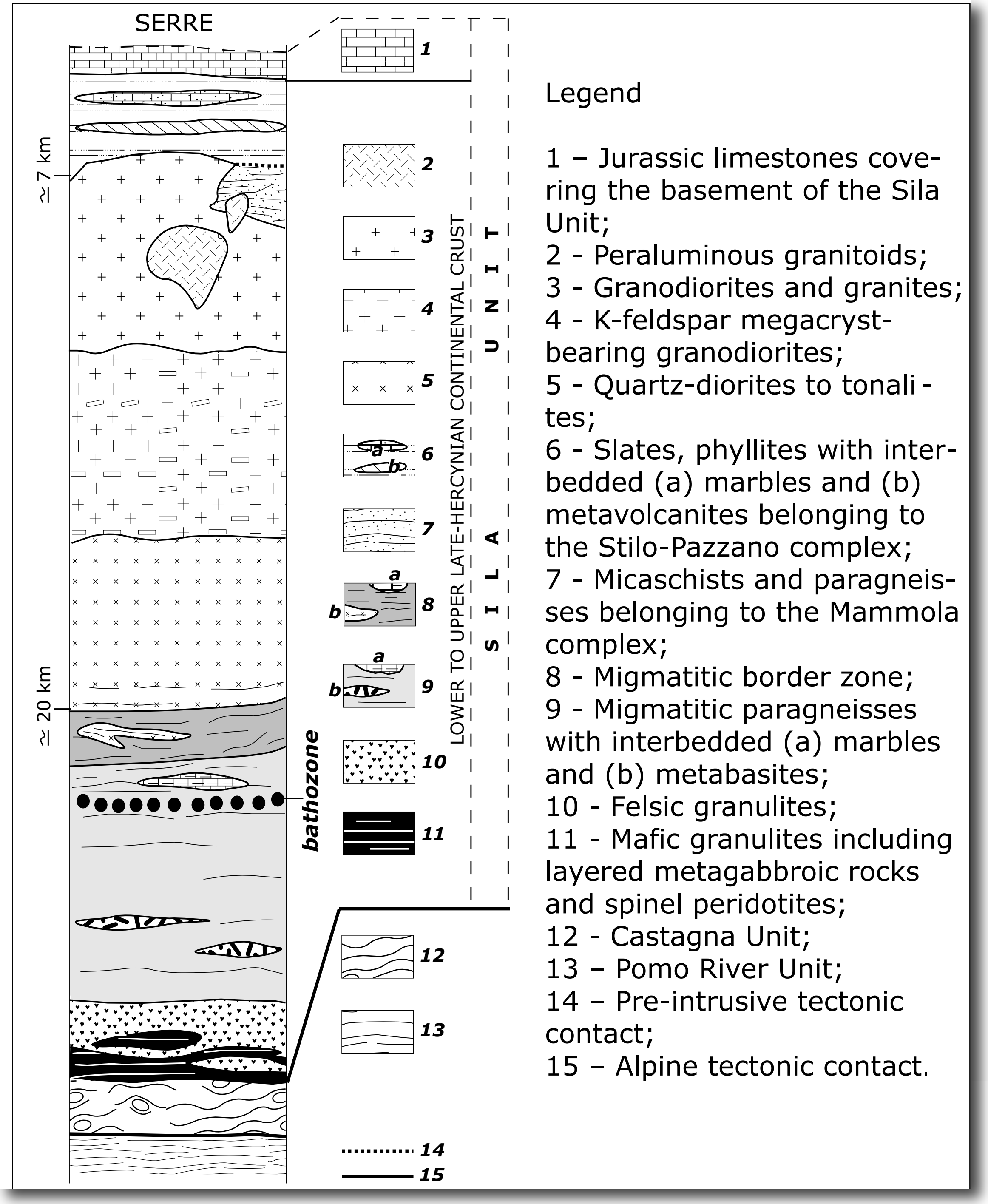


Fig. 3 - Geological sketch map of the Serre Massif, Capo Vaticano and Sant'Elia promontories (modified from: Borsi et al., 1976; Fornelli et al., 1994; Grässner & Schenk, 1999; Rottura et al., 1991).



Legend

1 – Jurassic limestones covering the basement of the Sila Unit;
2 - Peraluminous granitoids;
3 - Granodiorites and granites;
4 - K-feldspar megacryst-bearing granodiorites;
5 - Quartz-diorites to tonalites;
6 - Slates, phyllites with interbedded (a) marbles and (b) metavolcanites belonging to the Stilo-Pazzano complex;
7 - Micaschists and paragneisses belonging to the Mammola complex;
8 - Migmatitic border zone;
9 - Migmatitic paragneisses with interbedded (a) marbles and (b) metabasites;
10 - Felsic granulites;
11 - Mafic granulites including layered metagabbroic rocks and spinel peridotites;
12 - Castagna Unit;
13 – Pomo River Unit;
14 – Pre-intrusive tectonic contact;
15 – Alpine tectonic contact.

4) peraluminous K-feldspar megacrystal – bearing granites and granodiorites;
5) foliated tonalites and quartz diorites.

<u>Lower crust</u>:

6) migmatitic border zone and garnet-bearing quartz diorites;
7) migmatitic paragneisses;
8) felsic granulites;
9) mafic granulites.

Additional information can be gained examining the geological sketch map of Fig. 3 and the lithological column of Fig. 4. Owing to the crust-scale tilting produced by Tertiary tectonics, the lithological succession can be followed on map (Fig. 3) from the SE (top) to the NW (bottom). Thickness of the exposed lower, intermediate and upper crust are about 8, 13 and 3 km, respectively (Fig. 4). Spinel peridotites occur as intercalations in the lower crust and do not represent the evidence for the crust-mantle transition. Therefore, the real thickness of the former lower crust can be larger. The same holds for the upper crust, where Mesozoic limestones and thin siliciclastic deposits are in erosive contact with the basement.

Fig. 4 - Schematic lithological column for the Serre crustal section (modified from Festa et al., 2004).

The contact between the lower crust and the granitoids, usually involving migmatitic paragneisses and tonalites/quartz diorites, is transitional and can be described as a migmatitic border zone. Here, paragneisses are affected by a higher degree of partial melting and tonalites include abundant metamorphic basement xenoliths and giant crystals of garnet.

A strong impulse on the advanced study of granitoids in Calabria has been given by Alessandro Rottura in several papers (e.g. Rottura et al., 1990, 1991, 1993). Broadly, granitoids can be attributed to two main calc-alkaline types: (**i**) metaluminous granitoids, compositionally ranging from tonalite to granite and including more mafic rocks such as gabbros, diorite and quartz diorite; (**ii**) peraluminous granites compositionally restricted, essentially two-micas monzogranites with Al-silicates. Both granitoid types have in most cases a hybrid mantle-crust signature, and, therefore, genesis of parental magma cannot be attributed exclusively to partial melting of mantle or continental crust source rocks.

The contact between granitoids and upper crustal rocks, involving granodiorites and phyllite or paragneiss, is sharp and characterized by a well developed andalusite-cordierite metamorphic aureole (Colonna et al., 1973).

The simplified scheme outlined above, with few variations, can be applied also to the Sila Massif.

The thickness of the exposed crust is lower and can be estimated to about 20 km. Among granitoids, granites prevail over tonalites. In addition, mafic bodies of olivine-norite (Caggianelli et al., 1994) are present.

Attempts to estimate the overall chemical composition of the Calabria continental crust have been made by Schenk (1990), Caggianelli & Prosser (2001), Acquafredda et al. (2003). Results for the Sila and Serre massifs are portrayed in Table 1. A comparison with worldwide compilations by Christensen & Mooney (1995) and Rudnick & Gao (2003) shows that Calabria crust is characterized by a distinctly higher Al_2O_3 content and by lower contents in MgO and CaO. These differences reflect the abundance of metapelites both in the lower and upper crust of Calabria and possibly the presence of several peraluminous granites. They appear more pronounced in the Sila Massif, where granites are more abundant than tonalites. Another interesting feature of the crust exposed in Calabria is the high value of radiogenic heat production, resulting from the abundance of granitoids and the widespread presence of accessory minerals, such as allanite, zircon and monazite. In particular, monazite and zircon are relatively abundant also in the migmatitic paragneisses of the lower crust.

3 - Timing of the Hercynian metamorphic and magmatic events in the continental crust

The ages obtained for the events that shaped the Calabria crustal sections are presented. Before the Hercynian orogeny, the Calabria crust underwent some significant geological episodes witnessed by the occurrence of frequent neo-Proterozoic to Silurian ages obtained both from radiometric and paleontological methods. Only a short account is given here for these older ages. For a detailed discussion, the reader should refer to the paper by Micheletti et al., (2007) and Williams et al. (2011). A neo-Proterozoic-Cambrian magmatism with bimodal chemical character has been extensively documented in Calabria (e.g. Micheletti et al., 2007; 2008; 2011; Fornelli et al., 2011). Mafic magmatic bodies emplaced between 593±14 and 574±18 Ma whereas felsic ones provided ages between 562±15 and 526±10 Ma. Also in the Peloritani Mountains, neo-Proterozoic granitoids (~565-545 Ma) have been recognized as protoliths of granitic augen gneisses (Williams et al., 2011), whereas felsic igneous, usually volcanic rocks ("porphyroids"), give an Upper Ordovician age of 456-452 Ma (U-Pb data by Trombetta et al., 2004). Inherited zir-

Table 1 - Estimates of the chemical composition of the continental crust for the Sila (1) and Serre (2-4) crust sections. For comparison, global averages of the bulk (5, 6) and lower (7) continental crust are provided. Compositions in columns 1 to 3 recalculated anhydrous.

* Bulk radiogenic heat production in μW m^{-3}

1 - Caggianelli & Prosser (2001); 2, 3 – Acquafredda et al. (2003);
4 – Schenk (1990); 5 - Christensen & Mooney (1995); 6, 7 - Rudnick & Gao (2003).

	1 Bulk crust	2 Bulk crust	3 Lower crust	4 Lower crust	5 Bulk crust	6 Bulk crust	7 Lower crust
wt.%							
SiO_2	64.93	64.74	61.55	56.0	62.4	60.6	53.4
TiO_2	0.83	0.80	1.08	1.1	0.9	0.72	0.82
Al_2O_3	18.56	17.37	18.69	20.0	14.9	15.9	16.9
FeO_t	5.94	5.74	7.53	9.2	6.89	6.71	8.57
MnO	0.08	0.10	0.12		0.10	0.10	0.10
MgO	2.37	2.37	3.28	4.9	3.1	4.66	7.24
CaO	1.59	3.46	3.57	4.4	5.8	6.41	9.59
Na_2O	2.16	2.49	2.05	2.1	3.6	3.07	2.65
K_2O	3.38	2.78	1.99	2.1	2.1	1.81	0.61
P_2O_5	0.14	0.14	0.15		0.20	0.13	0.10
ppm							
Ba	585	844	724			456	259
Rb	137	83	58			49	11
Sr	126	204	217			320	148
Th	14.8	14.1	14.0			5.6	1.2
U	2.72	1.68	1.03			1.3	0.2
A*	2.11	1.73	1.48			0.92	0.19

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con and/or xenocrystic zircon cores from both metasedimentary rocks and orthogneisses confirm a widespread Cambrian-neo-Proterozoic magmatic activity. The spectra of these rocks suggest also a reworking of older basement rocks.

For a comprehensive discussion on Hercynian events, only geochronological data obtained with comparable methods and applied on minerals showing similar properties as geochronometers were considered. We focused our discussion on U-(Th)-Pb data obtained by TIMS, LA-ICP-MS, EMPA and SIMS methods on zircon and/or monazite and/or xenotime. Starting from 1980, geochronological studies were directed to high grade rocks from the lower crust segments. Among the high grade metamorphic rocks, more attention has been paid to the Serre Massif. Geochronological data relative to the other lower crustal rocks are scarce (e.g. Sila Massif, Northern Calabria) or lacking (Palmi area, Southern Calabria). A few data are available also for the greenschist-amphibolite facies rocks of the upper crustal levels. Instead, radiometric data for the granitoids of the intermediate crust are homogeneously distributed among the Calabria massifs. Large part of these data are explicitly attributed to the late stage of the Hercynian orogeny characterised by decompression, high-T metamorphism and granitoid magmatism.

U-(Th)-Pb data from different minerals (zircon, monazite and xenotime) point to a major high temperature metamorphic event at the Carboniferous-Permian boundary. This event is recorded by metasediments of both the lower and upper crustal rocks.

The data set for the lower crust exposed in the Serre and Sila massifs is adequate for a graphical representation and to outline an age spectrum of the Hercynian events (Fig. 5). It is evident that the major concentration of ages falls between 290 and 305 Ma (n = 20). Three other peaks are also

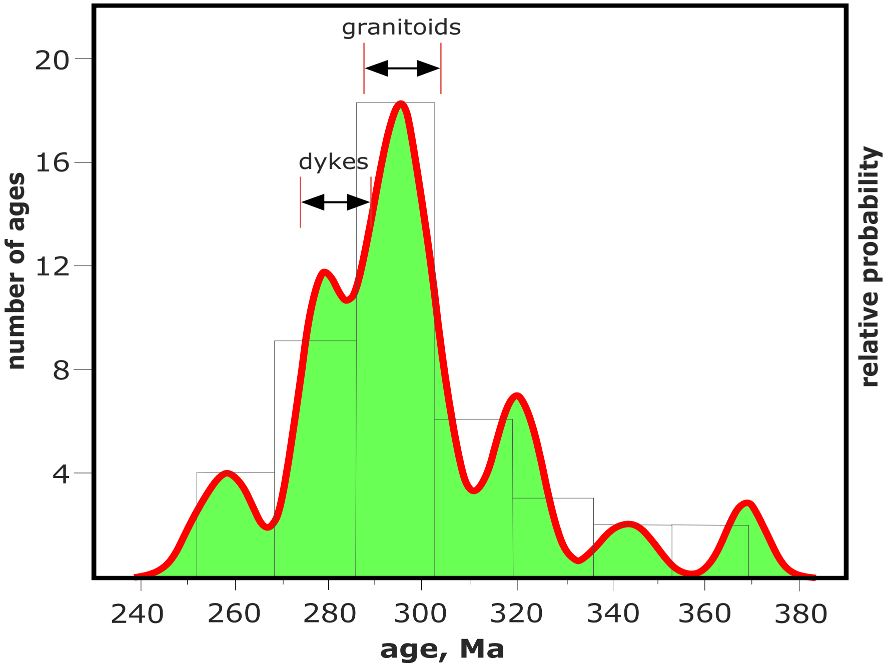

Fig. 5 - Spectrum of the Hercynian ages (n=44) recorded in the Serre and Sila lower crust. All ages were determined by U-(Th)-Pb method on zircon and monazite. Number of ages related to each peak are detailed in the text. Ranges of ages for granitoids and dykes are also indicated.

present, located approximately at 280 (n = 10), 320 Ma (n = 6) and 260 Ma (n = 4). Minor peaks (n=2), at 370 and 345 Ma may indicate, together with the 320 ma event, different steps in the prograde history. Interestingly, early Hercynian events, between 319 and 359 Ma, are recorded also in metamorphic rocks of the upper crust by Rb-Sr dates and chemical dating of monazite (e.g. Acquafredda et al., 1994; Grande, 2008). Magmatic activity appears to be synchronous with the two main metamorphic events recorded in the lower crust. In fact, ages related to granitoids of the intermediate crust fall mostly in the 290-305 Ma range whereas zircon U-Pb ages, recently obtained for late magmatic dykes of the Sila and Serre massifs, are close to 280 Ma and mark the Lower Permian magmatic activity (Festa et al., 2010; Romano et al., 2011).

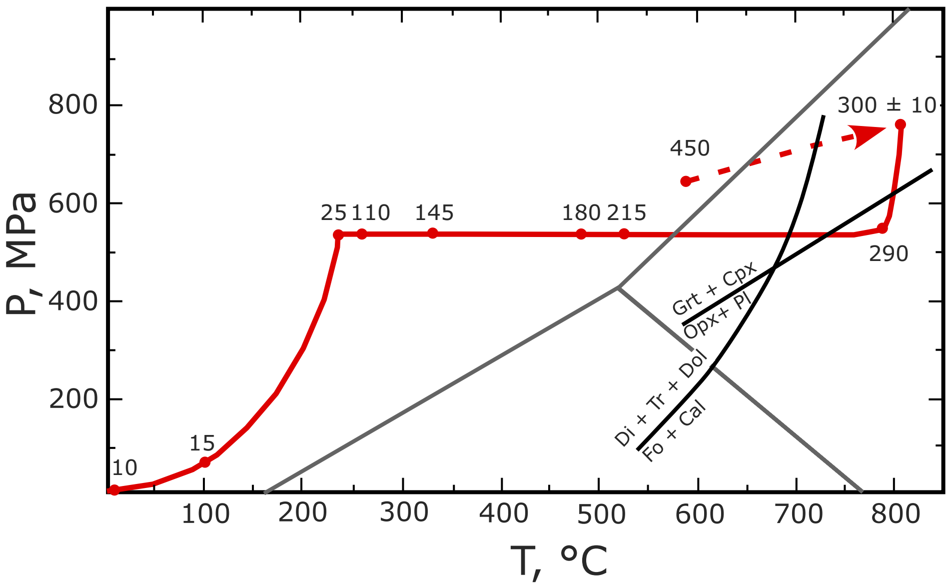

Fig. 6 - Classical P-T-t path defined by Schenk (1989) for the deeper level of the Serre lower crust. The twin path for the top level of the Serre lower crust proposed in the original figure has been omitted. Numbers along the path indicate time in Ma.

4 - Hercynian P-T evolution

P-T evolution has been determined for various levels of the continental crust exposed in the Calabria massifs. The P-T paths are here grouped for the lower and upper to intermediate crust, respectively.

4.1 - Lower crust

For the lower crust numerous determination are now available, starting from the classical Serre P-T-t path by Schenk (1989; Fig. 6). This is characterized by peak granulite facies metamorphic conditions of 790 ± 30 °C and 750 ± 50 MPa at 300 ± 10 Ma. In this state the fertile lower crust underwent widespread partial melting. Metapelites were mostly affected by this process with a maximum degree of melting of 50-60% (Caggianelli et al., 1991). Restites left after melting are massive rocks (fels) with high content in garnet and sillimanite or garnet and cordierite. After peak metamorphism, rocks of the lower crust underwent a nearly isothermal decompression followed by a significant isobaric cooling. Both trajectories were constrained by recognition of reaction textures (Schenk, 1984) related to equilibria:

garnet + clinopyroxene = orthopyroxene + plagioclase
(in mafic rocks, Fig. 6), and

garnet + sillimanite = cordierite + spinel
(in metapelites)

Decompression from 750 to 550 MPa took place between 300 ± 10 and 290 Ma whereas isobaric cooling proceeded at a progressively slower pace, up to 25 Ma when Tertiary tectonics promoted final exhumation of the lower crust.
P-T paths recently published are more complex and characterized by more elevated peak values of P and T. In addition, a P-T path, recently proposed by Fornelli et al. (2011), outlines for the lower crust a step-wise evolution with two distinct episodes of decompression (Fig. 7a).
What is the relationship between lower crust P-T paths and geologic evolution? Schenk (1990) suggested that the most likely geological setting for the development of granulite facies metamorphism is an active continental margin overlying a subduction zone.
The question has been also addressed by Caggianelli et al. (2007) through numerical modelling. The result was that extensional tectonics and heat advected by magmas emplaced in the intermediate crust reproduce satisfactorily the P-T paths outlined by Schenk (1989) and Grässner & Schenk (2001).

4.2 - Upper to intermediate crust

For the upper to intermediate crust, three paths are shown in the P-T diagram of Fig. 7b. A peculiar characteristics of the upper to intermediate crust P-T paths is the preservation of the prograde trajectory, lacking in rocks affected by granulite facies metamorphism. Prograde trajectory in the paths of Fig. 7b is characterized by a moderate to very relevant crustal thickening.
A distinctive feature both for the Sila and Serre massifs, such as for Aspromonte (Grässner & Schenk, 1999) is the high thermal gradient, typical of basements affected by low-P metamorphism. This gradient reaches in Calabria the

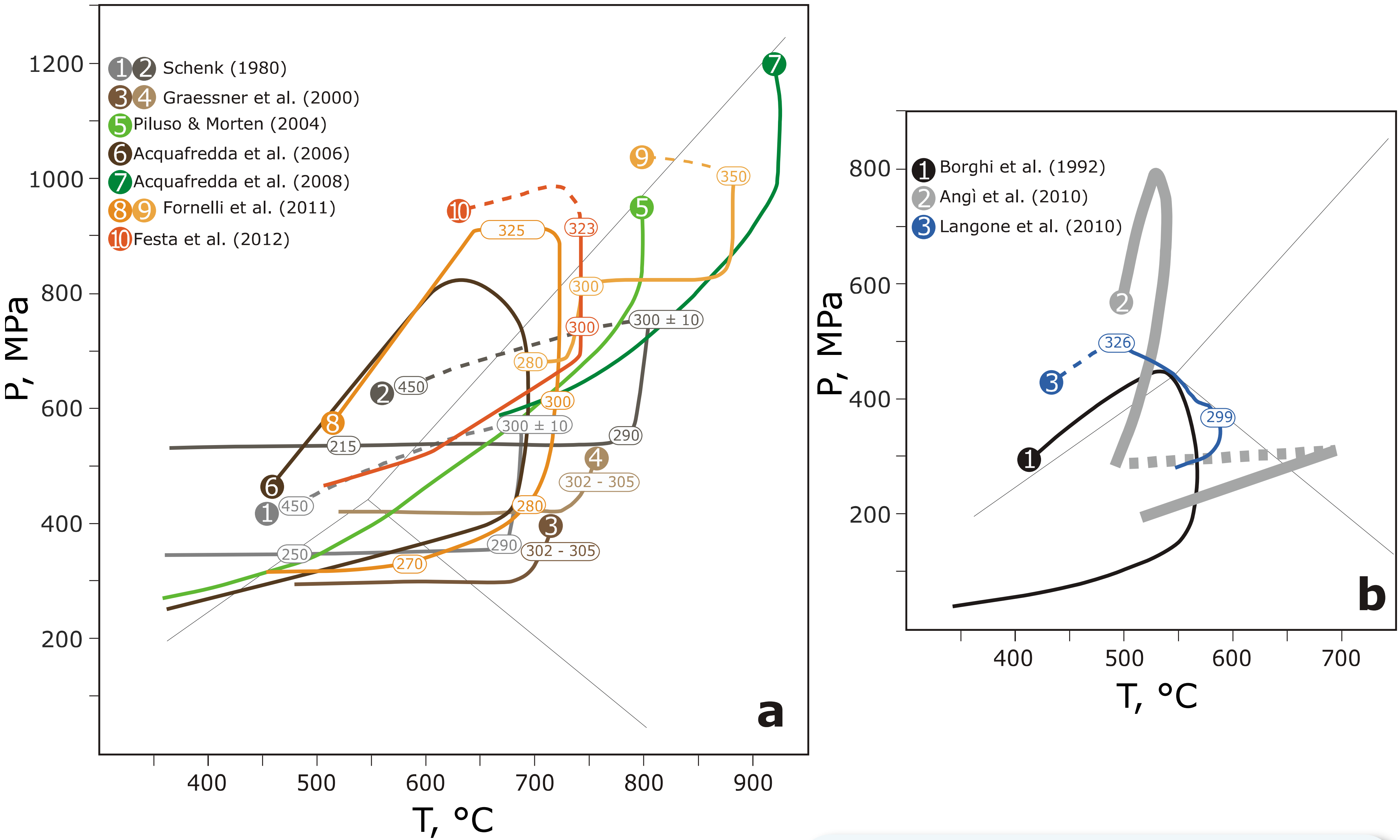

Fig. 7 - Available P-T paths for the Serre and Sila lower (**a**) and upper to intermediate (**b**) crust. Numbers in the oval frame indicate time in Ma.

remarkable value of 60 °C/km (Grässner & Schenk, 1999) and is generally ascribed to the heat advectively transported by the ascent and emplacement of magmas into the intermediate to upper crust (e.g., Lux et al., 1986).
A typical question related to the upper crust context is the transition from low-P regional to contact metamorphism. According to the Serre path, contact metamorphism is anticipated by Barrovian peak P-T conditions and by a considerable decompression (Angì et al., 2010). In contrast, metamorphic history in the Sila Massif is mostly in low-P conditions and is characterized by reduced exhumation (Borghi et al., 1992; Langone et al., 2010). Contact metamorphism takes place in the final part of the exhumation and is marked by a sharp T spike in the Serre path, but by absent (1) or smoother (2) discontinuities in the Sila paths (Fig. 7b).
Is the transition from low-P regional to contact metamorphism evidence of two distinct processes or alternatively the result of a single process acting at progressively lower crustal levels? A possible answer to this question comes from the analysis of the effects produced by the emplacement of granitoid bodies in the intermediate crust. Considering the notable size of the granitoids, pluton growth can be a process lasting for some million years. If this process is favoured and accompanied by extensional tectonics, we have the elements to obtain in a single path both exhumation and heating/cooling. The intensity of the last effect is however dependent on the crustal level in which takes place and on the way the pluton grows, i.e. by under-accretion or by over-accretion (Annen, 2011). A numerical model (Caggianelli et al., unpublished material, 2012) based on these considerations assumes that pluton growth took place by over-accretion during crustal extension in a time interval of 5-10 Myr. These results indicate that low-P and contact metamorphism can be considered the product of the same geological process where extension and magma injection are acting at the same time.

5 - Crust exhumation

After the Hercynian metamorphic and magmatic events the Calabria crust underwent cooling and exhumation during three main episodes: **i**) a first thinning episode during the Mesozoic continental rifting, leading to the opening of the Tethys Ocean; **ii**) a shortening episode, related to the incorporation of the Calabria crust in the Alpine/Apennine belt; **iii**) a further thinning and erosion episode during the evolution of the western Mediterranean basins and the Apennine Chain.

5.1 - Late Paleozoic – Mesozoic evolution

The emplacement of gabbros in the high-grade metapelites exposed in Northwestern Calabria (Catena Costiera area) may be considered the first evidence of crustal thinning indicating the onset of the Tethyan rifting event during the Permian-Triassic times (Liberi et al., 2011). The presence of Late Triassic conglomerates, sandstones and siltstones, lying unconformably above Paleozoic phyllites in the Sila and Serre massifs (Amodio Morelli et al., 1976; Critelli & Ferrini, 1988), indicates that during the Late Paleozoic and the early-middle Triassic times the Hercynian basement was affected by erosional processes. The moderate crustal thickness (about 6-7 km) eroded before the late Triassic sedimentation is consistent with slow erosion rates (0.05 mm yr^{-1}; Caggianelli et al., 2000). The relatively thin succession of Jurassic and Cretaceous limestones in the Stilo area is consistent with slow subsidence rate and frequent hiatuses, possibly related to uplift phases (Amodio Morelli et al., 1976). However, thick terrigenous deposits filling Early Jurassic half grabens in northeastern Sila (Young et al., 1986; Boullin et al., 1988) clearly indicate that in Northern Calabria the former Hercynian crust underwent extensional tectonics. In the same area, the presence of neptunian dykes, injected into normal faults crosscutting Jurassic limestones and Paleozoic phyllites, document that extensional tectonics lasted up to the Middle-Late Jurassic times (Bouillin & Bellomo, 1990). Rifting was followed by sea-floor spreading during the Late Jurassic-Early Cretaceous times (Liberi et al., 2006, and references therein), as testified by the presence of widespread ophiolites in Northern Calabria and Southern Apennines.

5.2 - Eocene - Early Oligocene contractional tectonics

After the sea-floor spreading, subduction of the Tethyan oceanic crust took place since Late Cretaceous, producing an accretionary wedge and contractional deformation in the former passive margin (Knott, 1987; Cello & Mazzoli, 1999; Faccenna et al., 2001). This process led to the formation of the Alpine peri-Mediterranean belt.

Several lines of evidence indicate that the Calabria continental crust was part of the peri-Mediterranean belt during the Eocene-Late Oligocene times (Rossetti et al., 2001, 2004; Langone et al., 2006; Heymes et al., 2010). An overall thrust transport directed towards the SE has been estimated in the Serre and in the Aspromonte area (Langone et al., 2006; Heymes et al., 2008), whereas in Northern Calabria (Sila and Catena Costiera) the thrust transport direction is oriented towards the NE. In the Serre and Sila massifs this process was responsible for underthrusting of the medium-grade Castagna Unit and the low-grade Bagni

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Unit at the base of the Hercynian crustal section. The main thrust contact, known as the Curinga-Girifalco line, has been compared to the Insubric Line of the Alps (Schenk, 1981), since it separates basement units almost unaffected by an alpine overprint (the Hercynian crustal section) from medium to low grade units showing a significant alpine overprint (the Castagna and Bagni units). In Northern Calabria this pile of tectonic units rests above ophiolites derived from subduction of the Tethyan oceanic domain.

Available radiometric ages from sheared gneisses of the Aspromonte and Serre massifs indicate that this deformation took place essentially during the middle Eocene. More specifically, ages are 43±1 Ma in the Serre massif (Rb-Sr method on biotite; Schenk, 1980) and about 45 Ma in the Aspromonte massif (Ar-Ar method on K-feldspar; Heymes et al., 2010). Younger ages, about the Eocene-Oligocene boundary, have been obtained for the crustal thickening episode in Northern Calabria (Rossetti et al., 2004). A different interpretation, provided by Bonardi et al. (2008), indicates a Late Oligocene - Early Miocene age for the Alpine stacking in the Aspromonte massif.

Looking at the sedimentary record, the time interval of the thickening event corresponds to a karstic or erosional surface comprising the Paleocene-Eocene interval, indicating absence of sedimentation or moderate erosion. This surface is usually located between the Cretaceous carbonates and the basal Capo D'Orlando conglomerate (Cavazza et al., 1997).

5.3 - Oligocene to Miocene evolution

The final exhumation stage of the Hercynian crust is connected with extension and erosion after the Eocene - Early Oligocene crustal thickening. Extensional tectonics during the Oligocene - Early Miocene is documented by the presence of low angle shear zones and faults in the Serre and the Aspromonte massifs and in the Palmi area (Platt & Compagnoni, 1992; Thomson, 1998; Langone et al., 2006; Heymes et al., 2008; Grande et al., 2009; Heymes et al., 2010). Direct Ar-Ar dating of fault-related pseudotachylites in the Palmi area indicates that extensional tectonics was active in the Calabria terrane since the Early Oligocene (33.55 ± 0.21 Ma; Grande et al., 2009). In the Serre area, an E-trending normal fault offsets the pre-existing Curinga-Girifalco thrust, uplifting the Castagna and Bagni units at the footwall (Langone et al., 2006). Zircon and apatite fission-track ages indicate that footwall uplift took place during the early Miocene (18 to 15 Ma).

Extension in the upper plate of the NW-dipping subduction of the Tethyan oceanic crust has been referred to: (**i**) gravitational instability of the Calabria accretionary wedge (Knott, 1987; Wallis et al., 1993; Thomson, 1994); (**ii**) slab retreat leading to the formation of the Western Mediterranean basins (Malinverno & Ryan,

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1986; Gueguen et al., 1998; Faccenna et al., 2001). This latter process is responsible for the migration of the Calabria terrane towards the SE, first during the counterclockwise rotation of the Corsica-Calabria block and then during the formation of the Tyrrhenian sea.

In the Calabria terrane extension was associated with fast erosion during the Oligocene-Miocene time (about 35 to 15 Ma) as indicated by the fission-track ages provided by Thomson (1994). Exhumation and erosion took place during an overall tilting towards the SE of the Calabria basement, producing a higher exhumation rate in the NW sector (Thomson, 1994). Intense erosion of the Hercynian crust is marked by sedimentation of abundant conglomerates, followed by thick terrigenous deposits of Late Oligocene - Early Miocene age (Stilo-Capo D’Orlando formation, Cavazza, 1989; Bonardi et al., 2005).

The evolution during the middle-late Miocene is driven by the interaction between the Calabria terrane and the western margin of the Adriatic plate.

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DAY 1

Stilo area

In the Stilo area a Paleozoic metasedimentary succession intruded by the shallower granitoids of the Serre batholith extensively crops out (Fig. 8). Granitoids are mainly represented by granodiorites, characterized by a nearly isotropic magmatic fabric (Borsi et al., 1976; Fornelli et al., 1994). Magmas intruded rocks of middle- to upper-crustal levels (Caggianelli et al., 2000) belonging to the Stilo-Pazzano phyllite Unit and southwards to the Mammola paragneiss Unit (Colonna et al., 1973). Hercynian tectonics was responsible for juxtaposition of these two units, subsequently affected by the emplacement of granodiorite magmas. Contact metamorphism sharply developed on low-grade metamorphic rocks of the Stilo-Pazzano phyllite Unit (Colonna et al., 1973).
Phyllites belong to a former sedimentary succession of Ordovician - Carboniferous age including pelite, siltstone and arenite with intercalations of mafic lavas shifting with time from tholeiitic to alkaline series (Acquafredda et al., 1994). A detailed description of the Paleozoic sedimentary succession is provided by Bouillin et al. (1987; Fig. 9) and by Acquafredda et al. (1994). A relic sedimentary layering is still recognizable in the phyllites, that were affected by two main dynamic phases during Carboniferous regional metamorphism. Later, contact metamorphism promoted blastesis of biotite, andalusite and cordierite, generating hornfelses and spotted schists. The metamorphic aureole trends rou-

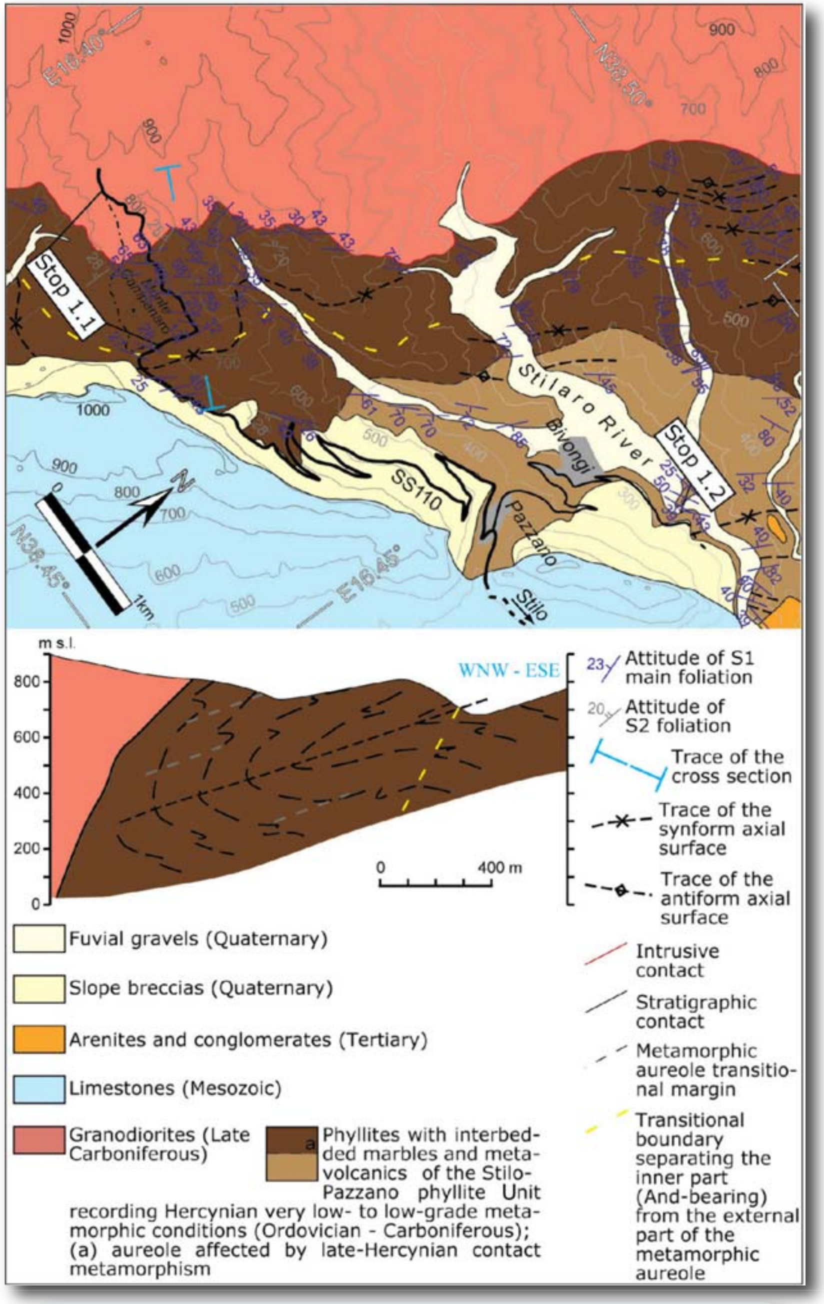

Fig. 8 - Geological sketch map and cross-section of the Stilo area.

ghly parallel to the intrusive contact, with a slightly variable thickness that reaches a maximum value of ~ 1800 m estimated on geological sections (Fig. 8). Adjacent to the contact with granodiorite, wall rocks are injected by granitoid and pegmatite dykes, as well as by veinlets filled with hydrothermal quartz (Colonna et al., 1973).
The intrusive contact can be represented by a surface having an complex shape. Consequently, the contact surface dips either northeastward or southeastward, at South and North of the Stilaro River, respectively (Fig. 8).

Stop 1.1: (N 38° 28′ 5″; E 16° 24′ 37″); Across the Serre contact metamorphic aureole along the southern flank of Monte Campanaro (Fig. 8).
The intinerary of this Stop starts from the old S.S. 110 of "Monte Cucco e Monte Pecoraro" in proximity of km 62. It stretches across the metamorphic aureole, from the granodiorite to the phyllites.
The hornblende-bearing biotite granodiorite shows a clear magmatic texture with an absent or very weak preferred orientation of feldspars and biotite (Fig. 10a). It contains some magmatic mafic enclaves and also xenoliths of the wall rocks. In this zone the intrusive contact with the Stilo-Pazzano phyllite Unit strikes NE-SW and dips towards the batholith (Fig. 8).

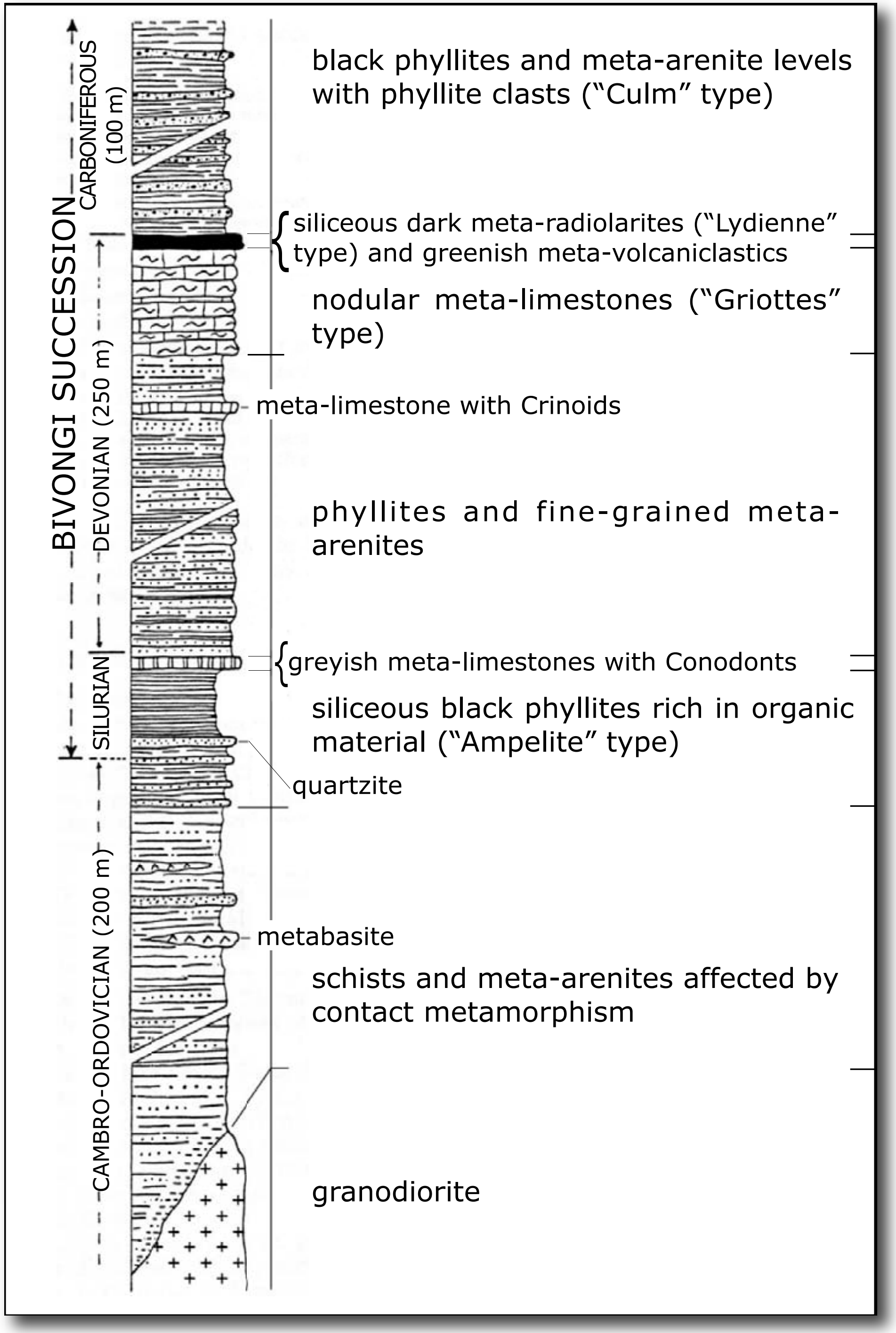

Fig. 9 - Stratigraphy of the Paleozoic succession in the Stilo area (modified from Bouillin et al., 1987).

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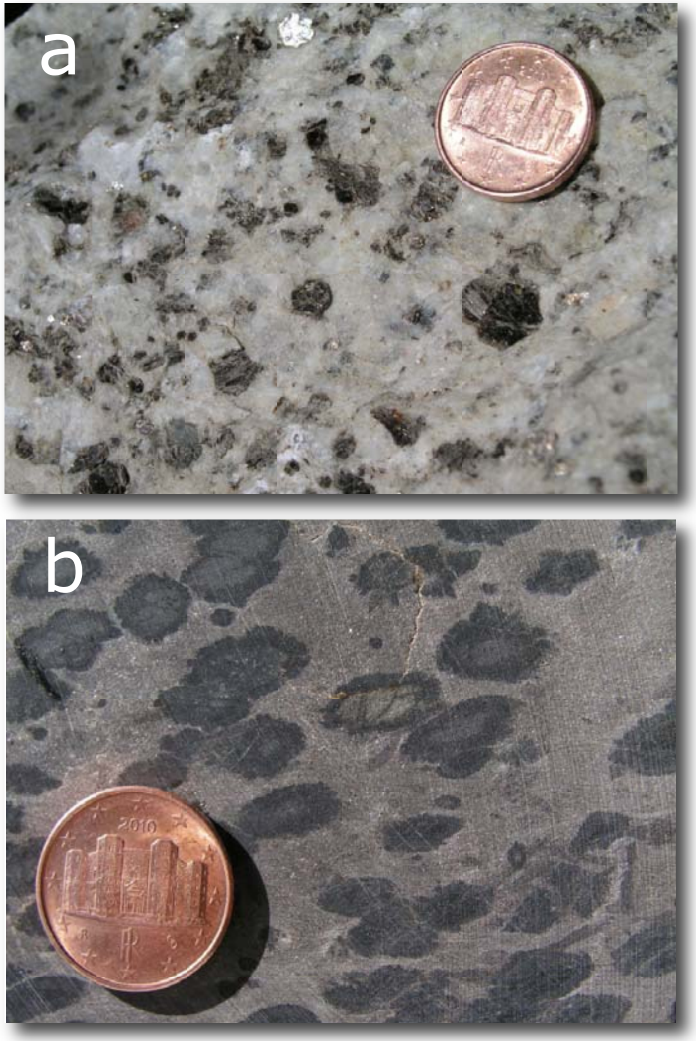

Fig. 10 - (**a**) Close up photograph of the Serre granodiorite outcropping in the Stilo area. Absence of an evident foliation and the common euhedral shape of biotite are evident. (**b**) Close up photograph of the zoned cordierite spots. A grey elliptical core is surrounded by an outer darker rim having a lobate outline.

Decimetre- to meter-thick granodioritic and pegmatitic dykes are diffusely present within the host rock close to the margin of the batholith, making up a typical injection zone.

Spotted schist is the most common rock in the contact aureole (Fig. 10b). Spots are mostly made up of cordierite and their size progressively decreases moving away from the pluton. True hornfels can be observed only very close to granodiorite.

Peak metamorphism of 570-590 °C at 210 MPa produced a mineral assemblage including quartz, muscovite, biotite, cordierite and andalusite. The latter may be present exclusively in the inner part of the aureole whereas cordierite is widely distributed up to an external and narrow biotite zone. Spots and porphyroblasts clearly grew post-kinematically on the main foliation labelled S_1 and related to an early stage of Hercynian deformation.

Tectonic perturbation related to magma emplacement produced a deformation in the aureole, here manifested by a synform with an axis trending approximately parallel to the intrusive contact (Fig. 8). The synform asymmetry and the attitude of the fold axial plane are coherent with the viscous drag of the country rocks consequent to an upward component of displacement during pluton growth.

The component of lateral shortening, generally related to pluton emplacement, is in turn outlined by the L_2 crenulation and the S_2 cleavage. These fabric elements are parallel to hinge lines and axial surfaces of the large-scale folds, respectively, suggesting that they were produced during the same deformation event. A lateral shortening of about 50% has been estimated for the deformed aureole.

Stop 1.2: (N 38° 29’ 13”; E 16° 27’ 37”); Paleozoic low grade rocks of the upper crust at Ponte Vina, in the neighbourhood of Bivongi village (Fig. 8).

This Stop is located, along the road to the byzantine church of San Giovanni Theresti soon after the bridge on the Stilaro river. A portion of the Paleozoic succession made up of phyllites and slates with intercalations of metacarbonate rocks can be observed.
Phyllites contain a mineral assemblage of fine-grained sericite + quartz + albite + chlorite. The evident foliation observed on the outcrops is the S_1, subparallel to axial surfaces of isoclinal folds. A relic sedimentary layering (S_0) is still recognizable where former compositional layering was present (Figs. 11a, b). At the thin section scale it is observed a continuous S_1 cleavage, mainly defined by sericite and secondly by chlorite. This S_1 is still recognizable within albite + quartz enriched microlithons bounded by spaced S_2 cleavage domains. Blastesis of sericite and chlorite occurred during D_1 deformation event, under very low grade metamorphic conditions. The cleavage domains, located in the flanks of asymmetric microfolds of the earlier S_1 foliation, are characterized by an enrichment of sericite, with flakes preferentially oriented along the S_2 foliation. Differentiation between cleavage domains and microlithons, although not fully developed, is related to formation of crenulation and solution transfer mechanisms.

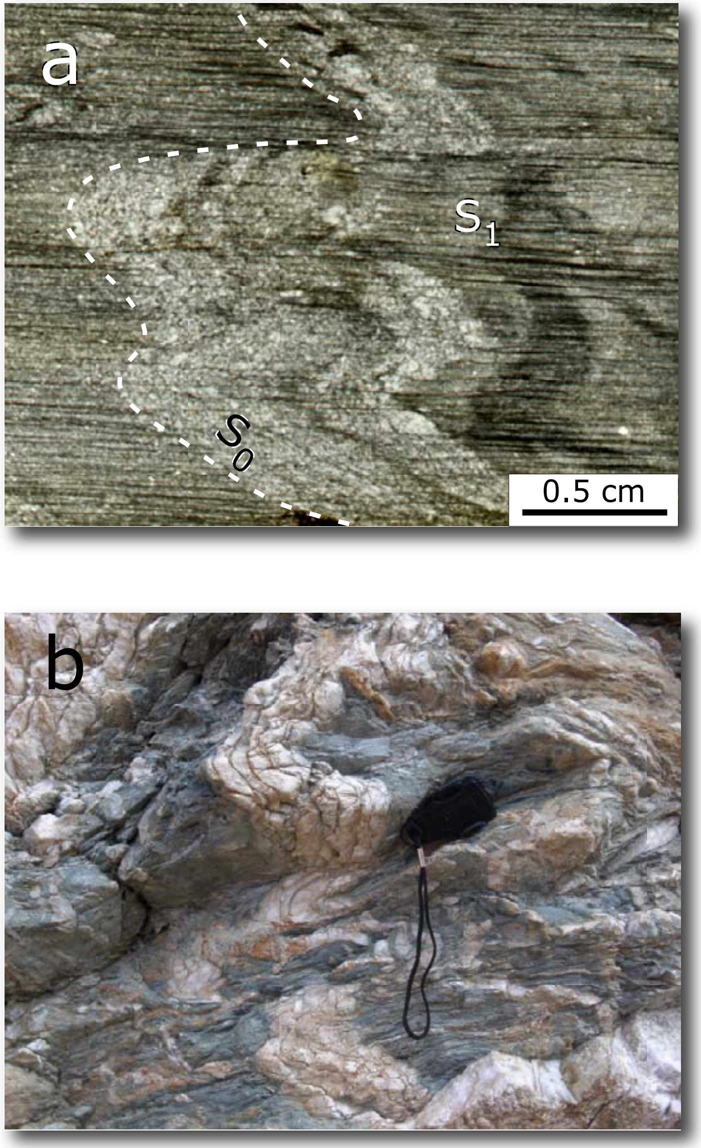

Fig. 11 - Relationships between S_0 and S_1 foliations in a metapelite thin section (**a**) and in metacarbonatic (**b**) rocks. The parallelism of S_1 to axial planes of isoclinal folds is evident.

Pietragrande and Squillace area

Granitoids outcropping between Squillace and Soverato are essentially tonalites with minor gabbros, quartz diorites, leucotonalites and peraluminous granites. Tonalites, characterized by the presence of amphibole (hornblende ± cummingtonite), are common in the northern area (Fig. 12), whereas biotite tonalites, sometimes with traces of muscovite, are typical of the southern zone.

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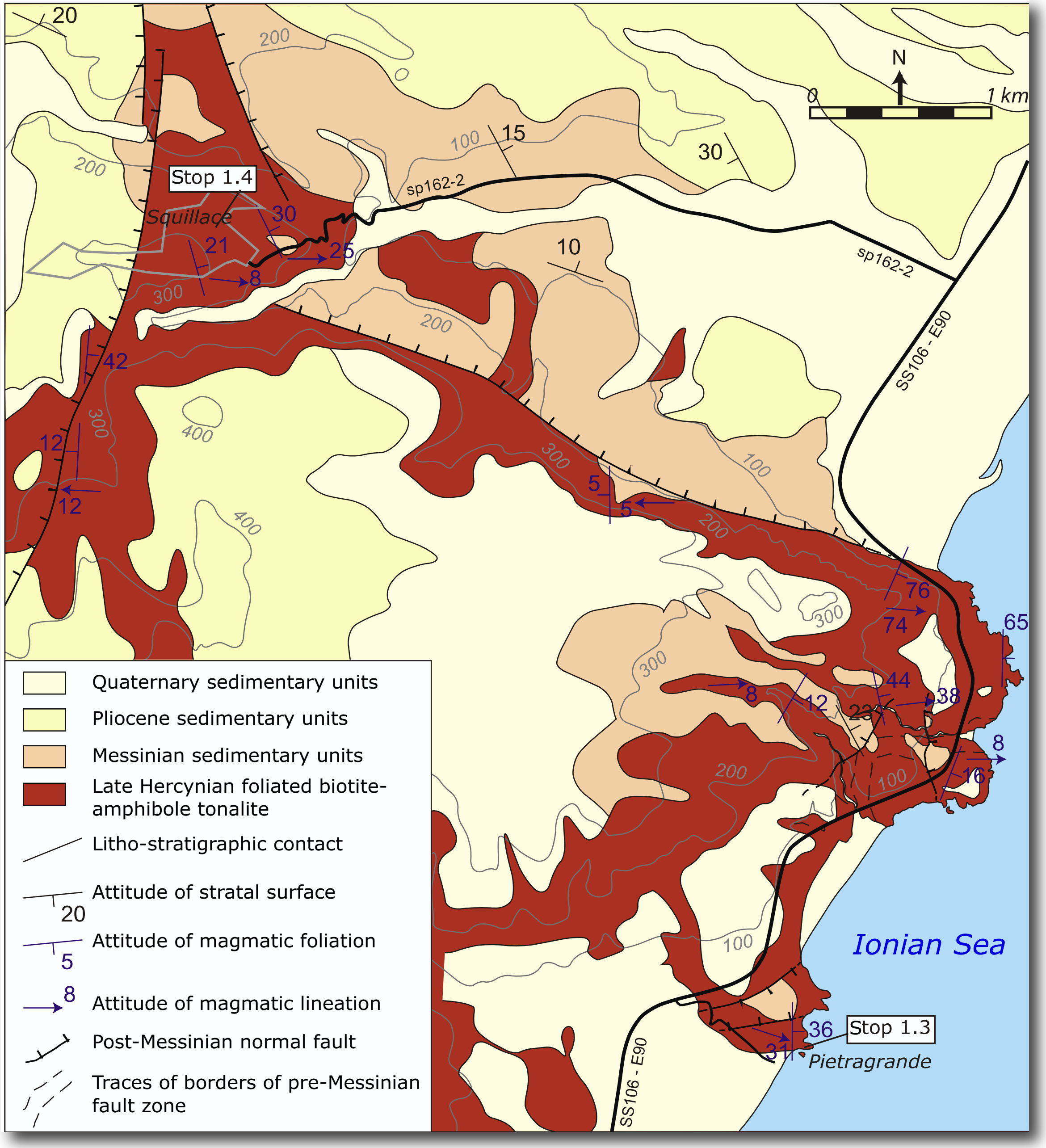

Fig. 12 - Geological map of the Squillace – Pietragrande area modified after Caggianelli et al. (2005) and Gerik et al. (2010).

Among accessory minerals, epidote is particularly abundant and is mostly of magmatic origin, sometimes zoned with allanite-rich core. Tonalites emplaced at a considerable depth with P conditions of 650 ± 60 MPa (Caggianelli et al., 2000), constrained by the Al-in-hornblende barometre and by the presence and composition of magmatic epidote. Tonalites are characterized by a strong fabric, developed in melt-present and solid state conditions at decreasing temperatures.

Emplacement of tonalites has been defined by zircon U-Pb method at 293 ± 2 Ma. Rb-Sr biotite – whole rock ages span from 141 to 160 Ma and are interpreted as cooling ages, implying that tonalites resided at temperature higher than 250 – 300 °C (biotite closure temperature range) for a long time. Magma differentiation followed a trend towards acidic low-K melts through compaction of a plagioclase, biotite and hornblende crystal mush. It was proposed that emplacement of tonalites took place in an extensional tectonic setting (Caggianelli et al., 2007) that in lower crustal rocks is recorded by a decompression episode between 300 ± 10 and 290 Ma (Schenk, 1989). Structural analysis is compatible with this interpretation, and kinematic indicators suggest a top-to-East shear sense.

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Stop 1.3: (N 38° 44′ 28″; E 16° 33′ 31″); Foliated tonalites at Pietragrande (Fig. 13).

Stop is located on Pietragrande cliffs, that can be easily reached from S.S. 106 between Montepaone Lido and Copanello.

In the Pietragrande Stop the main characteristics of biotite tonalites with rare amphibole can be observed (Fig. 13a). A well defined fabric, expressed in a foliation (dip direction and plunge ~ 090°/36°) and a lineation (trend and plunge ~ 110°/31°), originated in the magmatic state, as indicated by the preferred orientation of euhedral plagioclase crystals (Fig. 13b). A schlieren layering, defined by biotite-rich streaks is sometimes visible; it is related to magma flowage and compaction. Solid-state deformation

Fig. 13 - (**a**) The tonalite of Pietragrande. (**b**) Oblate mafic enclaves are parallel to the magmatic fabric outlined by tabular plagioclase crystals. (**c**) Pseudotachylite injection veins in tonalite outcropping along the old national road between Pietragrande and Copanello.
The road is in some stretches closed to car access, due to rock falls. A safety helmet must be used when approaching the road inner margin.

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Fig. 14 - (**a**) Tonalite rock makes up the basement of the Squillace castle. (**b**) A closer view shows that tonalite is characterized by a strong fabric with a preferred orientation of plagioclase and prismatic amphibole. With the aid of a lens it is possible to observe that some amphiboles are zoned, displaying a green core of cummingtonite and a dark shell of tschermakitic hornblende.

developed at progressively lower temperatures down to greenschist facies conditions. Fabric anisotropy was quantified by the Fry method analysing plagioclase distribution on oriented rock slabs and provided an X/Z ratio of the strain ellipsoid axes of 1.31 (Di Battista, 1997).

Mafic enclaves of tonalite to quartz diorite composition are very common (Fig. 13b) and display variable size and oblate ellipsoid shape.

At a short distance from the Pietragrande cliffs, the effects of Tertiary tectonics can be clearly observed in the form of pseudotachylite veins (Fig. 13c) and neptunian dykes. Pseudotachylites are mostly made up of plagioclase microlites, biotites, quartz and glass at more or less advanced stages of devitrification. Plagioclase microlites are frequently arranged in spherulitic texture around 'resorbed' quartz. It is supposed that genesis of pseudotachylite veins took place during Oligocene at a depth of ~ 10 km and at an ambient temperature of 250-300 °C. Heat generated during the frictional sliding event produced a peak temperature of at least 1470 °C constrained by massive plagioclase melting (Caggianelli et al., 2005). Neptunian dykes are mostly made up of diatomites and evaporitic carbonates and are related to Messinian tectonic events, responsible also for the origin of the neighbouring Catanzaro graben.

Stop 1.4: (N 38° 46′ 52″; E 16° 31′ 6″); Foliated cummingtonite-bearing tonalites at the Squillace Castle (Fig. 12).

In this Stop, located beneath the Squillace Castle (Fig. 14a), tonalites are characterized by a relevant content in coarse grained prismatic amphiboles (Fig. 14b). A careful examination with the aid of a lens reveals that amphiboles are zoned with a lighter cummingtonite core. The surrounding amphibole is zoned from Mg-Hornblende to Tschermakite, a compositional variation governed by the exchange: Si Mg = ^{IV}Al ^{VI}Al. Rock fabric is here very strong and mainly manifest as a lineation trending ~ 100° with a small plunge of ~ 10°. Rock anisotropy was analysed in a neighbouring outcrop with the Fry method applied to plagioclase distribution and provided a value of the X/Z ratio of 1.98 (Di Battista, 1997).

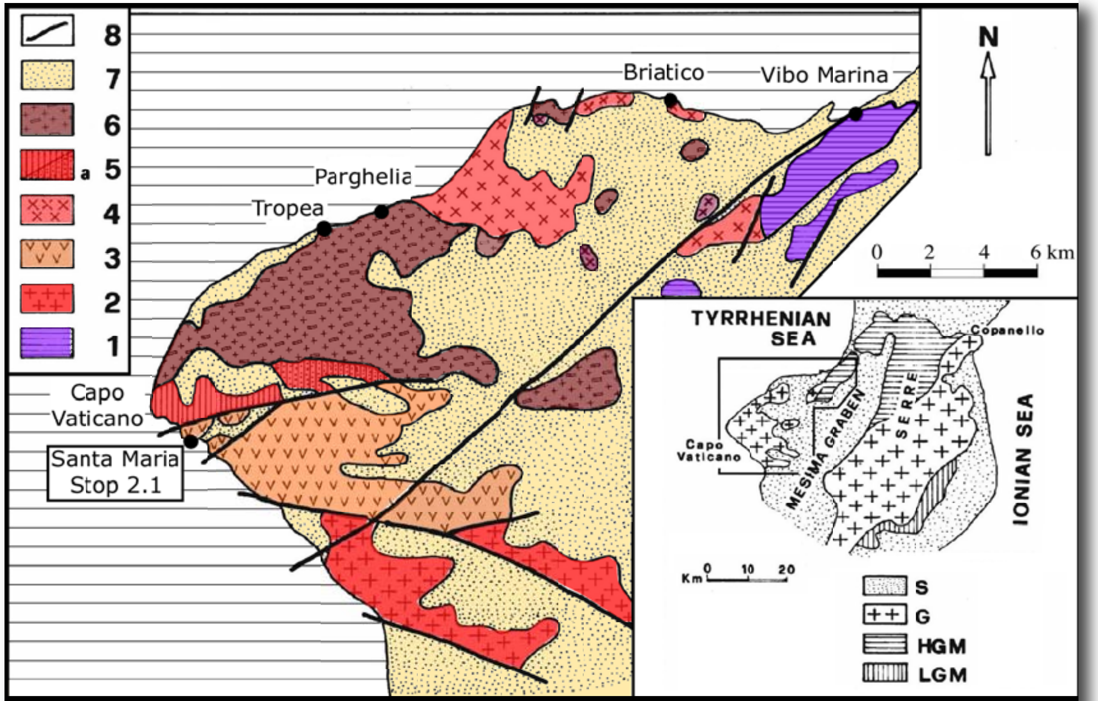
Quartz c-axis distribution was determined on a sample from the zone of Squillace. Stereogram showed mono-clinic symmetry coherent with top-to-East shear sense. The same conclusion was reached considering other kinematic indicators, such as σ-type porphyroclasts (hornblende or plagioclase) and tiled plagioclases.

DAY 2

Capo Vaticano area

Granitoids outcropping in the Capo Vaticano promontory are mainly tonalites and peraluminous granodiorites with K-feldspar megacrystals (Fig. 15). A detailed petrological and geochemical study was done by Rottura et al. (1991). From their results it may be concluded that both tonalites and peraluminous granodiorites crystallized from hybrid magmas. The mixing process involved mantle-derived magmas and melts with a more or less pronounced crustal parentage.

Fabric of the granitoids may be weak and exclusively of magmatic origin or very strong with a marked *subsolidus* overprint. Best outcrops, as usual in Calabria, are located along the coast. The relationships of the granitoids with the wall rocks are rarely exposed. A transitional contact with the medium- high-grade metamorphic basement can



1 - migmatitic paragneisses; 2 - Ioppolo tonalites; 3 - Santa Maria quartz diorites and tonalites; 4 - Briatico tonalites; 5 - Capo Vaticano tonalites and granodiorites (a); 6 - two-mica porphyritic granodiorites; 7 - Miocene to Quaternary deposits; 8 - faults
S - sediments; G - granitoids; HGM - high-grade metamorphic rocks; LGM - low- to medium-grade metamorphic rocks.

Fig. 15 - Geological sketch map of the Capo Vaticano promontory, modified after Rottura et al. (1991).

be observed in the Capo Vaticano zone. In a typical migmatitic border zone, tonalites and quartz diorites include metamorphic xenoliths and coarse garnet crystals (see Stop 2.1).

Stop 2.1: (N 38° 36′ 45″; E 15° 50′ 33″); Migmatitic border zone at Santa Maria beach (Fig. 15).
This Stop is located a short distance from the head of the Capo Vaticano promontory. Here, quartz diorites and tonalites from the migmatitic border zone crop out. They are characterized by a coarse grain size, and by the presence of abundant garnet crystals. Foliation is weak and is revealed by the preferred orientation of plagioclase, and sometimes by a schlieren layering. The dip direction of the foliation planes is ~ 350°, with a plunge of ~ 30°. The level of emplacement of the quartz diorites, estimated by Al-in-Hbl barometry, amounts to a depth of 19 km. Along the Santa Maria beach blocks deriving from the migmatitic border zone, can be seen (Fig. 16a). They are mostly granitoids containing abundant metamorphic xenoliths and outstanding coarse garnets (Fig. 16b).

Metamorphic xenoliths derive from the neighbouring metamorphic basement, and are chiefly metapelites and amphibolites. Concerning the origin of the coarse garnets, a detailed study was performed by Clarke and Rottura (1994), and only a short account of the main results is given here. Garnets in quartz diorites are characterized by a different composition with respect to garnet in wall rocks (mainly migmatitic paragneisses). These garnets developed from the metapelitic xenoliths (Bt + Crd + Sil) as a consequence of the heat released by the crystallizing quartzdioritic magma. They characteristically can be found as

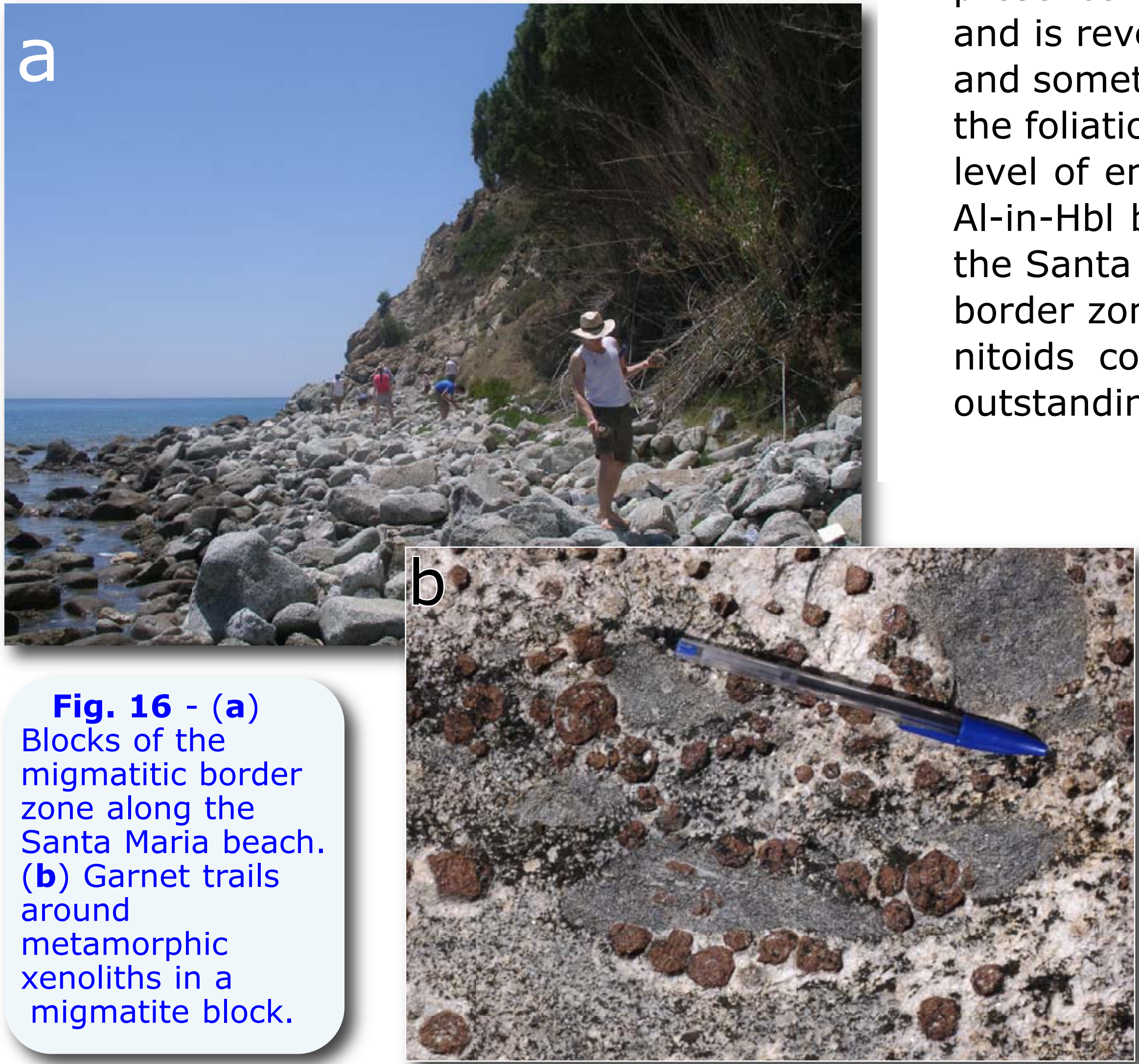


Fig. 16 - (**a**) Blocks of the migmatitic border zone along the Santa Maria beach. (**b**) Garnet trails around metamorphic xenoliths in a migmatite block.

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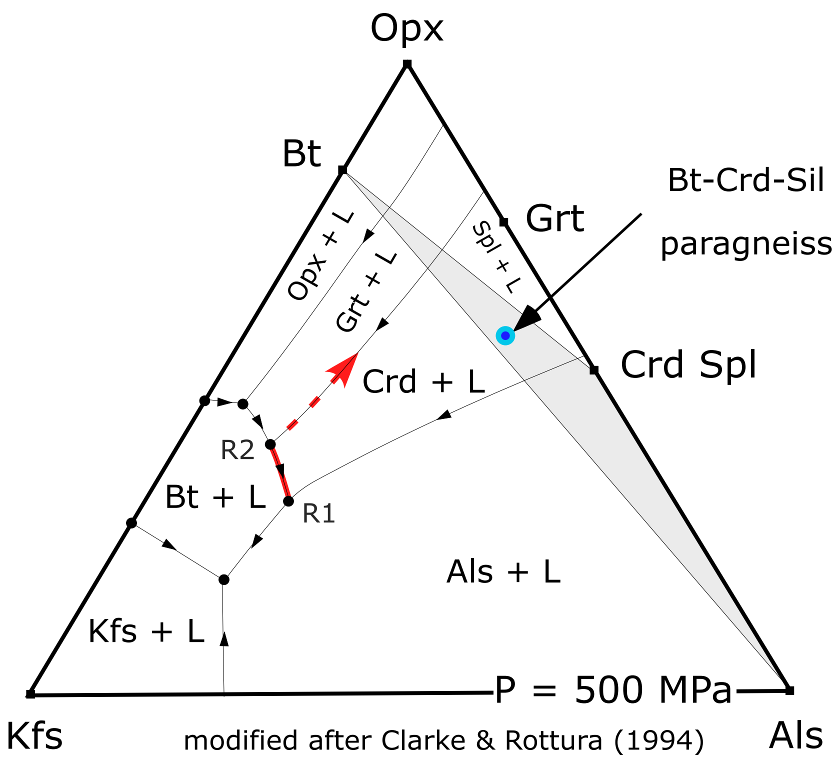
laces surrounding the metapelite xenoliths. The main garnet-forming reaction was Bt + Crd + Qtz -> Grt + Kfs + melt (*). In the initial stages, the proportion of melt was low, and garnet could not develop euhedral shapes. In a more advanced melting stage, garnet growth advanced in the anatectic melt, with free development of euhedral shapes. This interpretation is based on the phase diagram Opx-Kfs-Als by Vielzeuf & Holloway (1988). In Figure 17 it is outlined evolution of melt composition starting from a hypothetical source xenolith made up of Bt, Crd and Sil.



modified after Clarke & Rottura (1994)

Fig. 17 - Phase relations in the pseudoternary Kfs-Opx-Als system. Liquid path (in red), in case of equilibrium melting of a source rock made up Bt, Crd and Sil (blue circle), starts from R1 invariant reaction point. Garnet formation takes place when invariant reaction point R2 (Bt + Crd = Grt + L) is reached. When all biotite is consumed (ca. 20% partial melting) liquid leaves R2 and eventually proceeds along Grt = Crd + L reaction curve. Redrawn and modified from the Vielzeuf & Holloway (1988) diagram proposed in the Clarke & Rottura (1994) paper.

When the anatectic melt mixed with the quartzdioritic magma, the composition of the system became unfavourable for garnet growth. Eventually, the garnet started to be consumed, as indicated by the presence of biotite or amphibole rims. Biotite developed at the expense of garnet by the inversion of the reaction (*). Instead, formation of tschermakitic hornblende is related to the mixing of the anatectic melt with a larger proportion of the Ca-rich quartzdioritic magma. A walk along the cliff will show a pitted quartz diorite surface. The holes represent former garnets removed by wave erosion.

Palmi area

In the Palmi area the contact between high-grade basement and tonalites is exposed (Fig. 18). Strongly foliated amphibole-bearing tonalites crop out in the southernmost part of the area (Rottura, 1985). They contain abundant and flattened magmatic mafic enclaves and include metamorphic xenoliths and coarse garnet in the

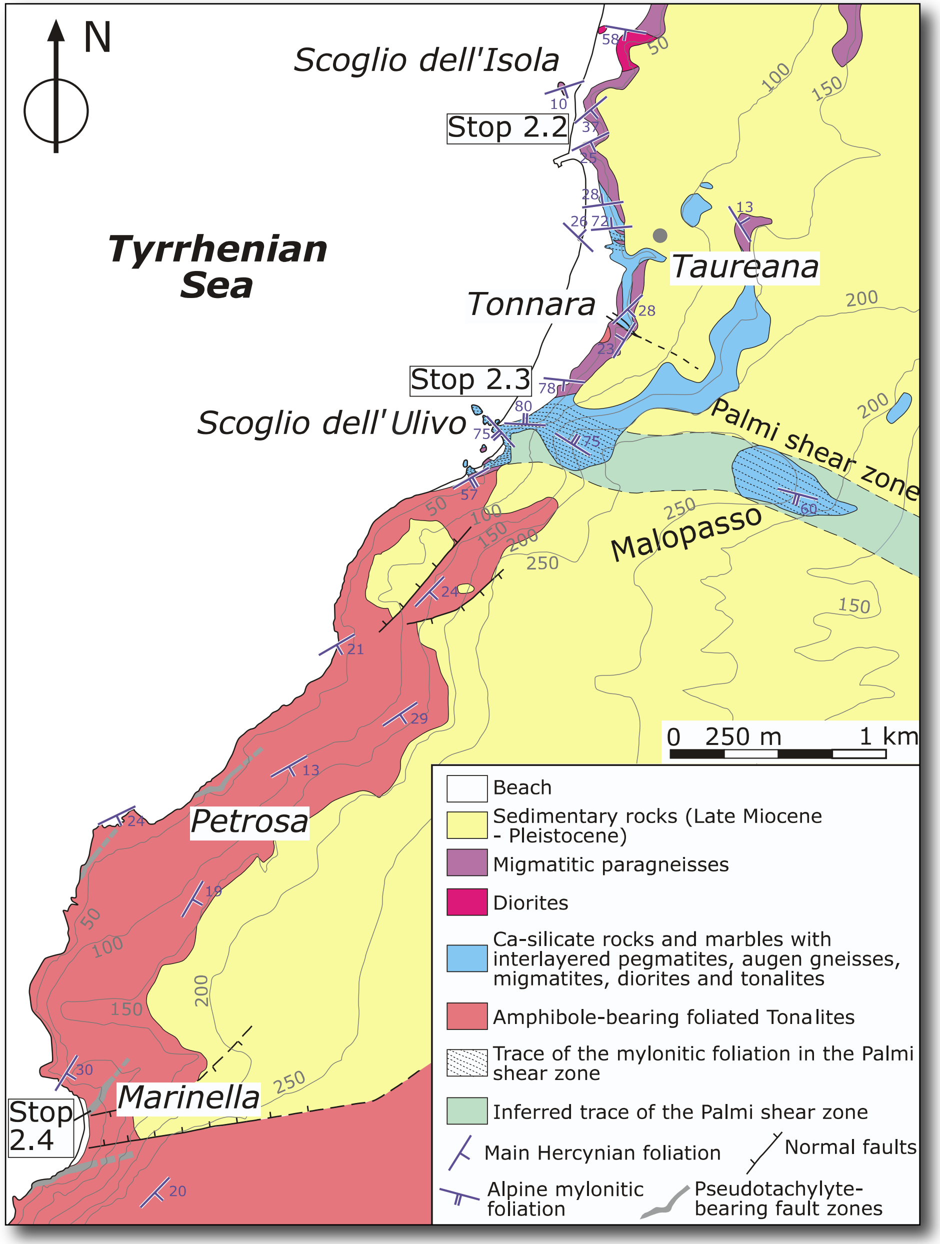


Fig. 18 - Geological sketch map of the Palmi area, modified after Prosser et al. (2003).

vicinity of the wall rocks. Tonalites emplaced at considerable depths, as indicated by P conditions of 610 ± 60 MPa obtained by Al-in-Hornblende barometry (Caggianelli et al., 1997). Widespread presence of dynamically recrystallized quartz indicates that the intense foliation developed mostly at the solid state. Several pseudotachylite-bearing shear zones, related to post-Hercynian deformations at the brittle-ductile transition, occur within tonalites. The best outcrop can be observed in the Marinella locality.

The metamorphic basement consists mostly of migmatitic paragneisses, augen gneisses and marbles and is intruded by minor diorites (Faraone, 1968; Baldanza & Faraone, 1972). Migmatitic layering of the dominant lithology is often folded and transposed by late-Hercynian deformation in high-grade conditions. The best outcrops are on the cliffs near Taureana.

Ca-silicate marbles are particularly frequent at the contact between tonalites and migmatitic paragneisses. They contain fragments of Ca-silicate rocks that can be interpreted as former skarns, crystallized during the intrusion of the tonalites. Marbles played a crucial role in this area, representing a weak horizon that allowed strain localization during the post- Hercynian deformation events. This produced a 400 m thick shear zone (the Palmi shear zone according to Prosser et al., 2003) where marbles, together with stretched layers of pegmatites, granitoids, migmatitic paragneisses and augen gneisses, display intense foliation, lineation and structures typical of non-coaxial deformation.

Stop 2.2: (N 38° 23′ 41″; E 15° 51′ 42″); Migmatitic paragneiss of the lower crust at Scoglio dell'Isola (Fig. 18, 19a). This Stop is located at Tonnara, a locality that can be reached from Palmi following direction to Lido di Palmi and then to the Tyrrhenian coast immediately to the north of Palmi.

Metamorphic rocks outcropping along the coast are migmatitic paragneiss, augen gneiss and Ca-silicate marble. Migmatitic paragneiss is the dominant rock type making up the cliffs beneath the Taureana tower and Scoglio dell'Isola. Peak assemblage includes biotite, K-feldspar, garnet and sillimanite. A migmatitic foliation of a stromatite type, characterized by the alternance of garnet-bearing quartzofeldspathic leucosomes with biotite, sillimanite, garnet ± cordierite ± spinel melanosomes. Grain size is coarse and can be outstanding both for garnet and sillimanite. Coarse garnet crystals (Alm_{74-86}) are flattened and sometimes assume, together with biotite pressure shadows, a monoclinic symmetry, typical of σ-type porphyroclasts. Frequently garnet contains inclusions of biotite, quartz, sillimanite and plagioclase. Sillimanite can be found in stubby prismatic crystals, reaching a length of 7 cm. Sharp mineral and stretching lineations (175°/10°) are clearly visible on the exposed migmatitic layering surfaces and are related to high temperature deformation.

Observations with the microscope reveal that biotite, sillimanite and quartz are sometimes involved in a symplectite texture.

On the basis of the microstructural analysis, Pascazio (2006) proposed that the following reactions were crossed during metamorphic evolution:

(1) Bt + Sil + Qtz + Pl -> Grt + Kfs + melt

(2) Bt + Sil + Qtz + Pl -> Grt + Crd + Kfs + melt

(3) Spl + Qtz -> Grt + Sil

(4) Grt + Kfs + H_2O -> Bt + Sil + Qtz

Fig. 19 - (a) Panoramic view of Scoglio dell'Isola. (b) Stubby prism of sillimanite in the migmatitic paragneiss.

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Reaction (1) to (3) are mainly favoured by a decompression from 800 to 400 MPa at high-T conditions (T > 750 °C), whereas reaction (4) is related to isobaric cooling and hydration.

Stop 2.3: (N 38° 22’ 50”; E 15° 51’ 31”); Palmi shear zone (Fig. 18).
From the Tonnara locality the Palmi shear zone can be observed at the southern termination of the beach, just in front of the Scoglio dell‘Ulivo (Fig. 20a). Sheared Ca-silicate bearing marbles occur in a WNW-trending belt that extends from Scoglio dell’Ulivo to the Malopasso and Sidaro localities. The following description is taken mostly from Prosser et al. (2003).
Marbles display a dark gray colour derived from fine inclusions of graphite and contain clasts of Ca-silicates. The peak mineral assemblage includes diopside, anorthite, grossular ± scapolite, ± hornblende. Using amphibole and plagioclase composition and fixing pressure conditions as those estimated for the nearby tonalites a peak temperature of 783 °C can be obtained with the edenite-richterite thermometer (Holland & Blundy, 1994). During Alpine shearing high temperature minerals have been dismembered and rounded within the carbonate matrix. Pressure and temperature conditions during the Alpine deformation can be estimated using the syntectonic mineral assemblage of mylonitic granitoid slices coupled with calcite thermometry in the carbonate matrix. The presence of phengitic white mica along foliation planes of mylonitic granitoids allows to estimate pressures of about 600 MPa at temperatures of about 400 °C, as deduced from calcite thermometry. Rb-Sr age determinations of biotite separated from samples of mylonitic granitoids provided ages of 51 and 56 Ma, corresponding to the Early Eocene.
Normally, the shear zone is characterized by nearly vertical foliation planes and horizontal stretching lineations, showing moderate plunges to the E-SE or W-SW. However, at Scoglio dell‘Ulivo shallow- to steeply-plunging lineations are closely associated with nearly horizontal lineations. Outstanding kinematic indicators, such as sigma- and delta-clasts (Fig. 20b) formed by rigid Ca-silicate fragments within the weak carbonate matrix, show that shear sense is mostly sinistral along horizontal lineations and south-side up along nearly vertical lineations. The gradual variation from shallow to steeply dipping lineations in the Scoglio dell’Ulivo outcrop can be explained by partitioning of strike-slip and dip-slip components during a single deformation episode. By this interpretation the Palmi shear zone is seen as a sinistral transpressive belt accommodating strain by deformation partitioning. Marbles acted as a lubricating layer, allowing the relative movement of the tonalites with respect to the neighbouring migmatitic paragneisses.

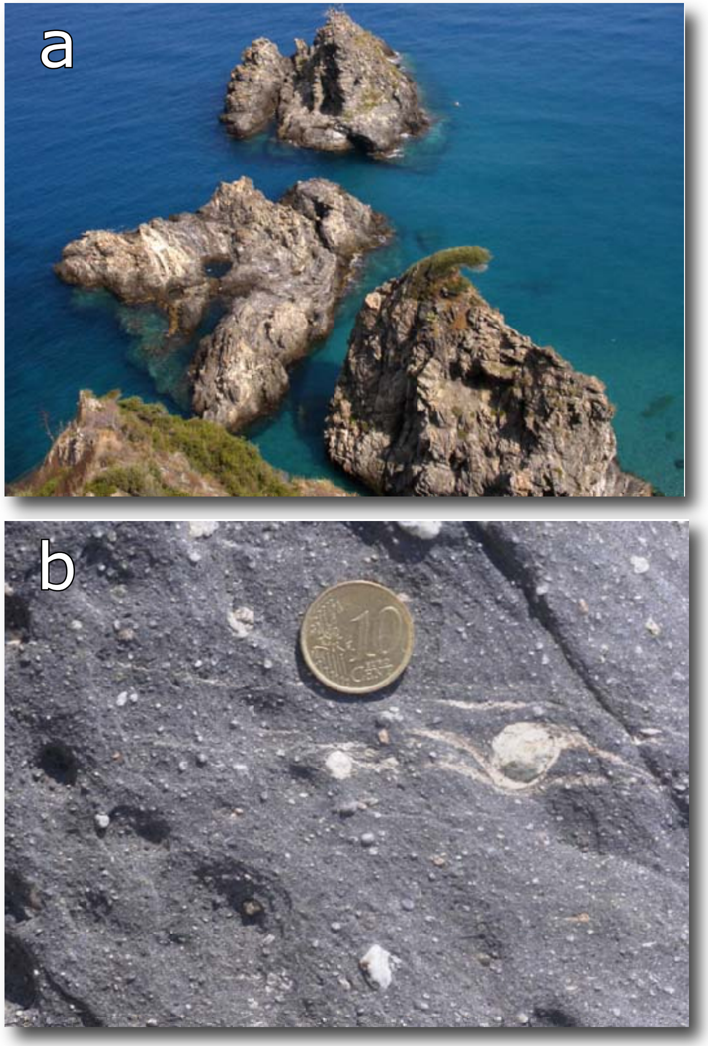

Fig. 20 - a) Panoramic view of Scoglio dell'Ulivo. The subvertical foliation related to the shear zone can be observed. (b) Delta porphyroclast in the Ca-silicate-bearing mylonitized marbles suggesting sinistral shear sense.

Stop 2.4: (N 38° 21′ 8″; E 15° 50′ 11″): Pseudotachylite veins at Marinella di Palmi (Fig. 18).

In the cliffs comprised between Scoglio dell'Ulivo and Marinella di Palmi several pseudotachylite-bearing fault zones crosscut the foliated tonalites. The best outcrops are visible in the tonalites that border the Marinella beach (Grande et al., 2009).

Tonalites show SE-dipping foliation planes, with inclinations ranging between 10° to 40°. Steeper dips are generally observed in the northern part of the tonalite body, close to the Palmi shear zone. Pseudotachylites are observed in nearly parallel fault zones, oriented from NE-SW to ENE-WSW and spaced about 1 km apart. Most of the fault zones are located within the tonalites; however, some pseudotachylite-bearing faults are observed also in sheared migmatitic paragneisses within the Palmi shear zone. Generally, attitude of faults is nearly parallel to the foliation of tonalites. However, within the Palmi shear zone pseudotachylite-bearing faults crosscut the steep mylonitic foliation of migmatitic paragneisses and tonalites. This indicates that seismic events generating pseudotachylites postdated ductile deformation along the Palmi shear zone.

Most of the fault planes show NE-trending nearly horizontal lineations. Fault veins are frequently overprinted by ductile deformation with generation of ultramylonites. Kinematic indicators, such as S-C and S-C′ composite foliations and drag folds, are all consistent with SW-directed shearing. In the Marinella locality, faults strike from nearly E-W to the NE-SW, with moderate to steep dips (up to 60°) towards the S and SW. Pseudotachylite fault and injection veins are generally unfoliated; pull-apart structures and synthetic microfaults are consistent with S- to SW-directed shearing, indicating dextral-normal oblique-slip movements.

Pseudotachylites consist of a microcrystalline matrix containing variable amounts of clasts made up of quartz, plagioclase, lithic fragments with subordinate K-feldspar, biotite and amphibole. The matrix is composed of microlitic biotite and plagioclase, forming frequently spherulitic textures around quartz and plagioclase rounded clasts. In some pseudotachylites a ductile overprint is indicated by the presence of flattened microlites and clasts near the contact with the wall rock. Ar-Ar age determinations on pseudotachylites indicate that faulting took place during the Middle Oligocene (33.55±0.21 Ma; Grande et al., 2009). This result is consistent with zircon fission track ages, indicating the onset of cooling and exhumation in the Calabria basement at about 35 Ma (Thomson, 1994). Therefore, pseudotachylites in the Palmi area mark the onset of extensional tectonics, connected with increasing rates of exhumation and erosion, in the Central Mediterranean area.

DAY 3

Curinga area

As already introduced in the excursion notes, the most complete cross-section of the lower continental crust is exposed in the Serre. The composition of the main lithologies is reported in Table 2.
The lower crust crops out in the NW sector of the Serre Massif and has an estimated thickness of 7-8 km (Schenk, 1984; Kruhl & Huntemann, 1991). The base of the lower crust is represented by metagabbroic rocks, belonging, according to Schenk (1980), to the granulite-pyriclasite unit (~ 2-3 km thick). The chemical composition of the metagabbroic rocks indicates a calc-alkaline affinity (Caggianelli et al., 1991).

Stop 3.1: (N 38° 49′ 25″ E 16° 17′ 50″); Granulites of the Turrino quarry (Fig. 21).
The best outcrops of the lowermost crustal levels are located near Curinga (Fig. 21), where metagabbroic rocks lie below felsic granulites (Fig. 22). All rocks are here characterized by an evident compositional layering plunging towards SE of about 40°, that is approximately the general dip of the whole Serre crustal section. This feature can be observed also on the front of a big quarry, that is cut in a metagabbroic body (Fig. 23a), along the left bank of the Strofolio stream (Fig. 21). In the quarry the rocks are crushed to produce materials for ballast.
The whole succession exposed in the quarry has a thickness of ~170 m (Fig. 22). The main rock type is a layered two-pyroxene metagabbro ± amphibole ± garnet. Other lithologies are represented by layers of metapyroxenite and meta-anorthosite, and lenses of spinel peridotite. In metagabbros, the original magmatic layering (Fig. 23b) due to crystal settling is locally well preserved. The thickness of single layers spans from cen-

Tab. 2 - Composition of the main rock types exposed in the Serre lower crust (from Caggianelli et al., 1991).

	Migmatitic paragneisses	Grt-Crd-rich rocks	Grt-Sil-rich rocks	Felsic granulites	Metagabbroic rocks
wt.%					
SiO_2	53.90	50.01	43.68	64.87	48.61
TiO_2	1.68	1.78	1.83	1.05	1.32
Al_2O_3	18.73	18.98	30.05	14.72	17.55
FeO_t	11.24	14.05	15.06	7.23	9.34
MnO	0.18	0.30	0.27	0.13	0.19
MgO	5.70	6.56	4.40	3.21	7.26
CaO	2.02	4.17	2.22	2.18	10.23
Na_2O	1.48	1.42	0.50	2.42	2.89
K_2O	3.10	0.52	0.25	2.57	0.68
P_2O_5	0.08	0.09	0.04	0.13	0.68
L.O.I.	1.62	1.84	1.68	1.30	1.25
tot	99.73	99.72	99.98	99.81	100.00
ppm					
Cr	114	156	308	75	197
Ni	82	70	96	56	73
Rb	80	16	6	67	13
Sr	224	287	29	236	534
Ba	731	173	148	716	292
Zr	228	481	298	238	164

timeter to meter scale. The presence of large garnets in gabbroic rocks with a lower color index (Fig. 23c) is confined to the upper part of the succession, where felsic granulites (Fig. 23d), made up of quartz, feldspars, and garnet ± orthopyroxene, are more abundant. These features are compatible with a contamination of the former gabbroic magma by host metasedimentary rocks. Minor intercalations of felsic granulites can be also found within the metagabbros (Fig. 22) and their repeated occurrence may be sometimes related to isoclinal folding (Fig. 23e).

Since an older foliation (S_n) is locally preserved within the thickened hinge zones of intrafolial, isoclinal folds, we identify the layering as the main foliation S_{n+1} (Fig. 23e).

Although the foliation of the felsic granulites is well developed, it rarely contains an evident lineation. When visible, it is defined by the alignment of stretched quartz crystals, showing a dip azimuth towards SSW and a plunge of about 10°.

In order to obtain indications on the temperature of deformation under which the main foliation developed, quartz c-axis measurements have been carried out. Results based on the diagram of Kruhl (1996) suggest that deformation took place under granulite facies conditions.

The emplacement age of the magmatic protholith is controversial. According to conventional U-Pb zircon ages, emplacement of the gabbros took place at about 550 Ma (Schenk, 1980). However, recent zircon spot analyses reveal a wide age spectrum (e.g. Micheletti et al., 2008; Langone, 2011) with some Ordovician and Carboniferous concordant ages that make the problem still open. This aspect is of critical importance for the interpretation of the metamorphic and geological evolution of the crustal section and for the comparison with the Ivrea crustal section, where lower crustal gabbros underplated during the late Hercynian stage (Voshage et al., 1990).

Peak metamorphism during the Late Hercynian phase reached a T of 790 °C and a P of 750 MPa at 300 Ma, according to Schenk (1989). Outstanding symplectites involving Pl, Opx and Amph (Fig. 23c) can be found between garnet and clinopyroxene. They are related to the reaction Grt + Cpx -> Pl + Opx ± Amph (Schenk, 1984; Acquafredda et al., 2008), that took place during a significant decompression event of about 200 MPa, between 300 and 290 Ma (Schenk, 1989). This reaction was reversely crossed during the cooling episode (Fig. 6).

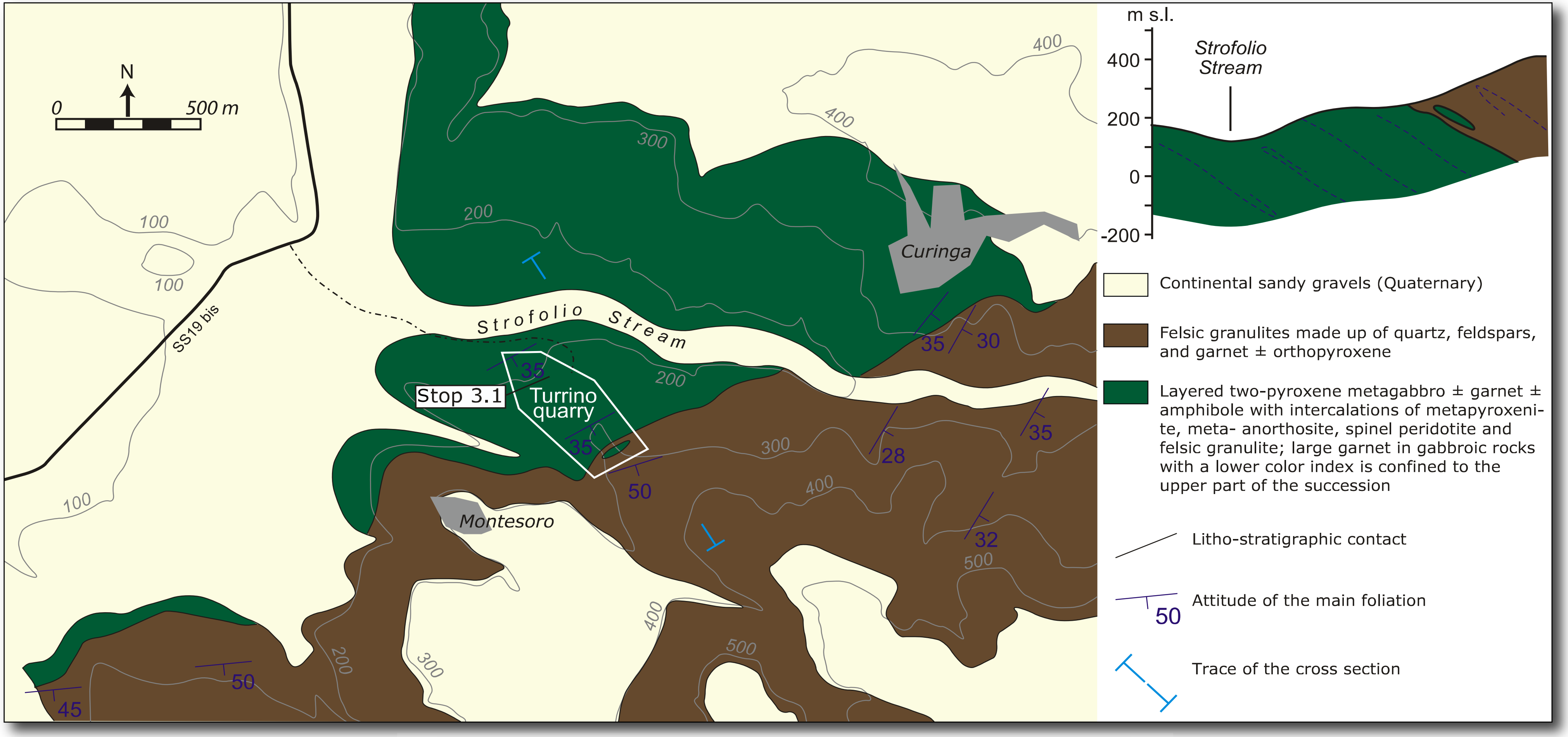

Fig. 21 - Geological sketch map of the Curinga area.

Girifalco area

The Curinga-Girifalco Line (CGL) is characterized by cataclastic and mylonitic rocks arranged in a 400 m thick belt (Fig. 24). The deformation zone mainly consists of mylonites that generally overprint migmatitic paragneisses of the lower crust (Polia-Copanello Unit of Amodio Morelli et al., 1976) and granitoid orthogneisses of an Alpine nappe (Castagna Unit). Thin bands of incohesive grey cataclasites a few metres thick, produced at low T conditions, are visible near the contact between the units. Schenk (1981) compared the CGL 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 Castagna Unit (Schenk, 1980).
The Curinga-Girifalco Line is roughly oriented WNW–ESE and the main contact dips 37° to the SSW (197°N; Fig. 24). The shear zone is offset by younger faults showing strike-slip or extensional kinematics. Migmatitic paragneisses of the lower crust are present in the hangingwall, whereas orthogneisses and paragneisses of the Castagna Alpine nappe are mostly located in the footwall. Outcropping conditions are quite good over the entire area from Curinga to Girifalco. However, around the Girifalco village two localities, close to the Addolorata church and the hydroelectric power station (Fig. 24), resulted of particular interest.

Stop 3.2: (N 38° 49’ 19”; E 16° 25’ 13”); Mylonitic orthogneisses of the Castagna Unit (Addolorata church; Fig. 24).
Orthogneisses of the Castagna Unit are the main lithology affected by shearing in the footwall of the CGL. These are metagranitoids mostly composed of quartz + K-feldspar + muscovite + biotite ± garnet, epidote and plagioclase (Fig. 25a).
Amphibolite lenses, consisting of hornblende + plagioclase + quartz + epidote + phengite ±biotite, chlorite and sphene, are closely associated with the orthogneisses. The Hercynian foliation, locally observed in migmatitic paragneisses, is here not

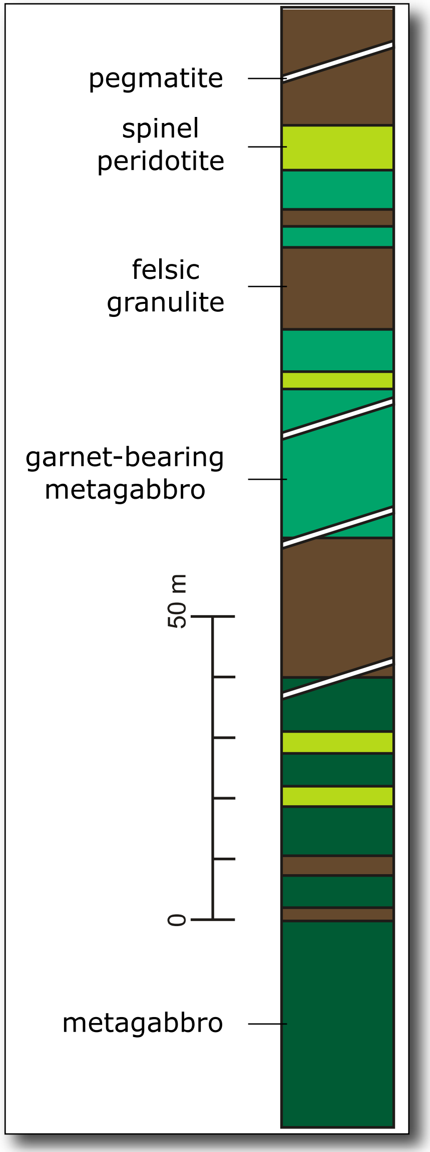

Fig. 22 - Stratigraphy of the lower crust succession exposed in the Turrino quarry.

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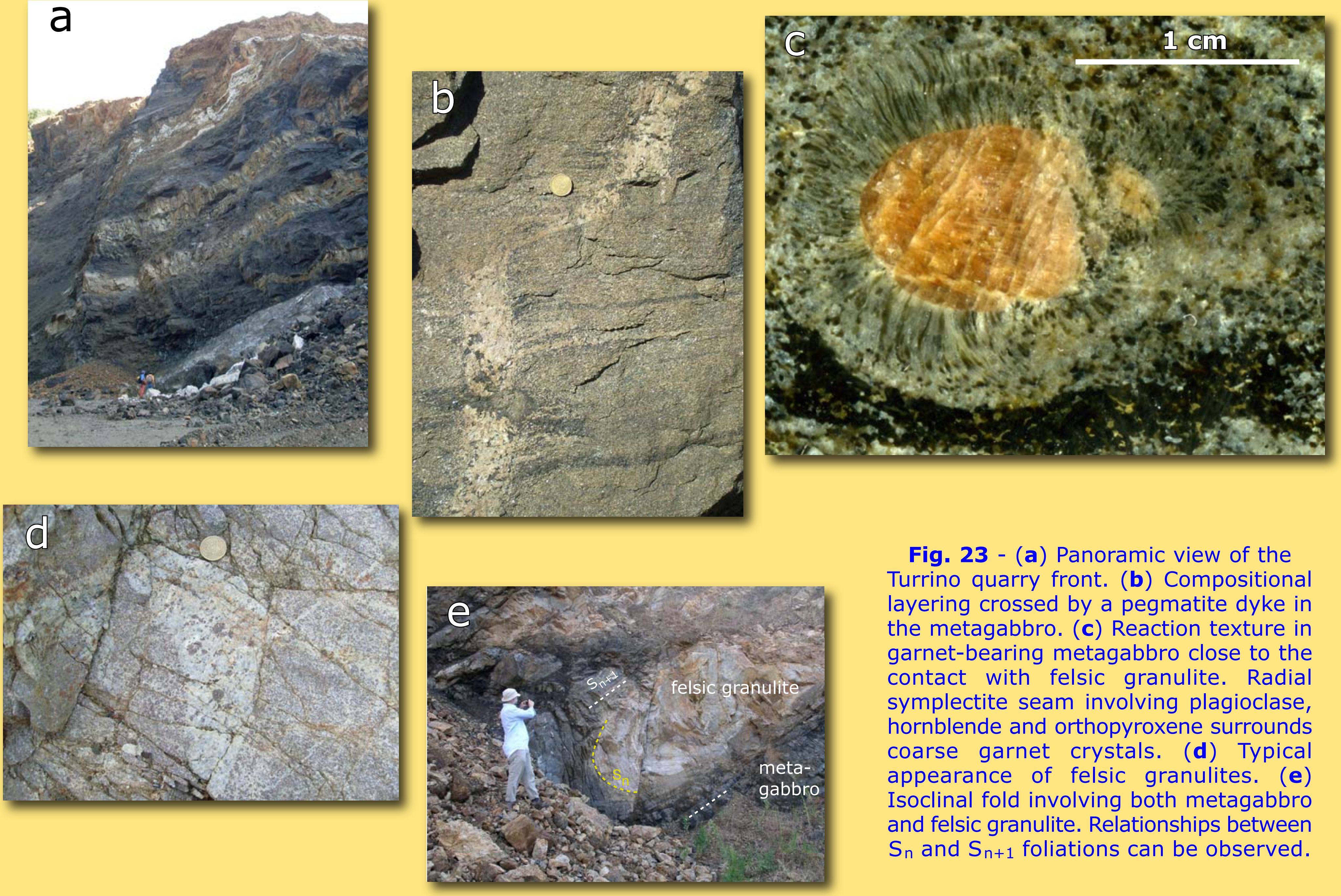

Fig. 23 - (**a**) Panoramic view of the Turrino quarry front. (**b**) Compositional layering crossed by a pegmatite dyke in the metagabbro. (**c**) Reaction texture in garnet-bearing metagabbro close to the contact with felsic granulite. Radial symplectite seam involving plagioclase, hornblende and orthopyroxene surrounds coarse garnet crystals. (**d**) Typical appearance of felsic granulites. (**e**) Isoclinal fold involving both metagabbro and felsic granulite. Relationships between S_n and S_{n+1} foliations can be observed.

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 micas and quartz grains defining an anastomosing foliation. 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 flakes 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. The presence of stable biotite on the foliation

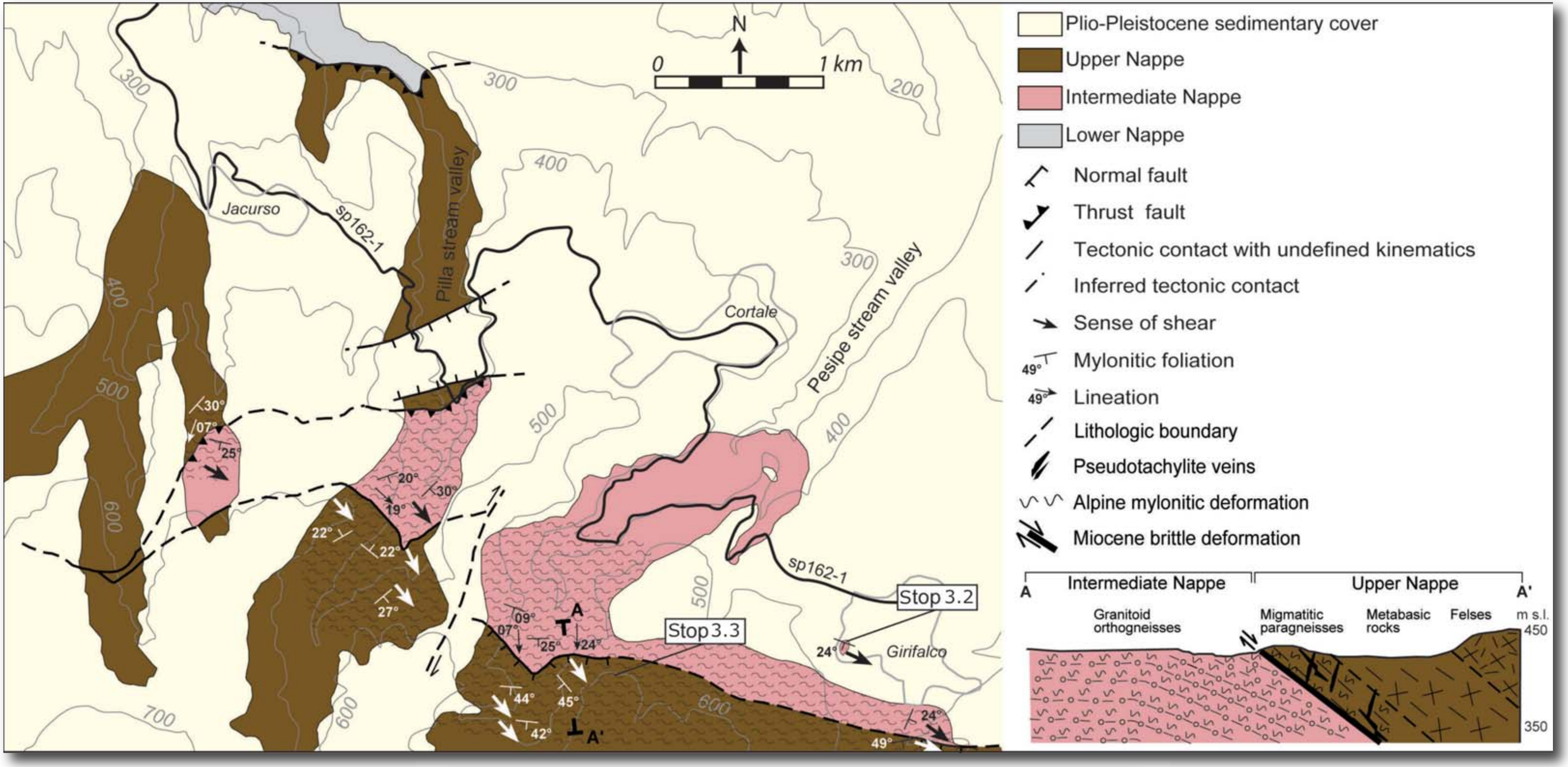

Fig. 24 - Geological sketch map of the Girifalco area.

planes indicates temperatures higher than 400 °C. The widespread evidence of dynamic recrystallization by subgrain rotation in quartz is consistent with deformation taking place at temperatures of about 400–500 °C. 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, wrapped by mica flakes and epidote grains (Fig. 25b, c). Mylonites of the intermediate nappe typically show overgrowths on hornblende and garnet with tschermakite and grossular-rich compositions, respectively (Fig. 25b, c and d). The Alpine mineral assemblage indicates that deformation took place in epidote-amphibolite facies at pressures ranging from 750 to 900 MPa.

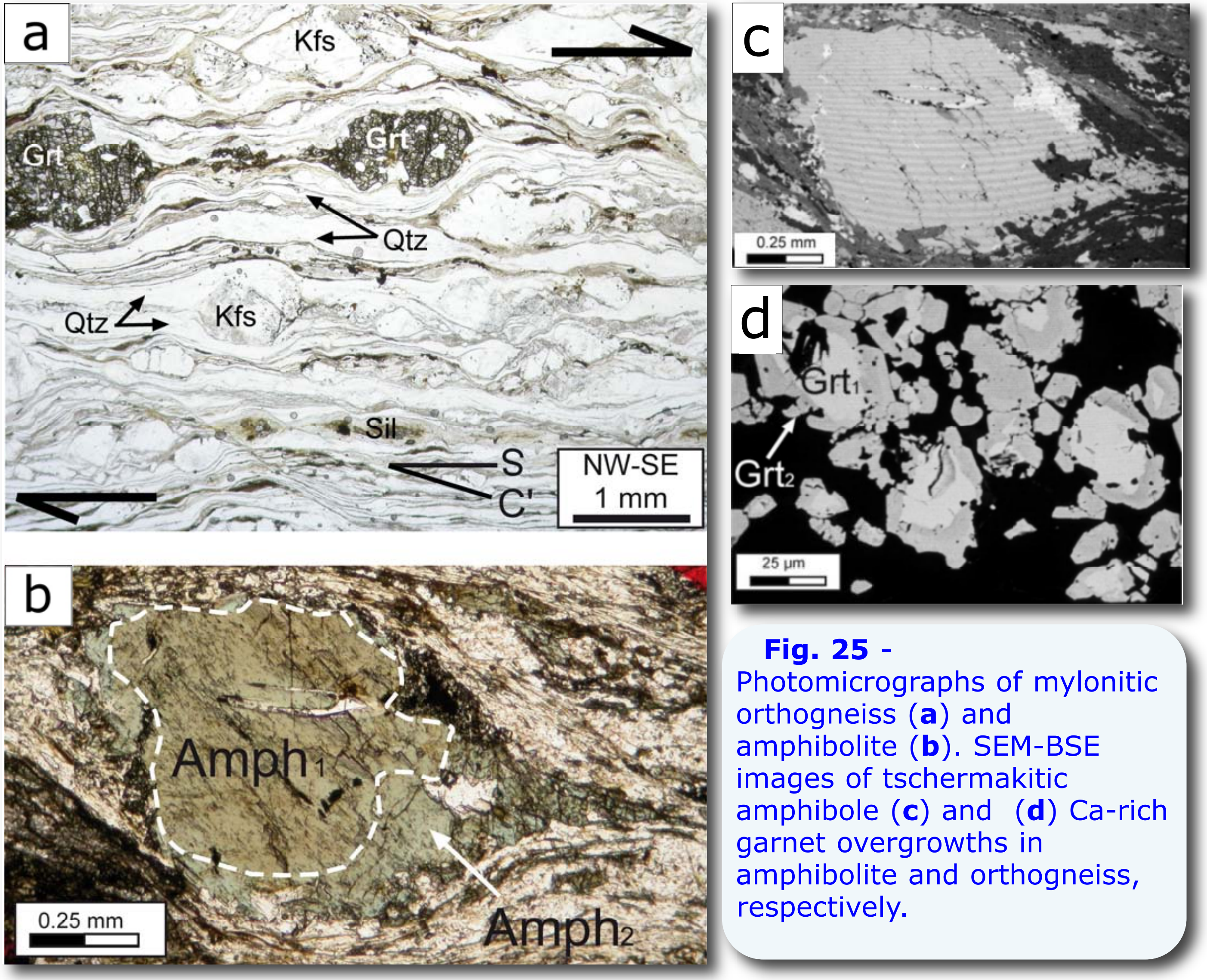

Fig. 25 - Photomicrographs of mylonitic orthogneiss (**a**) and amphibolite (**b**). SEM-BSE images of tschermakitic amphibole (**c**) and (**d**) Ca-rich garnet overgrowths in amphibolite and orthogneiss, respectively.

Stop 3.3: (N 38° 49' 10"; E 16° 24' 7"); Mylonitic migmatitic paragneisses with pseudotachylite veins of the hydroelectric power station (Fig. 24).

Near the hydroelectric power station the most beautiful outcrop of mylonitic migmatites of the Serre lower crust can be observed. The tectonic contact with the ortogneisses of the Castagna Alpine nappe is exposed along the Pesipe river, 150 meters below the power station.

The Hercynian mineral paragenesis of migmatitic paragneisses mainly consists of quartz + garnet + sillimanite + biotite ±K-feldspar and plagioclase defining transitional amphibolite to granulite facies conditions. Cordierite has been locally recognized by Spiegel (2003). During the late-Hercynian evolution (300–290 Ma), high grade metapelites underwent peak metamorphic conditions in a T range of 680–800 °C and a P range of 550–750 MPa (Schenk, 1984,1990). During the Alpine orogenesis, migmatitic paragneisses experienced a metamorphic overprint and deformation at lower temperature conditions (Fig. 26a). The Alpine metamorphic event caused a partial mineral re-equilibration. 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 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. 26b). Matrix mainly contains biotite, whereas clasts are represented by sillimanite, quartz and feldspar, both as single crystals and 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, 1985). Incomplete retrograde reactions and abundance of pseudotachylite veins indicate that deformation took place in water-deficient conditions (Passchier, 1985).

Fig. 26 - Scan of rocks slices showing the mylonitic fabric (a) and the occurrence of pseudotachylite veins within the migmatitic paragneisses (b).

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memorandum

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