TECTONICS, VOL. 27, TC2006, doi:10.1029/2007TC002157, 2008

Middle Oligocene extension in the Mediterranean Calabro-Peloritan belt (southern Italy): Insights from the Aspromonte nappes pile

T. Heymes, J.-P. Bouillin, and A. Pêcher

LGCA, UMR CNRS/UJF 5025, Université Grenoble 1,
Grenoble, France

P. Monié

Géosciences Montpellier, UMR 5243, Université Montpellier II,
Montpellier, France

R. Compagnoni

Dipartimento di Scienze Mineralogiche e Petrologiche, University of Turin,
Turin, Italy

Abstract

[1] The Calabro-Peloritan belt constitutes the eastward termination of the southern segment of the Alpine Mediterranean belt. This orogenic system was built up during the convergence between the Eurasian and the African plates, roughly north-south directed since the Upper Cretaceous. It was subsequently fragmented during the opening of the western Mediterranean basins since Oligocene times. The curved shape of the Calabro-Peloritan belt was acquired during the opening of the Tyrrhenian basin since the Tortonian. The origin, kinematics, and significance of the Calabro-Peloritan tectonic pile are still debated. Our data in the Aspromonte Massif of southern Calabria reveal an Alpine history marked by two main superimposed kinematic regimes. A first phase corresponds to the piling up of basement nappes with a top-to-the-SE vergence, i.e., in a direction orthogonal to the belt trend and toward the Adriatic foreland. This external vergence is similar to what is observed in both northeastern Sicily and northern Calabria. In Sicily, the age of nappe piling is Alpine, as evidenced by pinched slices of Mesozoic sediments. In the Aspromonte Massif, thrusting age is less constrained. Our data suggest remnants of late Hercynian structuration before the Alpine stacking. A second phase corresponds to the thinning of the continental crust, dated at around 30 Ma by both geochronological and stratigraphical data. This extension is mainly localized on two low-angle detachment contacts, with top-to-the-NE displacement. The lower one corresponds to the reworking of the former main nappe contact. The upper one is a large detachment fault cutting across the pile from upper sedimentary levels down to metamorphic basement. Extension of similar Alpine age and similar internal vergence has been already recognized in other parts of the Calabro-Peloritan Arc, i.e., in the basement nappes of northeastern Sicily and in the ophiolitic units of northern Calabria. Coming back to the original geometry and position of the Calabro-Peloritan belt, before its bending and the opening of the Liguro-Provençal and Tyrrhenian basins, we evidence a homogeneous Oligocene NE-SW extension all along the Calabro-Peloritan segment of the Alpine Mediterranean belt. This tectonometamorphic history is best explained within the framework of the continuous Tertiary westward dipping subduction of the Tethyan oceanic domain below

the European active margin and the progressive southeastward retreat of the Apennine trench since Oligocene times.

1. Introduction

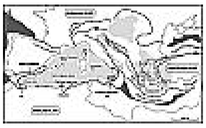


Figure 1. Simplified tectonic map of the Mediterranean region [after Jolivet et al., 1998]. Dark grey indicates the Mesozoic oceanic domain; light grey indicates the Cenozoic thinned continental crust and oceanic domains. The black box indicates location of the study area.

[2] The western Mediterranean and the surrounding belts (Figure 1) constitute the western part of the orogenic system formed during the convergence between the Eurasian and the African plates, roughly north-south directed since the Upper Cretaceous [e.g., Olivet et al., 1984; Dewey et al., 1989]. West of Italy, this convergence led to the complete closure of the Tethyan oceanic domain which separated Eurasia and Africa since the early Mesozoic and to the formation of the south Spain, North Africa, Sicily, Italian Peninsula, and Corsica orogenic belts. At the same time, several back-arc basins were opened in the western Mediterranean. The model of slab retreat [Malinverno and Ryan, 1986] is put forward to explain this tectonic evolution, marked by a spatial and temporal superimposition of compressional and extensional structures, which is known all around the Mediterranean basins [e.g., Doglioni, 1991; Royden, 1993; Lonergan and White, 1997; Doglioni et al., 1999; Brunet et al., 2000; Jolivet and Faccenna, 2000; Faccenna et al., 2004; Rosenbaum and Lister, 2004; Mascle et al., 2004].

[3] Because of its paleogeographical position during Oligocene times, the Calabro-Peloritan Arc recorded the whole Alpine tectonic evolution from subducted-related convergence to extension. In fact, the Calabro-Peloritan Arc is known to be an Alpine orogenic belt constituted by a pre-Alpine basement sheet overthrusted on ophiolitic units derived from a segment of the Tethyan oceanic lithosphere and together transported on the African-Apulian margin [e.g., Amodio-Morelli et al., 1976]. In addition, synorogenic extensional structures were recently recognized in the Calabro-Peloritan Arc: in the eastern part of the Peloritan Mountains (Sicily) [Somma et al., 2005] and in northern Calabria [Rossetti et al., 2004]. In southern Calabria, large ductile low-angle mylonites have been described and interpreted as extensional contacts [Platt and Compagnoni, 1990]. In the same area, we recognized a large extensional flat contact, which is considered as a detachment developed at much shallower levels. This detachment is visible from the Hercynian basement up to the paleoground level without being refracted in a layered Mesozoic sedimentary cover, here very thin or absent. The southern Calabria area allows the study of extension tectonics from the uppermost crust down to middle crust level.

[4] The aims of this work are (1) to define the geometry of the tectonic contacts, mainly the extensional ones, and their evolution from upper to middle crust conditions and (2) to unravel the tectonic contacts kinematics during the shortening and extension stages of the tectonometamorphic evolution. We will discuss their significance in the early geodynamic history of the western Mediterranean region.

Figure 2. Sketch map of the southern sector of the Calabro-Peloritan Arc [after Pezzino and Puglisi, 1980; Bonardi et al., 1984b; Somma et al., 2005; Ortolano et al., 2005]. Grey

indicates the tectonic pile sheets; white indicates the postorogenic sediments. In the Mandanici area, some small Mesozoic cover slivers have not been reported.

[5] The southern Calabria (south Italy) and the adjoining Peloritan Mountains (northeastern Sicily) (Figure 2) constitute the southern part of the Calabro-Peloritan belt. These massifs, together with Algerian Kabylian massifs, the Sardinia channel continental basement, and some parts of the Alboran domain, belong to the internal zone of the Maghrebian belt (AlKaPeCa domain) [Bouillin, 1986]. They mainly consist of a Hercynian basement, bounded to the south by Mesozoic and Cenozoic terranes, which are remnants of the paleotethyan margin. We consider that during Mesozoic times, Calabria was close to Sardinia on the European side of the Tethys [e.g., Alvarez et al., 1974; Bouillin, 1984], even if this model is not shared by some authors [e.g., Amodio-Morelli et al., 1976; Bonardi et al., 2003]. In our model, the internal zones have been transported during Miocene times onto the external zones after the subduction of the Tethyan oceanic lithosphere, which separated the African and Eurasian plates.

[6] The southern Calabria is a part of the Calabro-Peloritan Arc. But as it can be seen in the Peloritan Mountains, the main flat tectonic contacts are sealed by upper Oligocene to lower Miocene sediments [e.g., Amodio-Morelli et al., 1976; Bonardi et al., 1980b] (Figure 2). Accordingly, these structures are older than the Calabro-Peloritan Arc's bending, related to the opening of the Tyrrhenian basin since the Tortonian [e.g., Kastens et al., 1987].

[7] The most complete section of the Calabro-Peloritan Arc is exposed in northern Calabria where its lowermost part is made of the Liguride Complex, i.e., Mesozoic ophiolitic units and their sedimentary cover going up to late Oligocene [Amodio-Morelli et al., 1976]. These series, derived from the Tethyan oceanic domain, underwent a blueschist-facies metamorphism. In the orogenic wedge, the Calabride complex, a large sheet of pre-Alpine continental margin [Ogniben, 1973; Amodio-Morelli et al., 1976] is overthrusted on the Liguride Complex. As introduced above, a European origin is generally accepted for the Calabride Complex on the basis of structural and lithological similarities [Bouillin, 1984; Knott, 1987; Dietrich, 1988]. In northern Calabria, synorogenic extensional deformation is evident within the ophiolitic complex [Rossetti et al., 2001, 2004].

[8] Farther to the south, in the Aspromonte Massif of Calabria and in the Peloritan Mountains of Sicily, only the upper part of the Calabride Complex is exposed. In the Peloritan Mountains (Figure 2), the Calabride Complex is subdivided into two main parts: (1) a basement sheet overthrusted on (2) a composite footwall subdivided into several subunits constituted by Paleozoic cover series with some of them incorporating Mesozoic sediments from the European margin [Quitzow, 1935; Cirrincione and Pezzino, 1993]. In the Aspromonte Massif, almost all studies since Bonardi et al.'s [1979] agree on the presence of three tectonic units, which are (from the geometric bottom to the top) the Africo Unit (redefined here as the Africo-Polsi Unit (APU)), the Aspromonte Unit (AU), and the Stilo Unit (SU), separated from each other by two low-angle tectonic contacts (Figure 2).

2.1. Africo-Polsi Unit

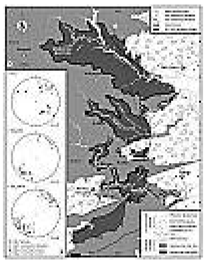


Figure 3. (a) Simplified tectonic map of the San Luca-Africo Vecchio area (modified and readapted after Pezzino and Puglisi [1980], Bonardi et al. [1984b], Ortolano et al. [2005], and new observations). (b) Stereoplots of the kinematic indicators for DA_1 and DA_2 events in the Aspromonte Unit (AU) and in the Africo-Polsi Unit (APU) (Wulff net, lower hemisphere). For EE' cross section, see Figure 9.

[9] The lower tectonic unit consists mainly of metasedimentary and metavolcanic rocks. Its upper part is best exposed in the Fiumara La Verde (Figure 3a). East of the Africo Vecchio, the following sequence can be observed (from bottom to top): decimeter-thick beds of carbonaceous-rich schist, then metachert and metacarbonate overlain by several meters of metasiltite, and about 10 m of metadolomite and metalimestone. The metacarbonates are intruded by dikes, most probably feeding metabasalts up to 30 m thick, overlain by volcaniclastics around 100 m thick, in turn covered by boudinaged and folded metacherts and by a thick metapelitic to metapsammitic foliated sequence. By comparison with paleontologically dated Paleozoic sequences from both Europe and North Africa, this lithostratigraphic sequence may be referred to as Silurian to Lower Carboniferous [Bouillin et al., 1987, and references therein]. No rocks ascribable to a Mesozoic series have been noticed.

[10] Recent data by Ortolano et al. [2005], together with our new data, indicate that the lower unit (Africo Unit) extends much farther to the north than previously regarded and that it actually merges into the Madonna dei Polsi Unit, as defined by Pezzino et al. [1990, 1992] (Figure 3a). This last unit consists almost exclusively of metasedimentary and metavolcanoclastic rocks which sharply contrast with the gneisses of the overlying Aspromonte Unit (see section 2.2). South of San Luca (Figure 3a), the series is composed of chloriteschists and carbonates very similar to those exposed in the Fiumara La Verde (Figure 3a). Toward the NW, along the Fiumara Bonamico, the straightforward comparison with the Africo Vecchio sector is less obvious as the series is composed of various micaschists and amphibolites. However, no tectonic discontinuity can be observed, the main metamorphic foliation being without breakup to the Madonna dei Polsi area. Thus we consider this lower part of the Aspromonte tectonic pile as a single unit that we will refer to as the Africo-Polsi Unit (APU). This lower unit is probably also exposed farther to the west in a small tectonic window near Cardeto (Figure 2), where very similar metamorphic rocks in the same structural position are observed, as already described by Bonardi et al. [1980a].

2.2. Aspromonte Unit

[11] Above the Africo-Polsi Unit, the Aspromonte Unit forms in Calabria the main part of the Aspromonte Massif and in Sicily the upper structural unit of the Peloritan Mountains. It is made of paragneisses with rare micaschist, amphibolite and marble intercalations, and characteristic large bodies of augen gneisses. In this unit, the Hercynian metamorphism seems rather uniform and reaches the sillimanite stability field [e.g., Messina et al., 1990].

[12] The Aspromonte Unit was intruded by kilometer-long lens-like bodies of Late Hercynian peraluminous granites (such as Punta d'Atò granite, in the central part of the Aspromonte Massif), which are mostly undeformed. The Aspromonte Unit is also intruded by many lens-like bodies and dikes of muscovite + tourmaline ± biotite ± garnet pegmatite, either

highly deformed and transported into in the main metamorphic foliation or undeformed and discordant to the Hercynian foliation.

2.3. Stilo Unit

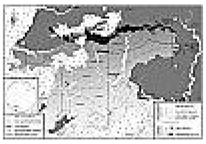


Figure 4. Simplified tectonic map of the central Aspromonte Massif (modified and readapted Bonardi et al. [1984b], Graessner and Schenk [1999], and new observations). The Punta d'Atò granite (in black with white crosses) is located in the Stilo Unit. Grey shades illustrate the metamorphic zoning of the Stilo Unit in agreement with field metamorphic isogrades after Graessner and Schenk [1999]. The Stilo Unit/Aspromonte Unit contact shown by a dotted thick curve is from Bonardi et al. [1984b]. Stereoplot represents the stretching lineations measured in the main shear bands near the detachment surface (Wulff net, lower hemisphere). AA', BB', CC', and DD' lines correspond to cross sections reported in Figure 6. Al, Allai; Ch, Choriò; Co, Condofuri; Fo, Fossato; Mb, Montebello Ionico; Slz, San Lorenzo; And, andalousite; Bt, biotite; Chl, chlorite; Grt, garnet; Ms, muscovite; Sil, sillimanite; St, staurolite.

[13] The upper part of the tectonic pile (Figure 4), which is separated from the Aspromonte Unit by a major tectonic contact, is a sequence only slightly metamorphosed in its southern part. Its apparent thickness, measured perpendicular to the metamorphic foliation, is up to 7 km (Figure 6). The top of the unit is made of Late Jurassic-Early Cretaceous neritic carbonates [Roda, 1965; Afchain, 1968]. Their upper surface is a paleokarst, filled with bauxitic clays and cupped by a transgressive lower Oligocene sequence [Bouillin, 1985]. Jurassic carbonates overlay unconformably a predominantly phyllitic series, part of which is Paleozoic (paleontologically dated as Lower Devonian [Gelmini et al., 1978]) and similar to the series recognized all along the Calabro-Peloritan Arc [Bouillin et al., 1987]. This Paleozoic fossiliferous sequence overlays stratigraphically a thick pile of metamorphic phyllite and metarhyolite. The metamorphism increases downward, i.e., from south to north on the map (Figure 4), from the chlorite to the sillimanite-muscovite zone [Graessner and Schenk, 1999]. As it does not affect the Mesozoic cover, but though lacking radiometric data, this sequence is considered by several authors to be of the same age as the Late Hercynian metamorphics of the Aspromonte Unit [Crisci et al., 1982; Graessner and Schenk, 1999]. On the basis of facies similarity of the Mesozoic lithologies, Bonardi et al. [1984b] correlate this uppermost southern Calabria unit to the Stilo Unit defined farther north in the Serre Massif [e.g., Amodio-Morelli et al., 1976].

2.4. Oligocene Stilo-Capo d'Orlando Formation

[14] The Aspromonte nappes pile is covered by the Stilo-Capo d'Orlando Formation (SCOF) [Bonardi et al., 1980b], a sedimentary sequence which extends all along the Ionian coast from the Peloritan Mountains in Sicily to the Serre Massif in Calabria (Figure 2). It is a detrital sequence made of breccias and conglomerates at the base, covered by coarse-grained sandstones, passing upward and laterally to finer sandstones or even to mudstones, suggesting a deposition in a subsiding environment [e.g., Weltje, 1992]. The basal breccias consist almost exclusively of clasts derived from phyllites and Jurassic carbonates of the Stilo Unit [Bonardi et al., 1984b]. According to Cavazza [1989] and Weltje [1992], the deposition of the Stilo-Capo d'Orlando Formation occurred in a series of basins from the Peloritan Mountains to the Serre Massif. The Peloritan Mountains and the Aspromonte Massif belong to the southern petrofacies described by Cavazza [1989]. The conglomerate bodies are mostly

composed of pebbles of various size, from decimeter to meter scale but locally even larger, and nature, typically high-grade metamorphics and granitoids probably derived from the Aspromonte Unit and low-grade phyllites derived from the Stilo Unit [Bonardi et al., 1980b; Cavazza, 1989]. No metapelite pebbles characteristic of the Africo-Polsi Unit have been described, suggesting that the latter was not yet exposed to erosion. However, in the northern part of the Aspromonte Massif, the basal surface of the Stilo-Capo d'Orlando Formation, as seen at the geologic map scale (Figure 3a), is discordant on the contact between the Aspromonte and the Africo-Polsi units. As we describe in section 3.3., the exhumation of the Aspromonte nappe pile seems to have occurred during Alpine kinematics. Consequently, the deposition of the Stilo-Capo d'Orlando Formation could be directly related to this kinematics.

[15] Concerning the age of the Stilo-Capo d'Orlando Formation, most of studies indicate that a depositional age occurred between upper Rupelian and lower Burdigalian [see Weltje, 1992, and references therein]. This chronological limit imposes a major constraint on the dating of the kinematic evolution of the Aspromonte nappes pile.

3. Tectonic Pile Architecture

3.1. Evidences for a Late Hercynian Shortening Phase (DH)

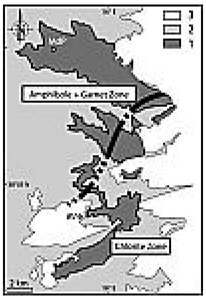


Figure 5. Schematic illustration of the probably Hercynian metamorphic zoning of the Africo-Polsi Unit, below the Aspromonte Unit nappe contact. The rough limit between the amphibole plus garnet-bearing paragenesis zone to the north and the chlorite-bearing paragenesis zone to the south is marked by the thick NE-SW curve. (1) Africo-Polsi Unit separated from (2) Aspromonte Unit by a nappe contact and both covered by (3) unconformable sediments. MdP, Madonna dei Polsi; AV, Africo Vecchio.

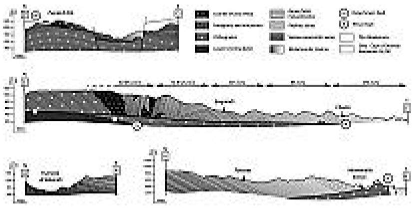


Figure 6. Geological cross sections of the central Aspromonte Massif (see location on Figure 4). The tectonometamorphic pile made by the Aspromonte and the Stilo units is cut by the upper detachment fault (Df). Metamorphic zoning reported on section CC' after Graessner and Schenk [1999]. Structure of the Aspromonte Unit is simplified, and because of its local thinness, the Stilo-Capo d'Orlando Formation is not always represented.

[16] According to Bonardi et al. [1979], Crisci et al. [1982], Atzori et al. [1984], and Graessner and Schenk [1999], the main metamorphic imprint in the Aspromonte Massif is Hercynian. It affects the three tectonic units defined by Bonardi et al. [1979] and previously described. In the lowermost Africo-Polsi Unit, we observed a NW-SE metamorphic zoning inherited from Hercynian stages (Figure 5), from amphibole and garnet zone to the NW to chlorite zone to the SE (prograde chlorite and lack of higher-grade metamorphism relics). Except for this apparent metamorphic zoning, it is rather difficult to identify large-scale, synmetamorphic structures essential to better constrain the kinematics of this local Hercynian deformation. Rb-Sr ages, which range from 331 to 22 Ma [Bonardi et al., 1987] are mixed ages. Our recent investigations using the $^{40}Ar/^{39}Ar$ technique (T. Heymes et al., manuscript in preparation, 2008) indicate a similar pre-Alpine age for this metamorphic event but do not

allow determination of its age. In the Aspromonte Unit, the main structural marker is the metamorphic foliation, formed under amphibolite-facies conditions [Bonardi et al., 1984a; Graessner and Schenk, 1999]. U-Pb ages on monazites from the gneisses are in the range 305–290 Ma [Graessner et al., 2000]. Such ages are very similar to the monazite U-Pb Permian age of 303 ± 0.7 Ma obtained for the peraluminous Punta d'Atò granite [Graessner et al., 2000] (see Figure 4 for location). In the uppermost Stilo Unit, the metamorphic zoning observed in the central part of the massif [Graessner and Schenk, 1999] is associated with a shortening deformation marked by a main metamorphic foliation and by a late E-W trending folding stage (Figures 4 and 6). The unconformable Mesozoic cover limited at the southeastern part of the Stilo Unit is not implied in this deformation and metamorphism, suggesting that this N-S shortening is Hercynian in age, as already suggested by Bonardi et al. [1979] or Graessner et al. [2000].

3.2. Evidences for an Alpine Nappe Stacking Event (DA_1)

[17] In the area between San Luca and Africo Vecchio (Figure 3a), the higher-grade metamorphics of the Aspromonte Unit overlie the lower-grade metasediments of the Africo-Polsi Unit [Burton et al., 1971; Pezzino et al., 1990, 1992]. This evidences a nappe structure. The same nappe geometry is observed in the Peloritan Mountains (NE Sicily), where the upper unit, equivalent of the Aspromonte Unit, overthrusts the Mandanici series [Quitzow, 1935] with a top-to-the-south vergence [e.g., Somma et al., 2005]. In the Peloritan Mountains, the nappe emplacement is clearly at least in part Alpine, as the footwall units include Mesozoic sediments pinched in the nappe contact toward the south [Truillet, 1962; Cirrincione and Pezzino, 1993] (see Figure 2).

[18] In the Aspromonte Massif, such stratigraphic constraints are not available to date the nappe emplacement. No Mesozoic rocks pinched in the contacts have been found, and the youngest metasediments of the footwall Africo-Polsi Unit are probably Lower Carboniferous in age. But the straightforward continuity of the Sicilian Peloritan nappe and the Aspromonte nappe implies that the nappe stacking event should also be at least in part Alpine, with a similar southward vergence.

[19] Mixed ages presented in section 3.1 [Bonardi et al., 1987] indicate a post-Hercynian (i.e., Alpine) partial metamorphic reequilibration of the Hercynian ages. Moreover, an Alpine metamorphic overprint has been described in the northeastern part of the Aspromonte Massif, marked by kyanite- and/or chloritoid-bearing paragenesis. According to the studies by Bonardi et al. [1984a], Platt and Compagnoni [1990], Messina et al. [1992], and Bonardi et al. [1992], the overprint indicates medium-pressure greenschist-facies conditions (500 ± 30°C and 5 ± 1 kbar) probably related to a main thickening event (DA_1). According to Pezzino et al. [1992] and Ortolano et al. [2005], this metamorphic overprint would be limited to the rocks of the Africo-Polsi Unit but would not have affected the Aspromonte Unit. In addition, we observed a widespread chlorite development close to the nappe contact both in the Africo-Polsi Unit and in the Aspromonte Unit. The Aspromonte Unit emplacement might be a good candidate to explain the Alpine metamorphic overprint.

[20] However, it is difficult to unambiguously fix the timing and kinematics of the nappe emplacement from structural and metamorphic data. Because of the superimposition of these two Hercynian and Alpine metamorphisms, interpretation and timing of both microstructural markers and regional structures remain difficult to establish. The basal contact of the Aspromonte nappe cuts the Hercynian metamorphic zoning, identified in the Africo-Polsi

Unit, from higher-grade zones to the NW to lower-grade metamorphic zones to the SE. In outline, it implies a bulk top-to-the-SE postmetamorphic nappe emplacement. At local scale, the metamorphic foliation is parallel to the nappe contact, both in the hanging wall and the footwall. This suggests a partial transposition of the Hercynian metamorphic foliation during the Alpine nappe thrusting. Actually, small-scale structural markers observed close to the thrust contact seem linked to the nappe emplacement: (1) In the upper Paleozoic series of the Africo Vecchio area along the Fiumara La Verde, dissymmetrical folds (Figure 3b, top stereoplot) indicate a top-to-the-SE rotational deformation in the footwall of the nappe. (2) In addition, at the base of the Aspromonte Unit (Figures 3a and 3b, top stereoplot), in domains unaffected by the DA_2 mylonitization described in section 3.3.1, the stretching lineation also underlines a NW-SE shearing in the hanging wall.

[21] Thus it appears that if a Hercynian nappe emplacement with the same vergence as the later Alpine vergence cannot be excluded, the basal contact of the Aspromonte Unit in southern Calabria is an Alpine nappe contact, with a probable top-to-the-SE transport direction (DA_1). Farther to the north in the Calabro-Peloritan belt, a similar top-to-the-SE sense of displacement is described in the Alpine nappes pile of the northern Serre [Langone et al., 2006]. Still farther along the arc strike, in northern Calabria, a first Alpine deformation phase associated with an external top-to-the-east vergence has also been pointed out in the lower part of the nappes pile of the Liguride Complex [Rossetti et al., 2004]. Thus, all along the Calabro-Peloritan belt, Alpine nappe stacking is evidenced. It is poorly dated but shares the same external vergence, with transport directions always roughly perpendicular to the local arc strike (see Figure 11).

3.3. Extensional Reworking (DA_2)

3.3.1. Structural Data

[22] In the upper part of the tectonic pile, the Stilo Unit overlays the Aspromonte Unit along a low-angle tectonic contact, usually interpreted as a thrust [Bonardi et al., 1979; Crisci et al., 1982; Bonardi et al., 1984b] (Figure 4). On the contrary, according to J. P. Bouillin et al. (unpublished data, 2008), it is a large detachment fault, which can be best observed in its southernmost part, where the nonmetamorphic Jurassic limestones and low-grade metamorphic Devonian and Silurian schists of the Stilo Unit directly overlie the medium-grade metamorphic rocks of the Aspromonte Unit along a flat silicified tectonic surface.

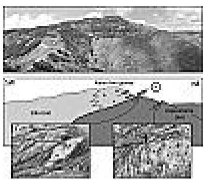


Figure 7. View and interpretative drawing of the Punta d'Atò area. The photographs illustrate two examples of meter-scale structures observed in the shear zones, both indicating a top-to-the-north or NE motion. Hammer gives scale.

[23] Farther to the north (Figure 4), the metamorphic grade of the Stilo Unit progressively increases [Graessner and Schenk, 1999], and the metamorphic contrast between the Stilo and the Aspromonte units fades out, making the tectonic contact more difficult to identify. North of Bagaladi, the contact defined by previous authors does not appear to be a real tectonic boundary (Figures 4 and 6). It seems that the Punta d'Atò granite, considered as a part of the Aspromonte Unit, has been used to locate the limit of the Stilo Unit. Actually, along the continuous geological section of the Fiumara Pietre Bianche (Figure 4), no lithological, tectonic, or metamorphic discontinuities can be recognized, but from south to north, the

lithologies progressively change, first from metapelite to metapsammite, then to paragneisses commonly referred to as Aspromonte gneisses. These gneisses form the country rocks of the Punta d'Atò granite, on both the south and north sides (Figure 6, section CC'). In a similar way, farther to the west, the fault drawn along the Fiumara di Valanidi [Crisci et al., 1982; Bonardi et al., 1984b] does not seem to be a major contact. Here again, there is a progressive lithological transition from the Stilo-type to the Aspromonte-type rocks (Figure 6, sections AA' and BB'). Thus, in these two sections, the actual lower limit of the Stilo Unit must be located farther to the north: however, we have not been able to find it because of the poor exposition of the central plateaus of the Piani di Aspromonte. But to the east, north of Roccaforte del Greco up to Punta d'Atò (Figure 4), the detachment surface has been identified: It appears to split into several low-angle shear zones (Figure 6, section DD', and Figure 7).

[24] Thus, the clear lithologically based distinction between a Stilo Unit (at the hanging wall) and an Aspromonte Unit (at the footwall), obvious farther to the south, is unnoticeable in the Punta d'Atò area, as both hanging wall and footwall are made of similar Aspromonte-type gneisses. Rather than two different series, the Stilo and Aspromonte units form the upper and the lower parts, respectively, of a former continuous single sedimentary and metamorphic pile. The detachment fault described here cuts this tectonic pile from the paleoground surface to the south through the Mesozoic cover to deeper levels toward the north.

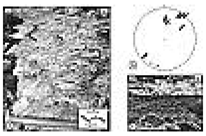


Figure 8. Mesostructural and microstructural kinematic indicators for the shearing direction in “cold” mylonites during the DA$_2$ event. (a) S-C' structures in the Africo-Polsi Unit just below the contact with the Aspromonte Unit. (b) Stereoplot of the transport direction derived from S-C'structures from the Africo-Polsi Unit below the lower contact (Wulff net, lower hemisphere). The hanging wall movement is shown by the arrows. Stars are postmetamorphic “a”-type fold axes roughly parallel to the transport direction. (c) Microstructures observed in “cold” mylonites from the main shear band in the Africo-Polsi Unit/Aspromonte Unit contact.

[25] In the southern sector, the deformation is mainly cataclastic, and the breccia associated with the detachment surface does not provide any clear kinematic indicators. In the northern sector (i.e., in the Punta d'Atò area), where the detachment occurred at deeper levels, deformation is more ductile, and shear zones cut both the Aspromonte gneisses and the late Hercynian Punta d'Atò granite. In those shear zones, the direction of transport for DA$_2$ is given by the stretching lineation, regularly oriented close to NNE-SSW (Figure 4, stereoplot) while a top-to-the-north sense of movement is given by S-C-type almonds, asymmetric boudinage, and rare drag folds (Figure 8).

Figure 9. Simplified geological cross section showing DA$_2$ top-to-the-NE shearing phase in the area between San Luca and Africo Vecchio. Location is shown in Figure 3. The grey shades of the box on the bottom represents the DH Hercynian metamorphic zoning of the Africo-Polsi Unit. APU, Africo-Polsi Unit; AU, Aspromonte Unit; SU, Stilo Unit; SCOF, Stilo-Capo d'Orlando Formation.

[26] DA$_2$ structures are localized not only at the base of the Stilo detachment but also within the lower part of the tectonic pile, down to the basal contact of the Aspromonte Unit and the upper part of the Africo-Polsi Unit. They are marked by the development of a mylonitic foliation in narrow bands (up to 10 m thick), already mentioned by Bonardi et al. [1984a] and

Platt and Compagnoni [1990]. These structures are relatively low temperature blastomylonites [Passchier and Trouw, 1996], best expressed when they cut or follow former quartz-rich pegmatite veins (Figure 8c). They are particularly continuous and thick in the contact zone between the Aspromonte Unit and the Africo-Polsi Unit. In those mylonites, the penetrative stretching lineation trends NNE-SSW (Figures 3a and 3b, middle and bottom stereoplots), while asymmetric S-C and S-C' fabrics indicate a top-to-the-NE sense of displacement (Figures 8 and 9). Below the contact, but close to it in the Africo-Polsi Unit, S-C' fabrics indicate the same trend and sense of displacement (Figures 8 and 9). Lower down in the Africo-Polsi Unit, the same sense of displacement is still indicated by both the late metamorphic stretching and mineral lineation and postmetamorphic “a”-type folds (Figures 8 and 9). It strongly suggests that they are due to the same DA_2 deformation.

[27] Thus, the top-to-the-NE deformation (DA_2) affects all the southern Calabria pile. In its upper part, extension is localized along a simple top-to-the-NE detachment fault, which is cutting across the pile from very shallow Mesozoic sediments to medium-grade metamorphic rocks. Lower in the pile, below this contact, extensional deformation is more pervasive, even if it is often localized along mylonitic shear zones. At the base of the Aspromonte Unit, the former nappe contact structures have been partly reactivated under ductile conditions.

[28] In addition to the kinematic markers, the extension/thinning process is also documented by thermobarometric estimates from the lower mylonitic zone between the Aspromonte and the Africo-Polsi units, which indicates a progressive decompression in the greenschist-facies conditions from 8 to 3 kbar during the top-to-the-NE shearing phase [Ortolano et al., 2005]. It corresponds to a tectonic denudation of some 15 km of the overlying rocks.

3.3.2. Age of the DA_2 Extensional Tectonics

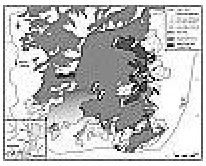


Figure 10. Average transport direction for the DA_1 top-to-the-SE thickening (black arrows) and the DA_2 top-to-the-NE thinning (white arrows) events from the Aspromonte. White star indicates the location of sample BOV-30 after Thomson [1994]. See text for further explanations.

[29] Both stratigraphical and thermochronological data can help to date the detachment. The extensional tectonics is bracketed by (1) the age of the youngest lower Oligocene sediments [Bouillin, 1985] transported above the detachment surface with the Stilo Unit and (2) the upper Oligocene age [Weltje, 1992] of the oldest deposits of the Stilo-Capo d'Orlando Formation, cartographically unconformable to the detachment surface. An Oligocene apatite fission track (FT) age of 32.8 ± 1.4 Ma (sample BOV-30 from Thomson [1994]; see location on Figure 10), obtained from a sample from the footwall of the detachment surface in the southern area, i.e., in the shallower zone of the detachment, indicates very fast denudation at this period. It would reflect the tectonic denudation consecutive to the detachment activation. In lower structural levels, Rb-Sr data on white micas from Alpine shear zones [Bonardi et al., 1987] provide ages ranging between 25 and 30 Ma. It is difficult to estimate an exhumation rate from these published data and to understand if they reflect tectonic or erosional denudation. Nevertheless, these geochronologic data combined with a 32.8 Ma apatite FT age and around 30 Ma $^{39}Ar/^{40}Ar$ ages from muscovites from the contact zone between the Aspromonte and the Africo-Polsi units (T. Heymes et al., manuscript in preparation, 2008) also imply a fast cooling at this period which is best explained by tectonic thinning. Thus, even if additional cooling ages are needed in order to time the extensional tectonics precisely,

both available geochronological and sedimentary constraints lead to a middle Oligocene age for the northeastward spreading of the orogenic edifice of the Aspromonte Massif.

4. Discussion

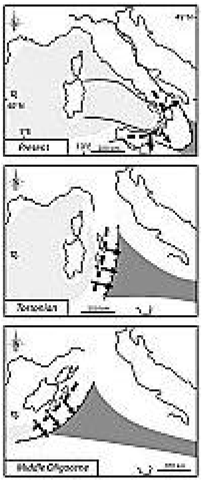


Figure 11. Schematic reconstruction of the orientation of the two Alpine stacking/unstacking transport direction described in the Calabro-Peloritan Arc from present to initial (middle Oligocene) positions. Restoration of the Calabro-Peloritan belt position at Tortonian is after Rosenbaum and Lister [2004]. Restoration of the position of the Calabro-Corsica-Sardinian blocks at middle Oligocene is after Lonergan and White [1997], Gelabert et al. [2002], and Michard [2006].

[30] The tectonometamorphic history recorded in the upper part of the orogenic wedge exposed in southern Calabria is best explained within the framework of the continuous Tertiary westward dipping subduction of the Tethyan oceanic domain below the European active margin and the progressive southeastward retreat of the Apennine trench [Doglioni, 1991; Jolivet et al., 1998; Faccenna et al., 2001; Rossetti et al., 2004]. In this geodynamic evolution, the present shape and location of the Calabro-Peloritan Arc result from the following multistage extensional history of the western Mediterranean: (1) opening of the Liguro-Provençal basin and rotation of the Corsica-Sardinia block, initiated in the lower Miocene times, around 20 Ma ago [Vigliotti and Langenheim, 1995]; (2) opening of the Tyrrhenian basin between Corsica and Apulia in the Tortonian, around 10 Ma ago (this opening is most probably already initiated since Serravalian times as evidenced by the lamproite intrusions of Sisco in Corsica [Serri et al., 1993] or by the Cornacya submarine mountain in the Sardinia channel [Mascle et al., 2001]); and (3) coeval rollback of the Ionian subduction since the Tortonian [e.g., Doglioni, 1991; Faccenna et al., 2001], during which the bent shape of the Calabro-Peloritan Arc has been progressively acquired, with complex counterclockwise and/or clockwise rotations of the blocks. By restoring these rotations, it is possible to reconstruct both the shape and the position of the Calabro-Peloritan segment from the Present back to the Tortonian [Rosenbaum and Lister, 2004] and the thickening and thinning transport directions in the Calabro-Peloritan Arc during the main steps of this history (Figure 11).

4.1. Thickening Phase

[31] In the Peloritan Mountains, no transport lineation data are available. But N-S transport direction can be inferred from the trend of the fold axes, systematically E-W trending [see Somma et al., 2005, Figure 2]. In addition, the bulk geometry of the nappes implies a general top-to-the-south nappe stacking. In southern Calabria, our data also indicate a transport direction with top-to-the-SE movement perpendicular to the belt trend. In northern Calabria, data of Rossetti et al. [2004] indicate a consistent top-to-the-ENE nappe piling up that is very

different from the one observed southward but is still perpendicular to the belt trend. Considering now the geometry of the belt at the Tortonian [Rosenbaum and Lister, 2004], it was not curved, and the thickening direction appears to be very homogeneous all along the belt, visually top-to-the-east. Before the opening of the Liguro-Provençal basin, it would correspond to a top-to-the-SE displacement (Figure 11). This vergence of the Alpine nappe emplacement in the Calabro-Peloritan belt prior to 30 Ma is in good agreement with the interpretative tectonic models of the African vergence of the orogenic wedge proposed by most authors [e.g., Ogniben, 1973; Thomson, 1994; Jolivet et al., 1998; Faccenna et al., 2001; Rossetti et al., 2004].

4.2. Thinning Phase

[32] In the Peloritan Mountains, extensional tectonics has been described within the nappes pile [Somma et al., 2005]. The available structural data related to this extension, which are fold trends, cleavage orientations, and few S-C fabrics, indicate a top-to-the-north or-NE displacement. In southern Calabria, our data clearly indicate a top-to-the-NE displacement. In northern Calabria, this direction is apparently quite different, having a top-to-the-NW motion according to Rossetti et al. [2004], although a part of their data must be revisited [Alvarez, 2005]. But again, if we plot the extension directions at Tortonian before the bending of the Calabro-Peloritan Arc, all these orientations become consistent, making a constant angle of about 30° with the belt trend. If we consider the direction at the beginning of the extension, i.e., just before the opening of the Ligurian-Provençal basin, the extension direction was top-to-the-NE in the entire Calabro-Peloritan belt (Figure 11). The extension probably occurred just after the main stacking event, i.e., the nappes emplacement. It is sealed by the deposition of the Stilo-Capo d'Orlando Formation which might be contemporaneous with the first step of the opening of the north Algerian basin. In the Kabylian, this opening is marked by the deposition of the “Oligo-Miocene Kabyle,” considered as the lateral extension of the Calabro-Peloritan Stilo-Capo d'Orlando Formation [e.g., Gelard et al., 1973]. It is thus possible to propose that the Calabro-Peloritan belt was located at the eastern edge of the north Algerian basin before the onset of the counterclockwise rotation of the Corso-Sardinian block since 20.5 Ma [Vigliotti and Langenheim, 1995] and the opening of the Tyrrhenian basin.

5. Conclusion

[33] The Aspromonte Massif is a link between Sicily (southwestern ending of the Calabro-Peloritan belt), where Alpine nappe tectonics with an external (top-to-the-south) vergence is the most obvious structure, and northern Calabria (north ending of the Calabro-Peloritan Arc), where two opposite Alpine shearing events are described. In the intermediate Aspromonte segment, our structural data, together with the metamorphic and published or unpublished geochronological data, point to a two-step structuring during (1) a post-Hercynian crustal thickening event (DA_1) with an external (top-to-the-SE) vergence and (2) a middle Oligocene spreading event (DA_2), with an internal (top-to-the-NE) vergence, stretching apart the previously structured nappe edifice (Figure 10). This subsequent detachment-style extension in the Calabride complex of southern Calabria is contemporaneous with the initiation of the exhumation of the Alpine oceanic-derived metamorphic units of northern Calabria [Rossetti et al., 2004]. Using the paleomagnetic data compiled by Rosenbaum and Lister [2004], it appears (1) that a common vergence (i.e., toward the Adriatic foreland) during the crustal thickening and nappe construction can be described all along the Calabro-Peloritan Arc and (2) that the extensional tectonics is a crucial feature in the entire tectonic edifice of the

Calabro-Peloritan belt since Oligocene times, probably related to the beginning of the retreat of the Apennine trench initially N-S directed.

Acknowledgments

[34] We thank Stephane Guillot for his useful suggestions on a first version of the paper. Critical reading of Guillaume Duclaux, discussions with Benjamin Le Bayon, and detailed constructive reviews of two anonymous reviewers significantly improved the paper.

References

Afchain, C. (1968), Le témoin calcaire de Sideroni, près de Bova Marina (Calabre méridionale), C. R. Somm. Seances Soc. Geol. Fr., 9, 329–330.

Alvarez, W. (2005), Structure of the Monte Reventino greenschist folds: A contribution to untangling the tectonic-transport history of Calabria, a key element in Italian tectonics, J. Struct. Geol., 27, 1355–1378.

Alvarez, W., et al. (1974), Fragmentation of the Alpine orogenic belt by microplate dispersal, Nature, 248, 309–312.

Amodio-Morelli, L., et al. (1976), L'Arco Calabro-Peloritanio nell'orogene Appenninico-Maghrebide, Mem. Soc. Geol. Ital., 17, 1–60.

Atzori, P., et al. (1984), Remnants of the Hercynian orogen along the Calabrian-Peloritan arc, southern Italy: A review, J. Geol. Soc. London, 141, 137–145.

Bonardi, G., et al. (1979), Osservazioni geologiche e petrografiche sull'Aspromonte, Boll. Soc. Geol. Ital., 98, 55–73.

Bonardi, G., et al. (1980a), La finistra tettonica di Cardeto (Reggio Calabria), Rend. Soc. Ital. Mineral. Petrol., 3, 3–4.

Bonardi, G., et al. (1980b), Osservazioni sull'evoluzione dell'Arco Calabro-Peloritano nel Miocene inferiore: La Formazione di Stilo-Capo d'Orlando, Boll. Soc. Geol. Ital., 99, 279–309.

Bonardi, G., et al. (1984a), Riequilibrazioni metamorfiche di probabile età alpina nell'unità dell'Aspromonte-Arco Calabro-Peloritano, Rend. Soc. Ital. Mineral. Petrol., 39, 613–628.

Bonardi, G., et al. (1984b), L'unità di Stilo nel settore meridionale dell'arco Calabro-Peloritanio, Boll. Soc. Geol. Ital., 103, 279–309.

Bonardi, G., et al. (1987), Riequilibrazioni tettono-metamorfiche alpine nell'unità dell'Aspromonte, Calabria meridionale, Rend. Soc. Ital. Mineral. Petrol., 42, 301.

Bonardi, G., et al. (1992), Sovrimpronta metamorfica alpina nell'unità dell'Aspromonte (settore meridionale dell'Arco Calabro-Peloritano), Boll. Soc. Geol. Ital., 111, 81–108.

Bonardi, G., et al. (2003), Oligocene-to-early-Miocene depositional and structural evolution of the Calabria-Peloritani Arc southern terrane (Italy) and geodynamic correlations with the Spanish Betics and Morocco Rif, Geodin. Acta, 16, 149–169.

Bouillin, J.-P. (1984), Nouvelle interprétation de la liaison Apennin-Maghrébides en Calabre: Conséquences sur la paléogéographie téthysienne entre Gibraltar et les Alpes, Rev. Geol. Dyn. Geogr. Phys., 25, 321–338.

Bouillin, J.-P. (1985), Transgression de l'Oligocène inférieur (formation de Palizzi) sur un karst à remplissage bauxitique dans les zones internes calabro-péloritaines (Italie), C. R. Acad. Sci., Ser. II, 301, 415–420.

Bouillin, J.-P. (1986), Le bassin maghrébin: Une ancienne limite entre l'Europe et l'Afrique à l'ouest des Alpes, Bull. Soc. Geol. Fr., 8, 547–558.

Bouillin, J.-P., et al. (1987), Les formations paléozoïques de l'arc calabro-péloritain dans leur cadre structural, Boll. Soc. Geol. Ital., 106, 693–698.

Brunet, C., et al. (2000), Migration of compression and extension in the Tyrrhenian Sea, insights from $^{40}Ar/^{39}Ar$ ages on micas along a transect from Corsica to Tuscany, Tectonophysics, 321, 127–155.

Burton, A. N., et al. (1971), Carta Geologica della Calabria, scale 1:25,000, 255 IIISW Africo, Cassa per il Mezzogiorno, Poligrafica and Cartevalori Ercolano, Inst. Geogr. Militare, Florence, Italy.

Cavazza, W. (1989), Detrital modes and provenances of the Stilo-Capo d'Orlando Formation (Miocene), southern Italy, Sedimentology, 36, 1077–1090.

Cirrincione, R., and A. Pezzino (1993), Nuovi dati strutturali sulle successioni mesozoiche metamorfiche dei Monti Peloritani orientali, Boll. Soc. Geol. Ital., 13, 195–203.

Crisci, G. M., et al. (1982), L'unità superiore dell'Aspromonte: Studio geologico e petrografico, Rend. Soc. Ital. Mineral. Petrol., 38, 989–1014.

Dewey, J. F., et al. (1989), Kinematics of the western Mediterranean, Geol. Soc. Spec. Publ., 45, 265–283.

Dietrich, D. (1988), Sense of overthrust shear in the Alpine nappes of Calabria (southern Italy), J. Struct. Geol., 10, 373–381.

Doglioni, C. (1991), A proposal for the kinematic modelling of W-dipping subductions: Possible applications to the Tyrrhenian-Apennines system, Terra Nova, 3, 423–434.

Doglioni, C., et al. (1999), On the origin of W-directed subduction zones and applications to the western Mediterranean, in The Mediterranean Basins: Tertiary Extensions Within the Alpine Orogen, edited by B. Duran et al., Geol. Soc. Spec. Publ., 156, 541–561.

Faccenna, C., et al. (2001), History of subduction and back-arc extension in the central Mediterranean, Geophys. J. Int., 145, 809–820.

Faccenna, C., C. Piromallo, A. Crespo-Blanc, L. Jolivet, and F. Rossetti (2004), Lateral slab deformation and the origin of the western Mediterranean arcs, Tectonics, 23, TC1012, doi:10.1029/2002TC001488.

Gelabert, B., et al. (2002), A new proposal for the late Cenozoic geodynamic evolution of the western Mediterranean, Terra Nova, 14, 93–100.

Gelard, J.-P., et al. (1973), L'âge de la transgression (Oligocène terminal-Aquitanien basal) sur le socle de Grande Kabylie (Algérie), C. R. Somm. Seances Soc. Geol., 7–9.

Gelmini, R., et al. (1978), Rinvenimento di fossili devoniani nel cristallino dell'Aspromonte (Calabria), Rend. Soc. Ital. Mineral. Petrol., 1, 45–47.

Graessner, T., and V. Schenk (1999), Low-pressure metamorphism of Paleozoic pelites in the Aspromonte, southern Calabria: contraints for the thermal evolution in the Calabrian crustal cross-section during Hercynian orogeny, J. Metamorph. Geol., 17, 157–172.

Graessner, T., et al. (2000), Geochronological constraints on the timing of granitoid magmatism, metamorphism and post-metamorphic cooling in the Hercynian crustal cross-section of Calabria, J. Metamorph. Geol., 18, 409–421.

Jolivet, L., and C. Faccenna (2000), Mediterranean extension and the Africa-Eurasia collision, Tectonics, 19, 1095–1106.[AGU]

Jolivet, L., et al. (1998), Midcrustal shear zones in post-orogenic extension: Example from the northern Tyrrhenian Sea (Italy), J. Geophys. Res., 103, 12,123–12,160.[AGU]

Kastens, K., et al. (1987), Proceedings of the Ocean Drilling Program: Initial Reports, vol. 107, Ocean Drill. Program, College Station, Tex.

Knott, S. D. (1987), The Liguride complex of southern Italy, a Cretaceous to Paleogene accretionary wedge, Tectonophysics, 142, 217–226.

Langone, A., et al. (2006), The Curinga-Girifalco fault zone (northern Serre, Calabria) and its significance within the Alpine tectonic evolution of the western Mediterranean, J. Geodyn., 42, 140–158.

Lonergan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, Tectonics, 16, 504–522.[AGU]

Malinverno, A., and W. B. F. Ryan (1986), Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, Tectonics, 5, 227–245.[AGU]

Mascle, G. H., et al. (2001), Evolution of the Sardinia channel (western Mediterranean): New constraints from a diving survey on Cornacya seamount of SE Sardinia, Mar. Geol., 179, 179–201.

Mascle, G. H., et al. (2004), Structure of the Sardinia channel: Crustal thinning and tardi-orogenic extension in the Apenninic-Maghrebian orogen; results of the Cyana submersible survey (SARCYA and SARTUCYA) in the western Mediterranean, Bull. Soc. Geol. Fr., 175, 607–627.

Messina, A., et al. (1990), Alpine metamorphic overprint in the Aspromonte nappe of northeastern Peloritani Mts (Calabria-Peloritani Arc, southern Italy), Boll. Soc. Geol. Ital., 109, 655–673.

Messina, A., et al. (1992), Alpine metamorphic overprint in the crystalline basement of the Aspromonte Unit (Calabrian-Peloritani arc-southern Italy), IGCP Proj. 276 Newsl. 5, pp. 353–379, Int. Geosci. Programme, Jakarta.

Michard, A. (2006), Extension in Alpine western Europe and west Mediterranean, C. R. Geosci., 338, 225–228.

Ogniben, L. (1973), Schema geologico della Calabria in base ai dati odierni, Geol. Rom., 12, 243–585.

Olivet, J. L., et al. (1984), Cinématique de l'Atlantique nord et central, rapports scientifiques et techniques, 108 pp., Cent. Natl. pour l'Exploit. des Oceans, Paris, France.

Ortolano, G., et al. (2005), P-T evolution of Alpine metamorphism in the southern Aspromonte Massif (Calabria-Italy), Schweiz. Mineral. Petrogr. Mitt., 85, 31–56.

Passchier, C. W., and R. A. J. Trouw (1996), Microtectonics, 325 pp., Springer, New York.

Pezzino, A., and G. Puglisi (1980), Indagine geologico-petrografica sul cristallino dell'Aspromonte centro-settentrionale (Calabria), Boll. Soc. Geol. Ital., 99, 255–268.

Pezzino, A., et al. (1990), Geometry and metamorphic environment of the contact between the Aspromonte-Peloritani Unit (Upper Unit) and the Madonna di Polsi Unit (Lower Unit) in the central Aspromonte area (Calabria), Boll. Soc. Geol. Ital., 109, 455–469.

Pezzino, A., et al. (1992), Due unità cristalline a grado metamorfico diverso in Aspromonte centrale. Geometria dei loro rapporti, ambientazione metamorfica del loro contatto e caratteri petrografici delle metamorfiti, Boll. Soc. Geol. Ital., 111, 69–80.

Platt, J. P., and R. Compagnoni (1990), Alpine ductile deformation and metamorphism in a calabrian basement nappe (Aspromonte, south Italy), Eclogae Geol. Helv., 83, 41–58.

Quitzow, H. (1935), Der Deckenbau des Kalabrischen Massivs und seiner Randgebiete, Abh. Ges Wiss. Goettingen Math Phys. Kl., III Folge, 13, 63–179.

Roda, C. (1965), Il calcare portlandiano a Dasycladaceae di M. Mutolo (Reggio Calabria), Geol. Rom., 4, 259–290.

Rosenbaum, G., and G. S. Lister (2004), Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides, Tectonics, 23, TC1013, doi:10.1029/2003TC001518.

Rossetti, F., C. Faccenna, B. Goffé, P. Monié, A. Argentieri, R. Funiciello, and M. Mattei (2001), Alpine structural and metamorphic signature of the SiIa Piccola Massif nappe stack (Calabria, Italy): Insights for the tectonic evolution of the Calabrian Arc, Tectonics, 20, 112–133.[AGU]

Rossetti, F., B. Goffé, P. Monié, C. Faccenna, and G. Vignaroli (2004), Alpine orogenic P-T-t-deformation history of the Catena Costiera area and surrounding regions (Calabrian Arc, southern Italy): The nappe edifice of north Calabria revised with insights on the Tyrrhenian-Apennine system formation, Tectonics, 23, TC6011, doi:10.1029/2003TC001560.

Royden, L. H. (1993), Evolution of retreating subduction boundaries formed during continental collision, Tectonics, 12, 629–638.[AGU]

Serri, G., et al. (1993), Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy, Tectonophysics, 223, 117–147.

Somma, R., et al. (2005), Synorogenic extension in the Peloritani Alpine thrust belt (NE Sicily, Italy): Evidence from the Alì unit, C.R. Geosci., 337, 861–871.

Thomson, S. N. (1994), Fission track analysis of the crystalline basement rocks of the Calabrian Arc, southern Italy: Evidence of Oligo-Miocene late-orogenic extension and erosion, Tectonophysics, 238, 331–352.

Truillet, R. (1962), Présence de Berriasien coincé entre les phyllades et la nappe de cristallin des Monts Péloritains (Sicile), Bull. Soc. Hist. Nat. Doubs, 64, 29–30.

Vigliotti, L., and E. Langenheim (1995), When did Sardinia stop rotating—New paleomagnetic results, Terra Nova, 7, 424–435.

Weltje, G. (1992), Oligocene to early Miocene sedimentation and tectonics in the southern part of the Calabrian-Peloritani Arc (Aspromonte, southern Italy): A record of mixed-mode piggy-back basin evolution, Basin Res., 4, 37–68.

Figures

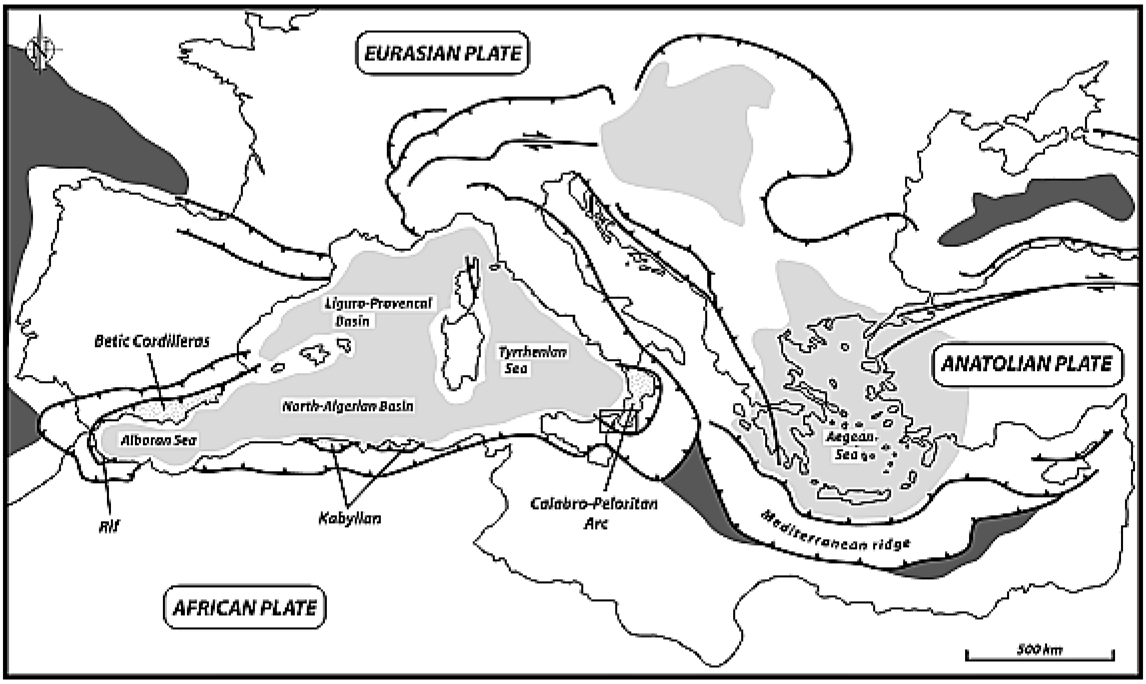


Figure 1. Simplified tectonic map of the Mediterranean region [after Jolivet et al., 1998]. Dark grey indicates the Mesozoic oceanic domain; light grey indicates the Cenozoic thinned continental crust and oceanic domains. The black box indicates location of the study area. Enhanced EPS [756 KB]

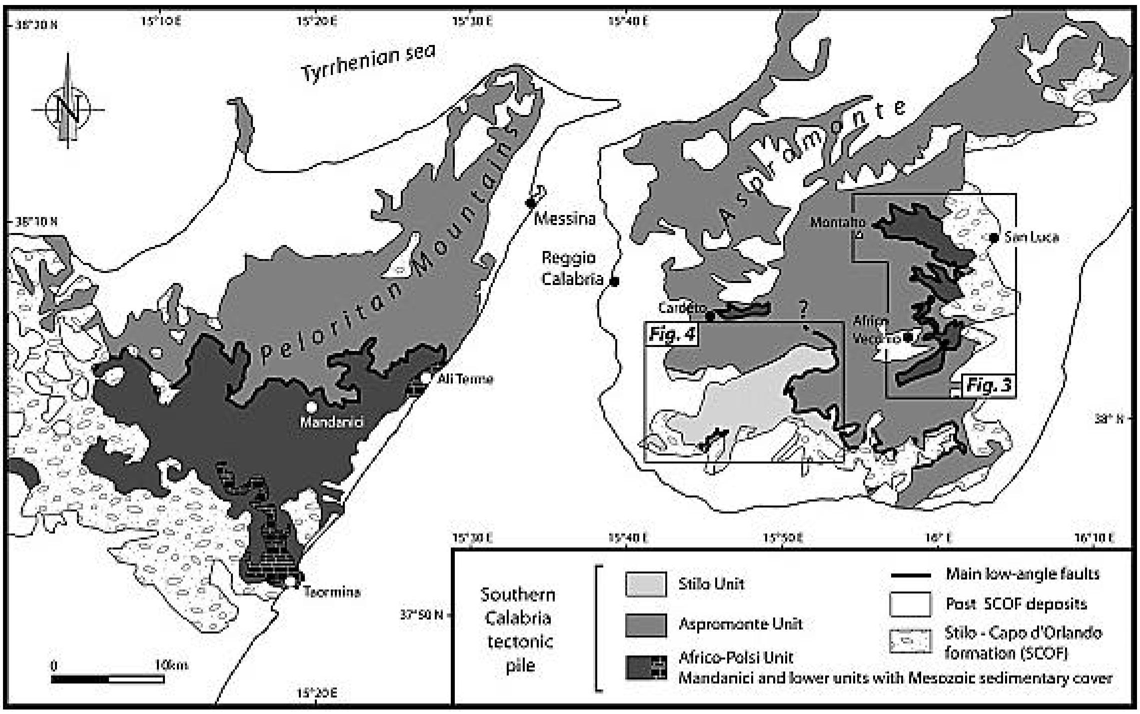


Figure 2. Sketch map of the southern sector of the Calabro-Peloritan Arc [after Pezzino and Puglisi, 1980; Bonardi et al., 1984b; Somma et al., 2005; Ortolano et al., 2005]. Grey indicates the tectonic pile sheets; white indicates the postorogenic sediments. In the

Mandanici area, some small Mesozoic cover slivers have not been reported. Enhanced TIF [415 KB]

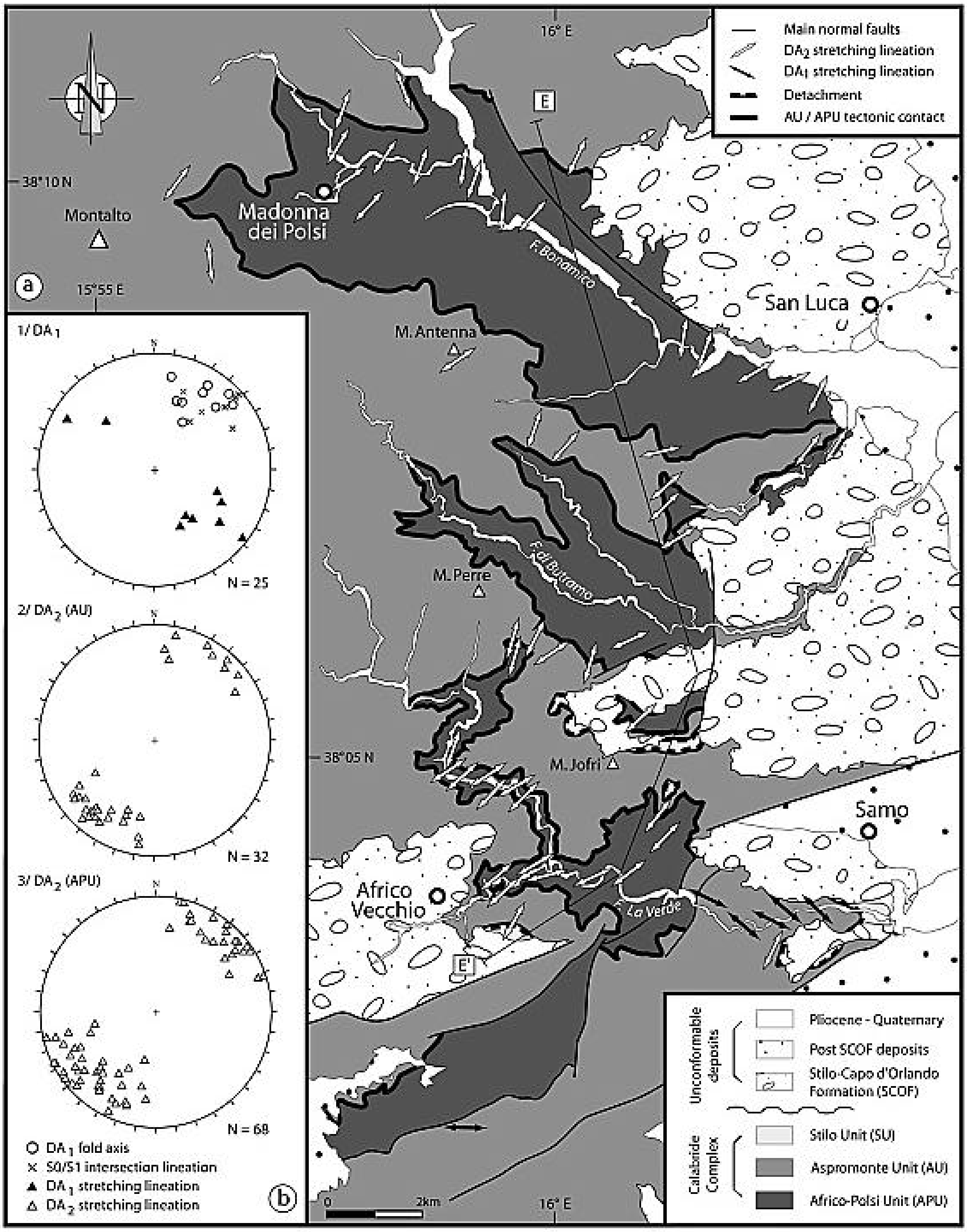


Figure 3. (a) Simplified tectonic map of the San Luca-Africo Vecchio area (modified and readapted after Pezzino and Puglisi [1980], Bonardi et al. [1984b], Ortolano et al. [2005], and new observations). (b) Stereoplots of the kinematic indicators for DA_1 and DA_2 events in the Aspromonte Unit (AU) and in the Africo-Polsi Unit (APU) (Wulff net, lower hemisphere). For EE' cross section, see Figure 9. Enhanced TIF [525 KB]

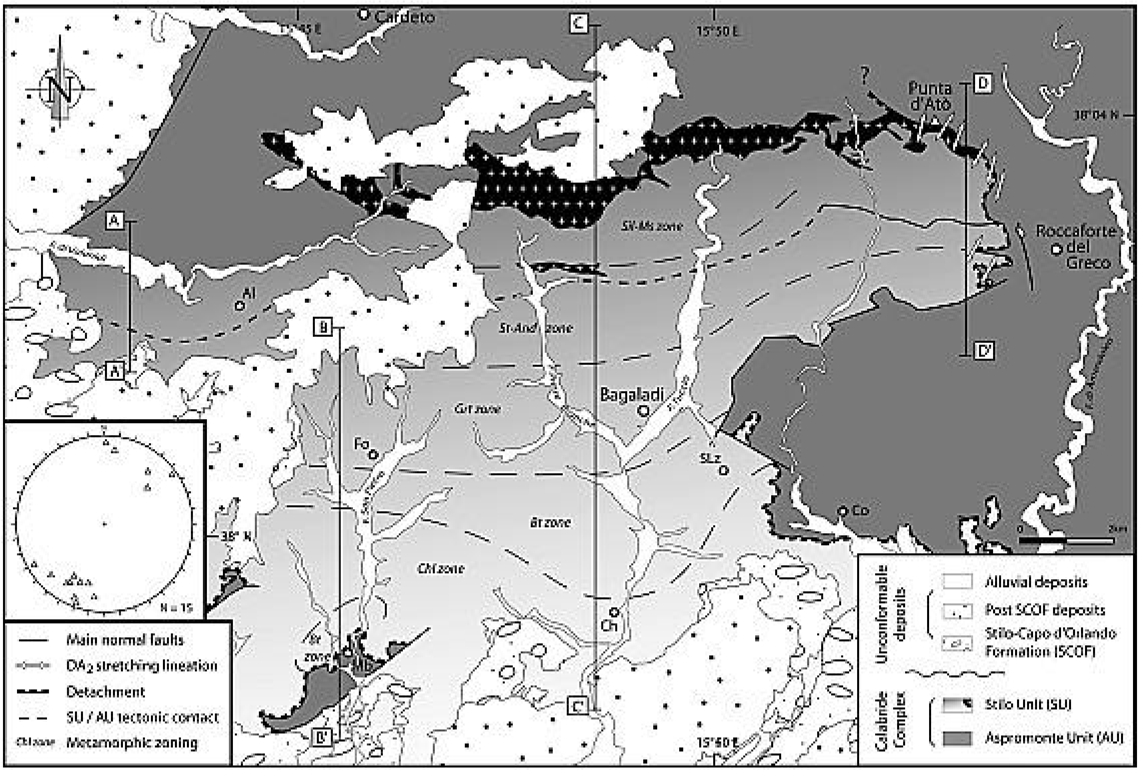


Figure 4. Simplified tectonic map of the central Aspromonte Massif (modified and readapted Bonardi et al. [1984b], Graessner and Schenk [1999], and new observations). The Punta d'Atò granite (in black with white crosses) is located in the Stilo Unit. Grey shades illustrate the metamorphic zoning of the Stilo Unit in agreement with field metamorphic isogrades after Graessner and Schenk [1999]. The Stilo Unit/Aspromonte Unit contact shown by a dotted thick curve is from Bonardi et al. [1984b]. Stereoplot represents the stretching lineations measured in the main shear bands near the detachment surface (Wulff net, lower hemisphere). AA', BB', CC', and DD' lines correspond to cross sections reported in Figure 6. Al, Allai; Ch, Choriò; Co, Condofuri; Fo, Fossato; Mb, Montebello Ionico; Slz, San Lorenzo; And, andalousite; Bt, biotite; Chl, chlorite; Grt, garnet; Ms, muscovite; Sil, sillimanite; St, staurolite. Enhanced TIF [477 KB]

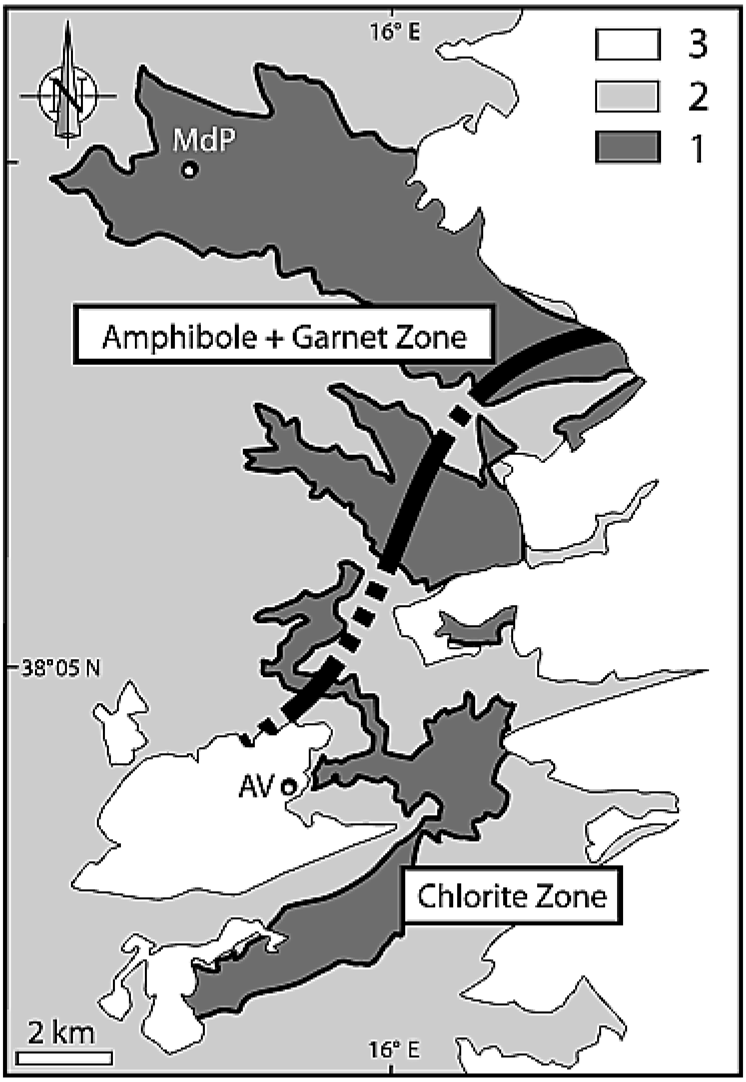


Figure 5. Schematic illustration of the probably Hercynian metamorphic zoning of the Africo-Polsi Unit, below the Aspromonte Unit nappe contact. The rough limit between the amphibole plus garnet-bearing paragenesis zone to the north and the chlorite-bearing paragenesis zone to the south is marked by the thick NE-SW curve. (1) Africo-Polsi Unit separated from (2) Aspromonte Unit by a nappe contact and both covered by (3) unconformable sediments. MdP, Madonna dei Polsi; AV, Africo Vecchio. Enhanced EPS [594 KB]

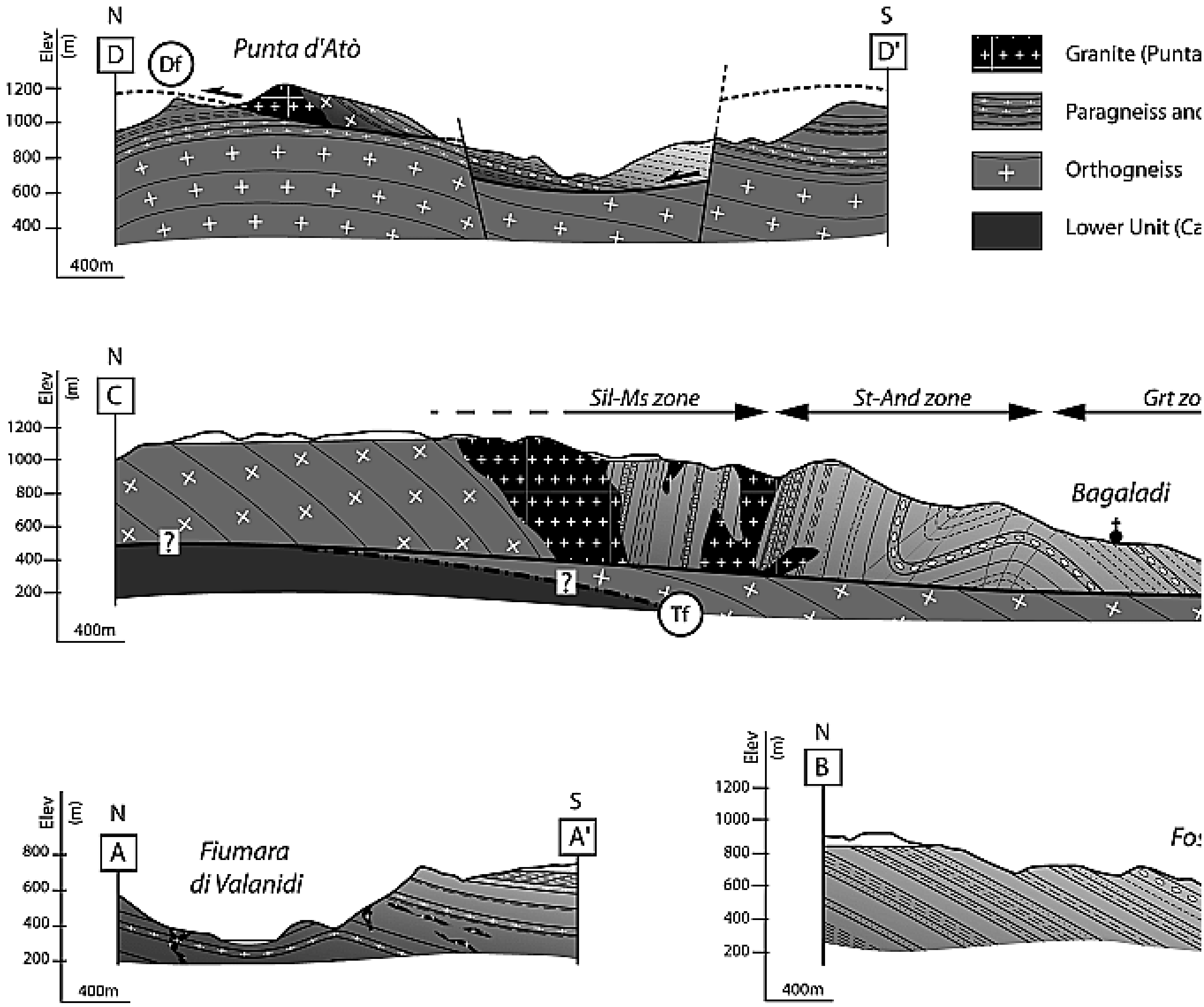


Figure 6. Geological cross sections of the central Aspromonte Massif (see location on [Figure 4]). The tectonometamorphic pile made by the Aspromonte and the Stilo units is cut by the upper detachment fault (Df). Metamorphic zoning reported on section CC' after [Graessner and Schenk [1999]]. Structure of the Aspromonte Unit is simplified, and because of its local thinness, the Stilo-Capo d'Orlando Formation is not always represented. Enhanced EPS [976 KB]

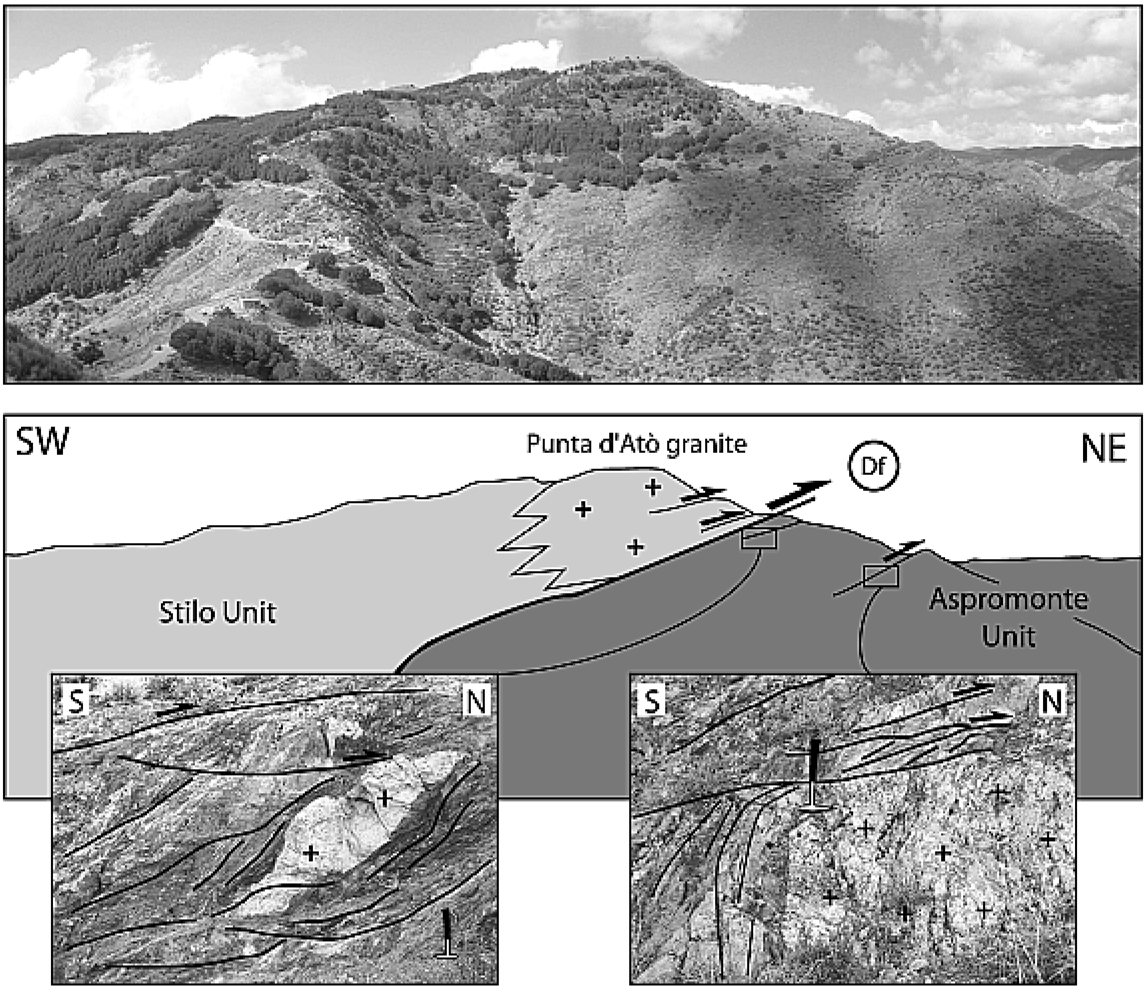


Figure 7. View and interpretative drawing of the Punta d'Atò area. The photographs illustrate two examples of meter-scale structures observed in the shear zones, both indicating a top-to-the-north or NE motion. Hammer gives scale. Enhanced EPS [3.2 MB]

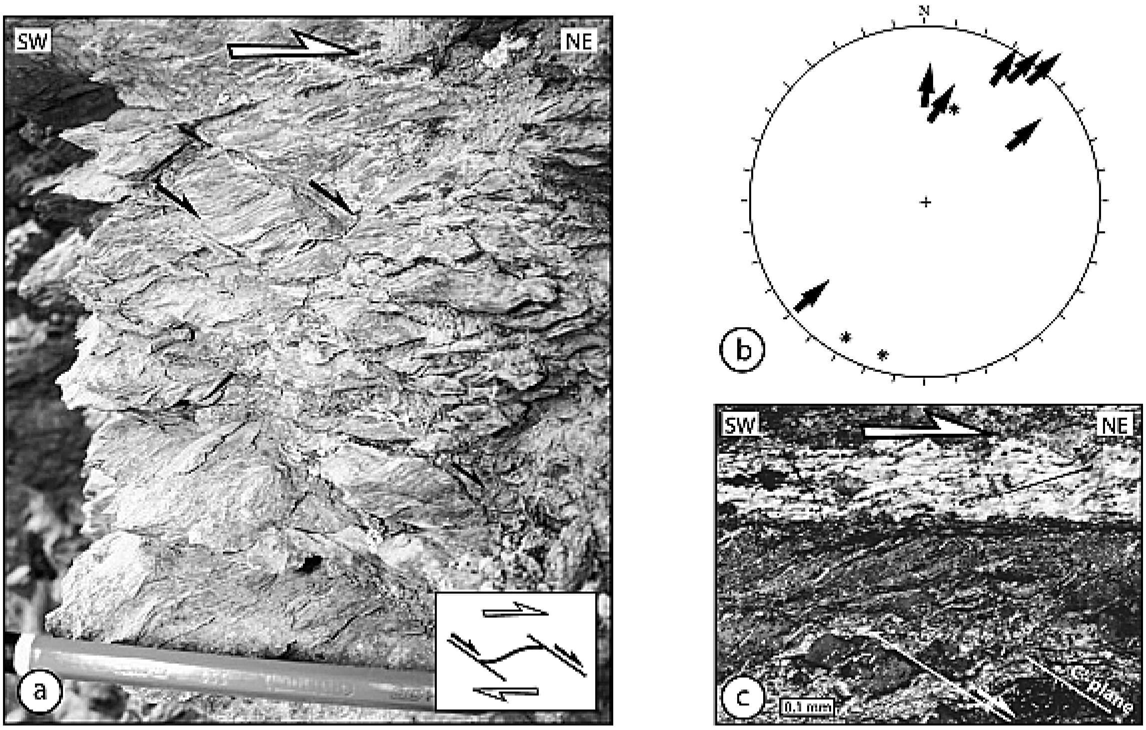


Figure 8. Mesostructural and microstructural kinematic indicators for the shearing direction in “cold” mylonites during the DA_2 event. (a) S-C' structures in the Africo-Polsi Unit just below the contact with the Aspromonte Unit. (b) Stereoplot of the transport direction derived from S-C'structures from the Africo-Polsi Unit below the lower contact (Wulff net, lower hemisphere). The hanging wall movement is shown by the arrows. Stars are postmetamorphic “a”-type fold axes roughly parallel to the transport direction. (c) Microstructures observed in “cold” mylonites from the main shear band in the Africo-Polsi Unit/Aspromonte Unit contact. Enhanced EPS [1.5 MB]

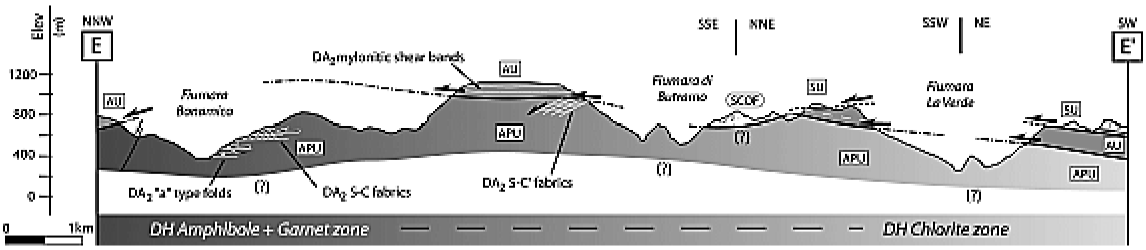


Figure 9. Simplified geological cross section showing DA_2 top-to-the-NE shearing phase in the area between San Luca and Africo Vecchio. Location is shown in Figure 3. The grey shades of the box on the bottom represents the DH Hercynian metamorphic zoning of the Africo-Polsi Unit. APU, Africo-Polsi Unit; AU, Aspromonte Unit; SU, Stilo Unit; SCOF, Stilo-Capo d'Orlando Formation. Enhanced EPS [720 KB]

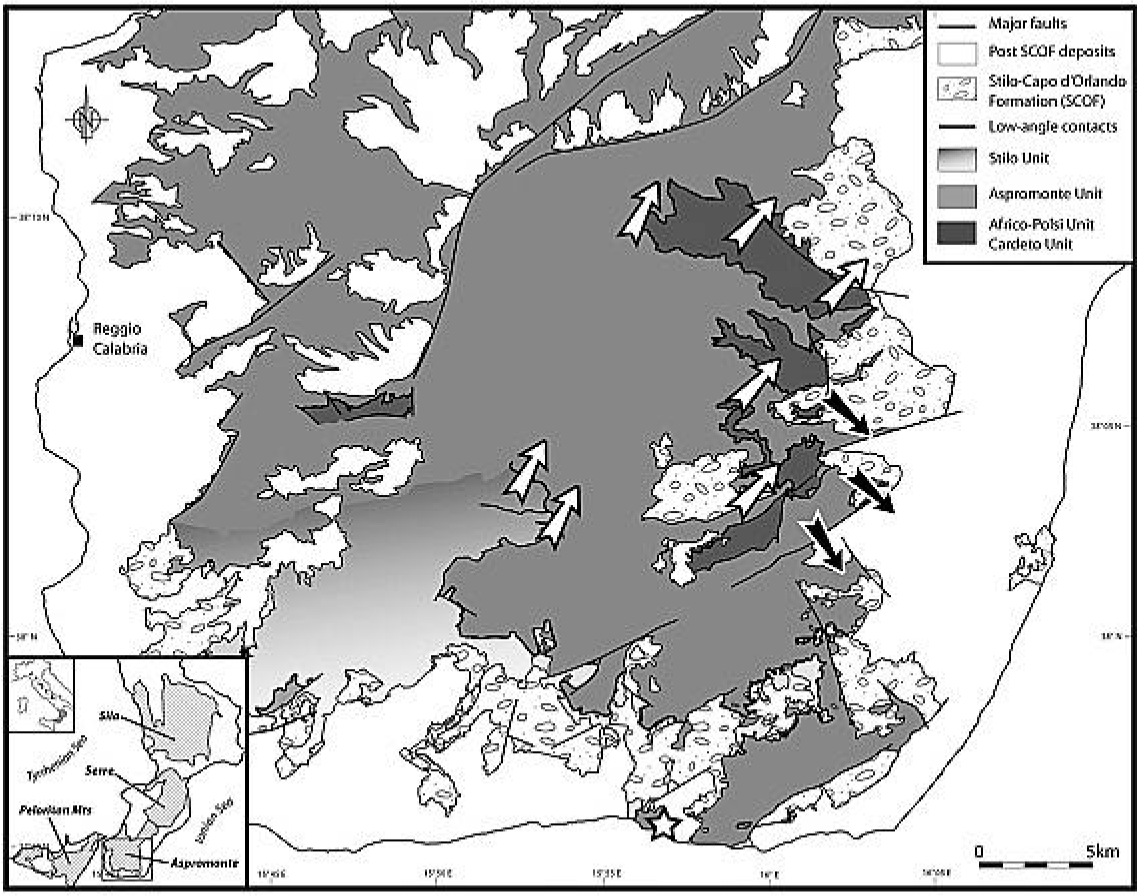
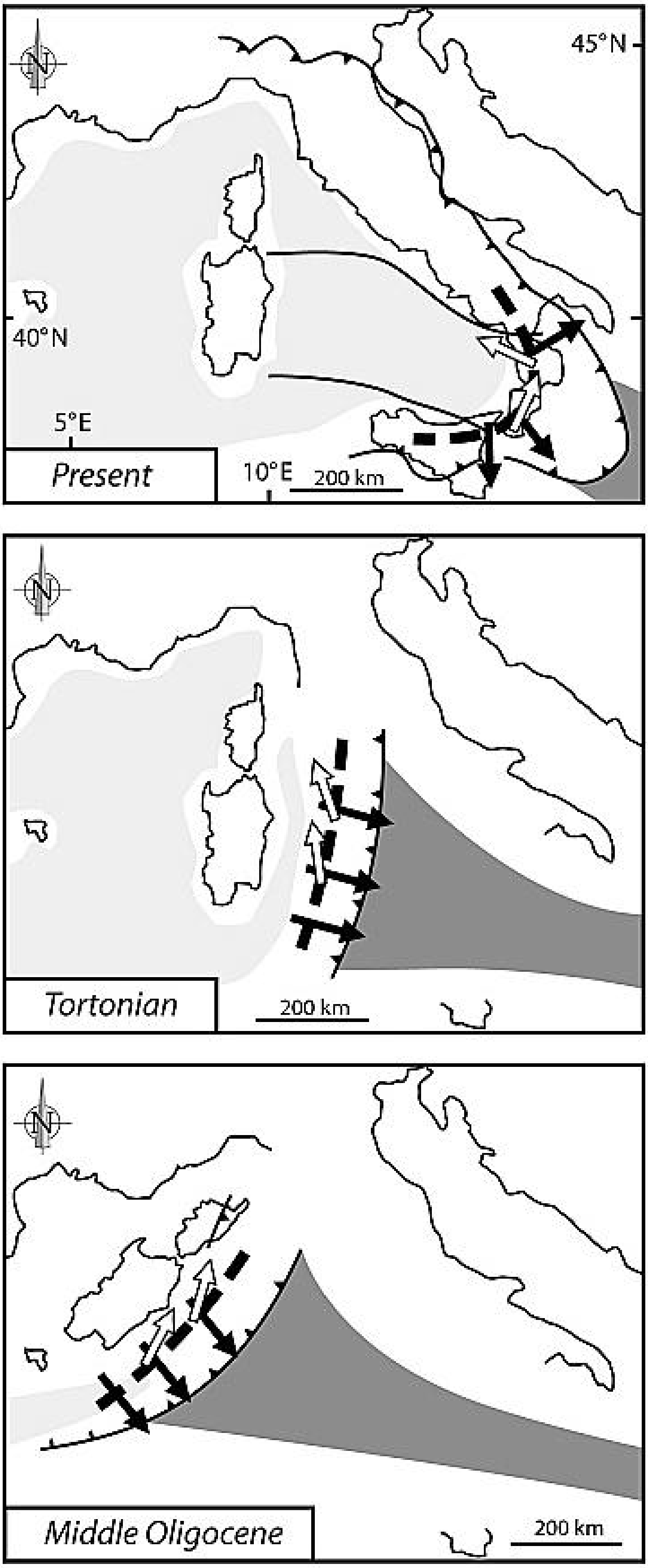


Figure 10. Average transport direction for the DA_1 top-to-the-SE thickening (black arrows) and the DA_2 top-to-the-NE thinning (white arrows) events from the Aspromonte. White star indicates the location of sample BOV-30 after Thomson [1994]. See text for further explanations. Enhanced TIF [456 KB]



45° N
40° N
5°E
Present
10°E
200 km
Tortonian
200 km
Middle Oligocene
200 km

Figure 11. Schematic reconstruction of the orientation of the two Alpine stacking/unstacking transport direction described in the Calabro-Peloritan Arc from present to initial (middle Oligocene) positions. Restoration of the Calabro-Peloritan belt position at Tortonian is after Rosenbaum and Lister [2004]. Restoration of the position of the Calabro-Corsica-Sardinian blocks at middle Oligocene is after Lonergan and White [1997], Gelabert et al. [2002], and Michard [2006]. Enhanced TIF [137 KB]