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

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Abstract

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 directed North-South 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 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. (i) 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 towards 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 Mesozoïc sediments. In the Aspromonte Massif, thrusting age is less constrained. Our data suggest remnants of late Hercynian structuration before the Alpine stacking. (ii) 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: 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 eastward retreat of the Apennine trench since Oligocene times.

1 – Introduction

The Western Mediterranean and the surrounding belts (Fig. 1) constitute the western part of the orogenic system formed during the convergence between the Eurasian and the African plates, roughly directed North-South 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 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 compressive and extensive 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].

Due to 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 syn-orogenic extensional structures were recently recognized in the Calabro-Peloritan Arc: in the western 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 extensive contacts [*Platt and Compagnoni*, 1990]. In the same area, we recognized a large extensive 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.

The aims of this work are the following: (i) to define the geometry of the tectonic contacts, mainly the extensive ones, and their evolution from upper to middle crust conditions, (ii) 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.

2 - Geological setting

The Southern Calabria (South Italy) and the adjoining Peloritan Mountains (Northeastern Sicily) (Fig. 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.

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] (Fig. 2). Accordingly, these structures are older than the Calabro-Peloritan Arc's bending, related to the opening of the Tyrrhenian basin since Tortonian [e.g. *Kastens et al.,* 1987].

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. 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, an 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, syn-orogenic extensional deformation is evident within the ophiolitic complex [*Rossetti, et al.*, 2001; *Rossetti, et al.*, 2004].

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 (Fig 2), the Calabride Complex is subdivided into two main parts: a basement sheet, overthrusted on 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.* [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), the Aspromonte Unit and the Stilo Unit, separated from each other by two low-angle tectonic contacts (Fig. 2).

2.1 - The Africo-Polsi Unit (APU)

The lower tectonic unit consists mainly of metasedimentary and metavolcanic rocks. Its upper part is best exposed in the Fiumara La Verde (Fig. 3a). East of Africo Vecchio, the following sequence can be observed (from bottom to top): decimetre-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 dykes, most probably feeding metabasalts up to 30 m thick, overlain by volcaniclastic 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 Silurian to Lower Carboniferous [*Bouillin*, 1987 and references there in]. No rocks ascribable to a Mesozoic series have been noticed.

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] and *Pezzino et al.* [1992] (Fig. 3a). This last unit consists almost exclusively of metasedimentary and metavolcanoclastic rocks which sharply contrast with the gneisses of the overlying Aspromonte Unit (see below). South of San Luca (Fig 3a), the series is composed of chloriteschists and carbonates very similar to those exposed in the Fiumara La Verde (Fig 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 break up 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 exposed also farther to the west in a small tectonic window near Cardeto (Fig. 2), where very similar metamorphic rocks in the same structural position are observed, as already described by *Bonardi et al.* [1980a].

2.2 - The Aspromonte Unit (AU)

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].

The Aspromonte Unit was intruded by kilometre-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 dykes 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 – The Stilo Unit (SU)

The upper part of the tectonic pile (Fig. 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 perpendicularly to the metamorphic foliation, is up to 7 km (Fig. 7). 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 up 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 downwards, i.e. from south to north on the map (Fig. 4), from the chlorite to the sillimanite-muscovite zone [*Graessner and Schenk*, 1999]. As it do 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 - The Oligocene Stilo - Capo d'Orlando Formation (SCOF)

The Aspromonte nappes-pile is covered by the Stilo - Capo d'Orlando Formation [*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 (Fig. 2). It is a detrital sequence made of breccias and conglomerates at the base, covered by coarse-grained sandstones, passing upwards 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 by pebbles of various size (from decimetre to metre scale, but locally even more) and nature, typically high-grade metamorphics and granitoids probably derived from the Aspromonte Unit, and by low-grade phyllite 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 (Fig. 3a), is discordant on the contact between the Aspromonte and the Africo-Polsi units. As we describe below, 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.

Concerning the age of the Stilo – Capo d'Orlando Formation, most of studies indicate a depositional age comprised between upper Rupelian and Lower Burdigalian [see *Weltje*, 1992 and reference there in]. This chronological limit brings a major constraint to date the kinematic evolution of the Aspromonte nappes-pile.

3 - The tectonic pile architecture

3.1 – Evidences for a Late-Hercynian shortening phase (DH)

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 (Fig. 5), from biotite and garnet zone to the NW to chlorite zone to the SE (prograde chlorite, and lack of higher grade metamorphism relics). Except this apparent metamorphic zoning, it is rather difficult to identify large-scale syn-metamorphic structures essential to better constraint the kinematics of this local Hercynian deformation. Rb-Sr ages, which range from 331 Ma to 22 Ma [*Bonardi, et al.* 1987] are mixed ages. Our recent investigations from $^{40}Ar/^{39}Ar$ technique [*Heymes et al*, work in progress] indicate a similar pre-Alpine age for this metamorphic event but do not allow to precise 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 late peraluminous Punta d'Atò granite [*Graessner et al.*, 2000] (see Fig. 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 to a shortening deformation marked by a main metamorphic foliation and by a late E-W trending folding stage (Fig. 4 and 6). The unconformable Mesozoic cover limited at the southeastern part of the Stilo Unit is not implied in these 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)

In the area between San Luca and Africo Vecchio (Fig. 3a), the higher grade metamorphics of the Aspromonte Unit, the large orthogneiss bodies included, overlie the lower grade metasediments of the Africo-Polsi Unit [*Burton, et al.*, 1971; *Pezzino, et al.*, 1990; *Pezzino, et al.*, 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-S 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 towards the south [*Truillet*, 1962; *Cirrincione and Pezzino*, 1993] (see Fig 2).

In the Aspromonte Massif, such stratigraphic constraints are not available to date the nappe emplacement. Nowhere 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 be at least in part Alpine too, with a similar southwards vergence.

Mixed ages presented above [*Bonardi et al.*, 1987] indicate a post-Hercynian (i.e. Alpine) partial metamorphic re-equilibration 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 parageneses [*Bonardi et al.*, 1984a; *Platt and Compagnoni*, 1990; *Messina et al.*, 1992; *Bonardi et al.*, 1992]. According to these authors, it indicates MP 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.

However, it is difficult to fix unambiguously timing and kinematics of the nappe emplacement from structural and metamorphic data. Due to the superposition of these two Hercynian and Alpine metamorphisms, interpretation and timing of both microstructural markers and regional structures remains 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 post-metamorphic 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: (i) In the upper Paleozoic series of the Africo Vecchio area along the Fiumara La Verde, dissymmetrical folds (Fig. 3b, stereoplot 1) indicate a top-to-the-SE rotational deformation in the footwall of the nappe. (ii) In addition, at the base of the Aspromonte Unit (Fig. 3a and 3b – stereoplot 1), in domains escaped to the DA_2 mylonitization described below, the stretching lineation also underlines a NW-SE shearing in the hanging wall.

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 sense (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-E 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 Fig. 11).

3.3 - Extensional reworking (DA_2)

3.3.1 – Structural data

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] (Fig. 4). On the contrary, according to *Bouillin et al.* [in prep], it is a large detachment fault, which can be best observed in its southernmost part, where the non-metamorphic 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.

Farther to the north (Fig. 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 be identified. North of Bagaladi, the contact defined by previous authors does not appear to be a real tectonic boundary (Fig 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 (Fig. 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 south and north sides (Fig. 6 - section CC'). In a similar way, farther to the west, the fault drawn along the Fiumara 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 (Fig. 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 (Fig. 4), the detachment surface has been identified: it appears to split into several meter thick low angle shear zones (Fig. 6 - section DD' and Fig. 7).

Thus, the clear lithological 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 hangingwall 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 part, 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.

In the southern sector, the deformation is mainly cataclastic and the breccia associated to 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 (fig 4, stereoplot) while a top-to-the-N sense of movement is given by S-C type almonds, asymmetric boudinage and rare drag folds (Fig. 8).

DA_2 structures are not only localized 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 rather low temperature blastomylonites [*Passchier and Trouw*, 1996], best expressed when they cut or follow former quartz-rich pegmatite veins (Fig. 7c). 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 trend NNE-SSW (Fig. 3a and 3b, stereoplots 2 and 3), while asymmetric S-C and S-C' fabrics indicate a top-to-the-NE sense of displacement (Fig 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 (Fig. 8 and 9). Lower down in the Africo-Polsi Unit, still the same sense of displacement is indicated by both the late metamorphic stretching and mineral lineation and post-metamorphic "a" type folds (Fig. 8 and 9). It strongly suggests that they are due to the same DA_2 deformation.

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 low-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.

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 indicate 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

Both stratigraphical and thermochronological data can help to date the detachment. The extensional tectonics is bracketed by: i) the age of the youngest Lower Oligocene sediments [*Bouillin et al.*, 1985] transported above the detachment surface with the Stilo Unit, and ii) 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 age of 32.8 +/- 1.4 Ma (sample BOV-30 in *Thomson* [1994] – see location on Fig. 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 flat shear-zones [*Bonardi et al.*, 1987] provide ages ranging between 25 Ma and 30 Ma. It is difficult to estimate from these published data an exhumation rate, 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 $^{40}Ar/^{39}Ar$ ages from muscovites from the contact zone between the Aspromonte and the Africo-Polsi units [*Heymes et al.*, work in progress], also implies a fast cooling at this period which is best explained by tectonic thinning. Thus, even if additional cooling ages are needed in order to precise the timing of the extensional tectonics, both available geochronological and sedimentary constraints lead to a Middle Oligocene age for the northeastwards spreading of orogenic edifice of the Aspromonte Massif.

4 – Discussion

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 eastward 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. (i) 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]; (ii) 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 (iii) coeval rollback of the Ionian subduction since 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 Present back to Tortonian [*Rosenbaum and Lister*, 2004], and the thickening and thinning transport directions in the Calabro-Peloritan Arc during the main steps of this history (Fig. 11).

(1) Thickening phase - 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 fig. 2 in *Somma et al.* [2005]). In addition, the bulk geometry of the nappes implies a general top-to-the-S 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 southwards, but still perpendicular to the belt trend. Considering now the geometry of the belt at 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-E. Before the opening of the Liguro-Provençal basin, it would correspond to a top-to-the-SE displacement (Fig. 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].

(2) Thinning phase - In 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-N 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 [*Rossetti, et al.*, 2004]. 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 all Calabro-Peloritan belt (Fig. 11). The extension probably occurred just later to 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

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-S) 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 main steps structuring, during (i) a post-Hercynian crustal thickening event (DA_1) with an external (top-to-the-SE) vergence. And (ii) a Middle Oligocene spreading event (DA_2), with an internal (top-to-the-NE) vergence, stretching apart the previously structured nappe edifice (Fig. 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. towards 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 NS-directed.

Acknowledgements

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Figures captions

Figure 1 - Simplified tectonic map of the Mediterranean region (modified after *Jolivet et al.* [1998]). In dark grey, the Mesozoic oceanic domain; in light grey, the Cenozoic thinned continental crust and oceanic domains. The studied area is localized with the black box.

Figure 2 - Sketch-map of the southern sector of the Calabro-Peloritan Arc. From *Pezzino and Puglisi* [1980], *Bonardi et al.* [1984b], *Somma et al.* [2005], *Ortolano et al.* [2005]. In grey, the tectonic pile sheets. In white, the post-orogenic sediments. In the Mandinici area, some small Mesozoic cover slivers have not been reported.

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). EE' cross-section: see Figure 9.

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. Gray 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 line 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. Additional localities: Al: Allai; Fo: Fossato; Ch: Choriò; Co: Condofuri; Mb: Montebello Ionico; Slz: San Lorenzo.

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 biotite + garnet bearing paragenesis zone to the north and the chlorite bearing paragenesis zone to the south is marked by the thick NE-SW line. (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. The tectonometamorphic pile made by the Aspromonte and the Stilo units is cut by the upper detachment fault (Df). Structure of the Aspromonte Unit is simplified and, due to its local thinness, the Stilo – Capo d'Orlando Formation is not always represented.

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

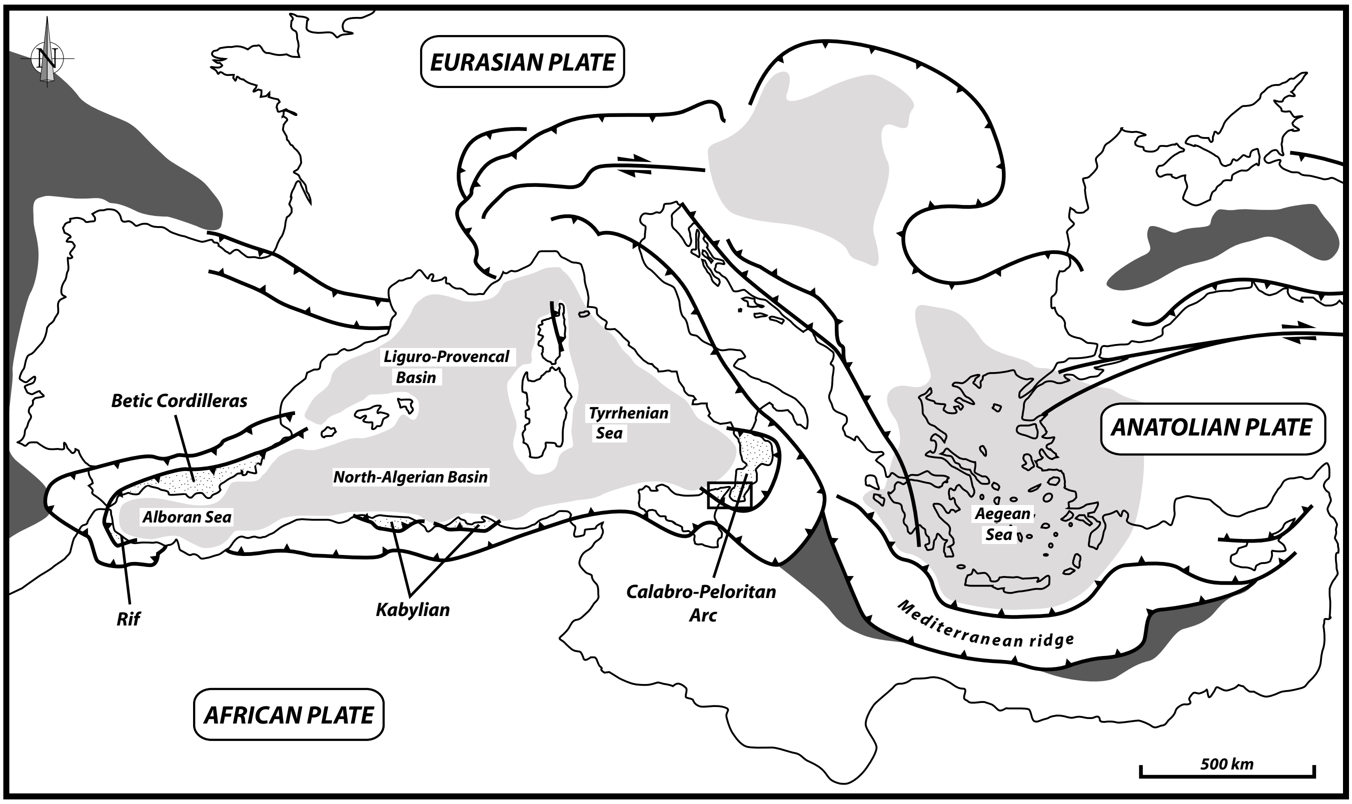
Figure 8 - Meso- and microstructural kinematic indicators for the shearing direction in "cold" mylonites during the DA_2 event. (a) S-C' structures in the Africo-Polsi Unit just below the contact with the Aspromonte Unit. (b) Stereoplot of the transport direction derived from S-

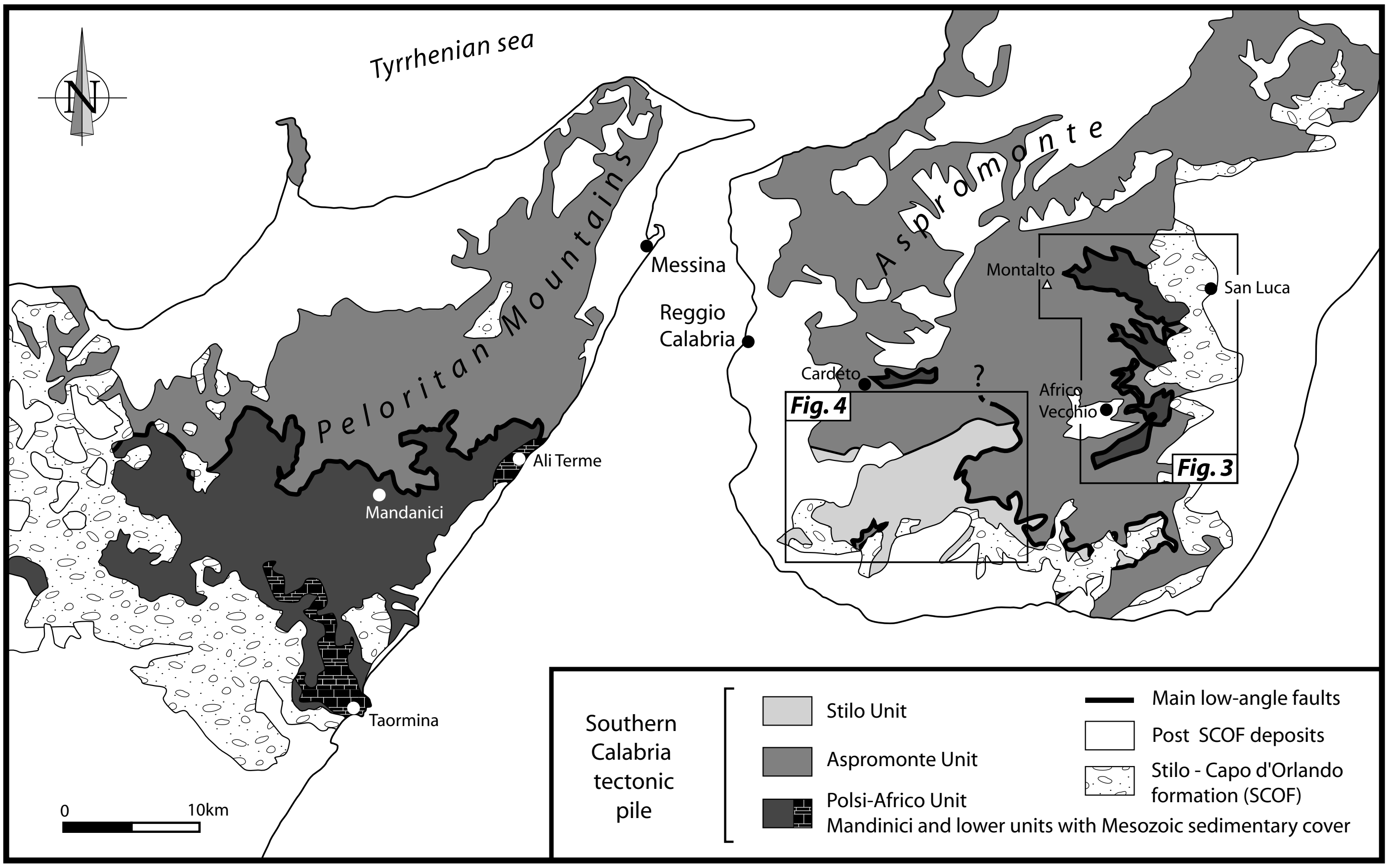
C'structures from the Africo-Polsi Unit below the lower contact (Wulff net, lower hemisphere). The hanging wall movement is shown by the arrows. Stars: postmetamorphic "a" type fold axes roughly parallel to the transport direction. (c) Microstructures observed in "cold" mylonites from the main shear band in the Africo-Polsi Unit / Aspromonte Unit contact.

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 and caption in Figure 3. The gray-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.

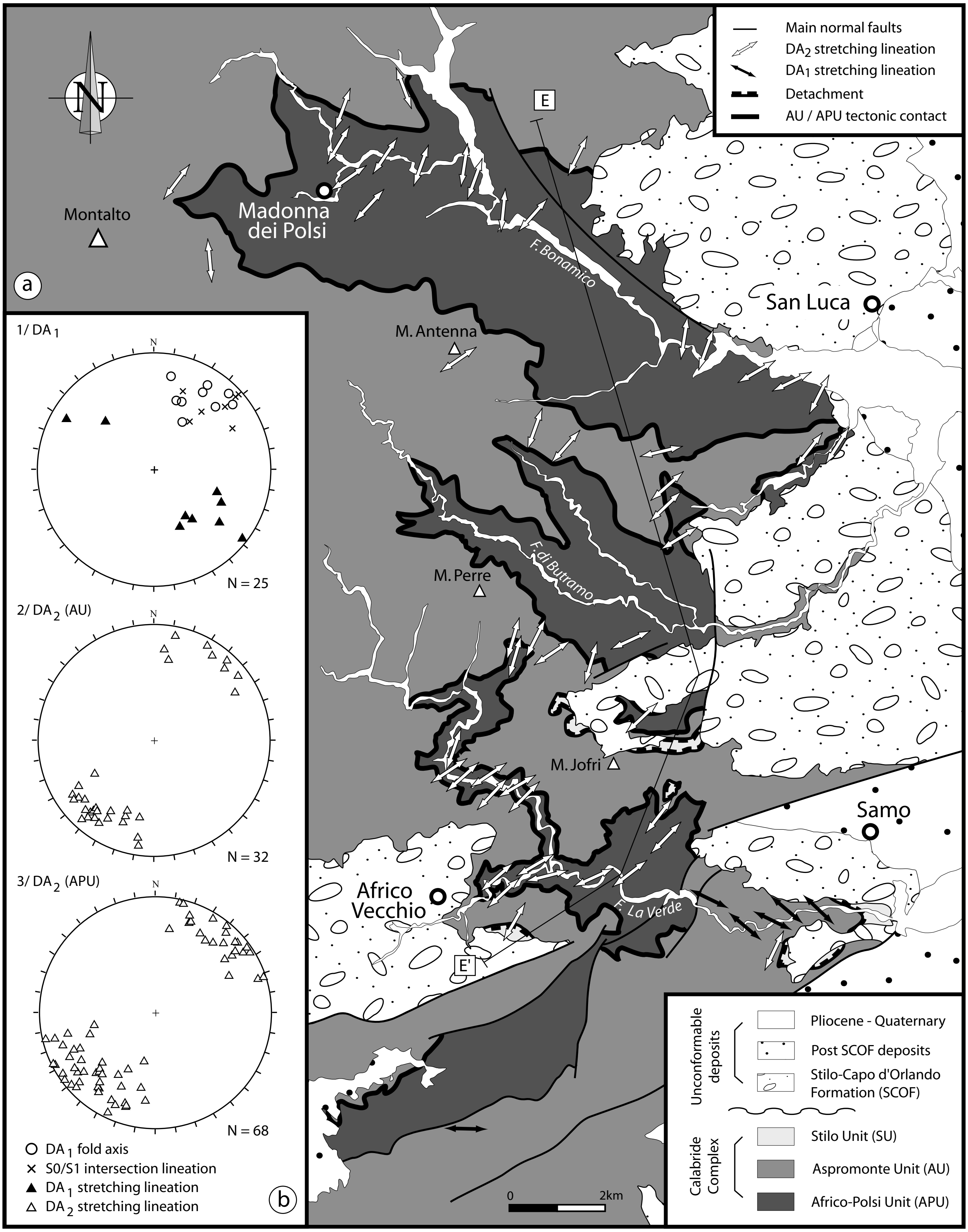
Figure 10 - Average transport direction for the DA_1 top-to-the-SE thickening (black arrows) and the DA_2 top-to-the-NE thinning (white arrows) events from the Aspromonte. White star indicates the location of sample BOV-30 [*Thomson*, 1994]. See text for further explanations.

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 after *Rosenbaum and Lister* [2004]. Restoration of the position of the Calabro-Corsica-Sardinian blocks at Middle Oligocene after *Lonergan and White* [1997], *Gelabert et al.,* [2002] and *Michard* [2006].

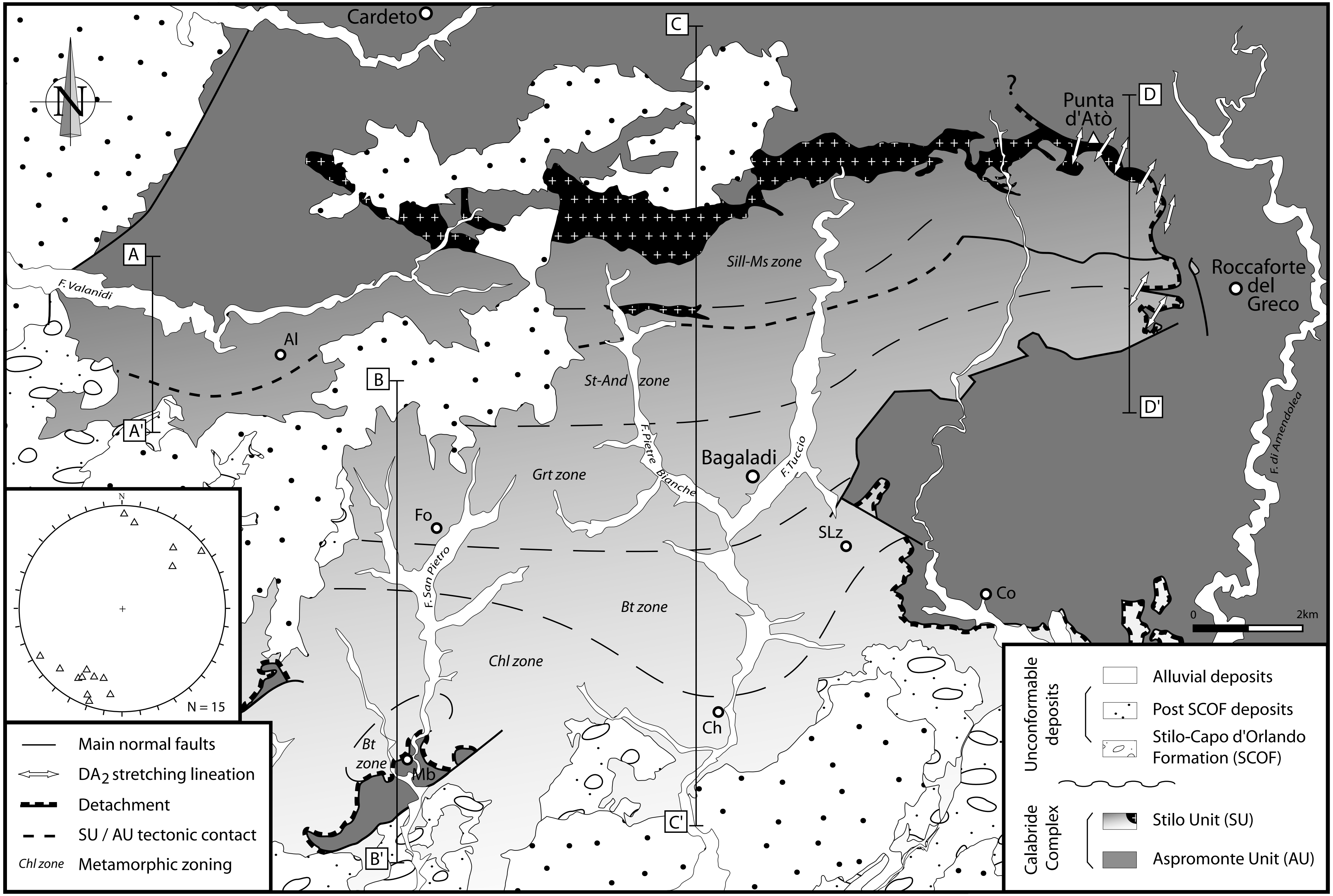

EURASIAN PLATE
ANATOLIAN PLATE
AFRICAN PLATE
Liguro-Provencal Basin
Betic Cordilleras
Tyrrhenian Sea
North-Algerian Basin
Alboran Sea
Aegean Sea
Rif
Kabylian
Calabro-Peloritan Arc
Mediterranean ridge
500 km
N

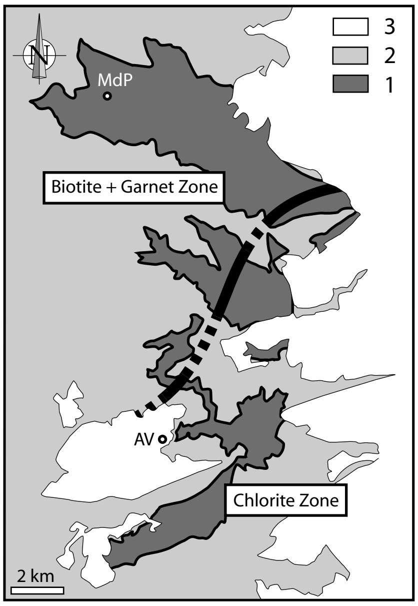


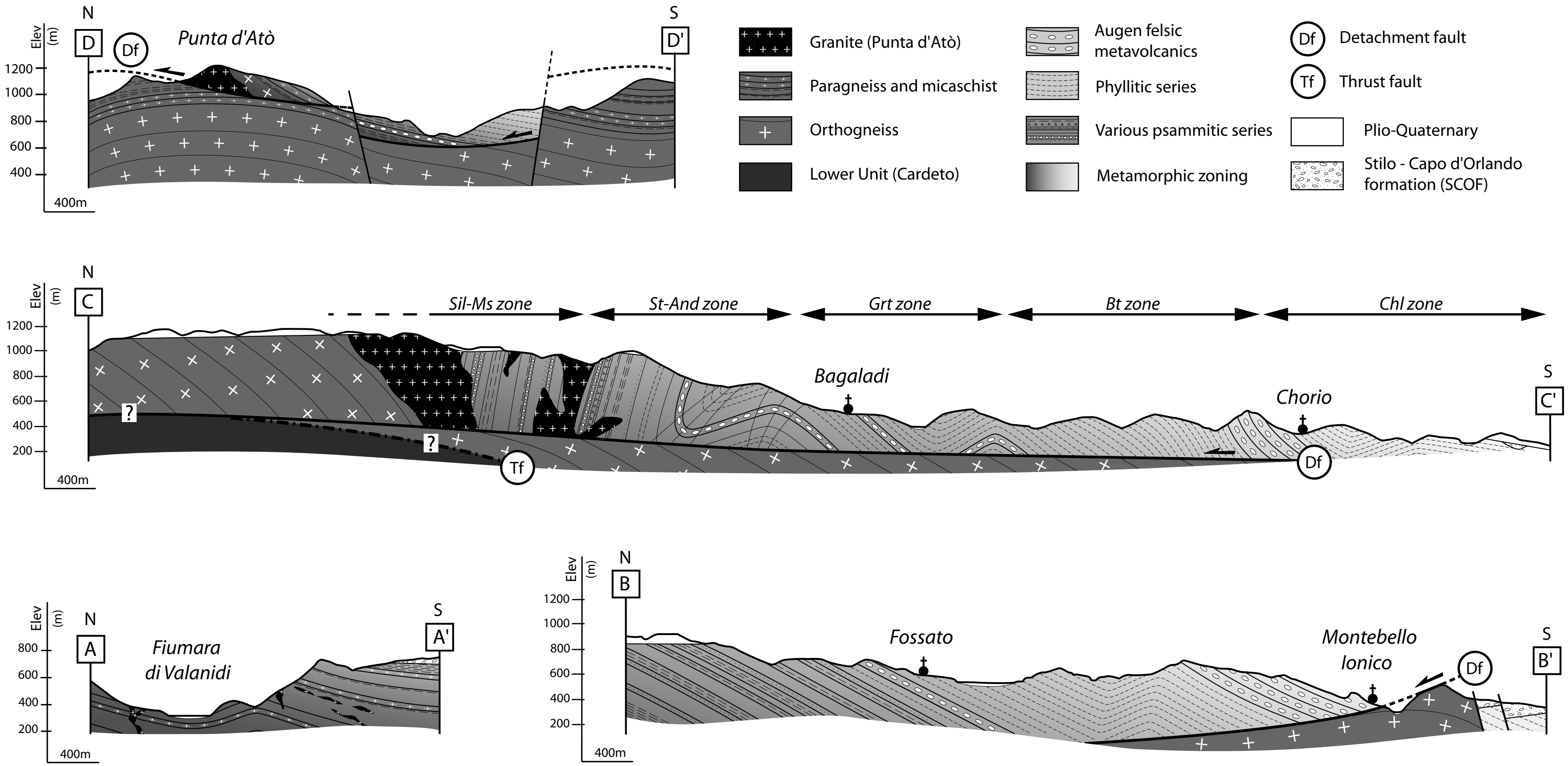
N
Tyrrhenian sea
Peloritan Mountains
Aspromonte
Messina
Reggio Calabria
Ali Terme
Mandanici
Taormina
Cardeto
Montalto
San Luca
Africo Vecchio
Fig. 4
Fig. 3
?
0
10km
Southern Calabria tectonic pile
Stilo Unit
Aspromonte Unit
Polsi-Africo Unit
Mandinici and lower units with Mesozoic sedimentary cover
Main low-angle faults
Post SCOF deposits
Stilo - Capo d'Orlando formation (SCOF)



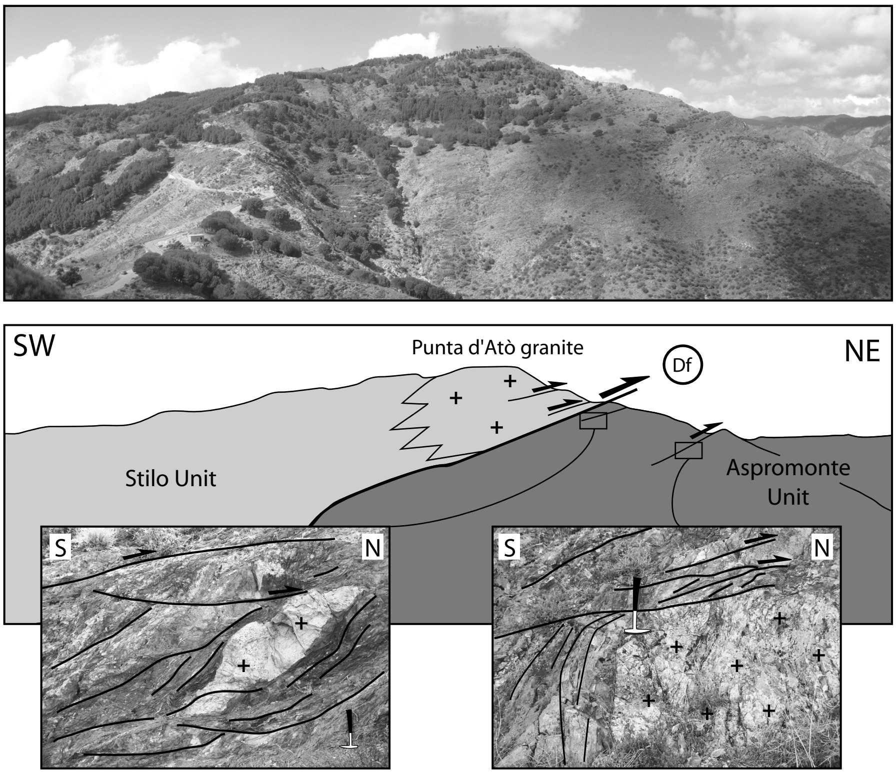
Main normal faults
DA2 stretching lineation
DA1 stretching lineation
Detachment
AU / APU tectonic contact
E
Montalto
Madonna dei Polsi
F. Bonamico
San Luca
M. Antenna
F. di Butramo
M. Perre
M. Jofri
Samo
Africo Vecchio
F. La Verde
E'
a
1/ DA1
N = 25
2/ DA2 (AU)
N = 32
3/ DA2 (APU)
N = 68
DA1 fold axis
S0/S1 intersection lineation
DA1 stretching lineation
DA2 stretching lineation
b
0
2km
Unconformable deposits
Pliocene - Quaternary
Post SCOF deposits
Stilo-Capo d'Orlando Formation (SCOF)
Calabride Complex
Stilo Unit (SU)
Aspromonte Unit (AU)
Africo-Polsi Unit (APU)

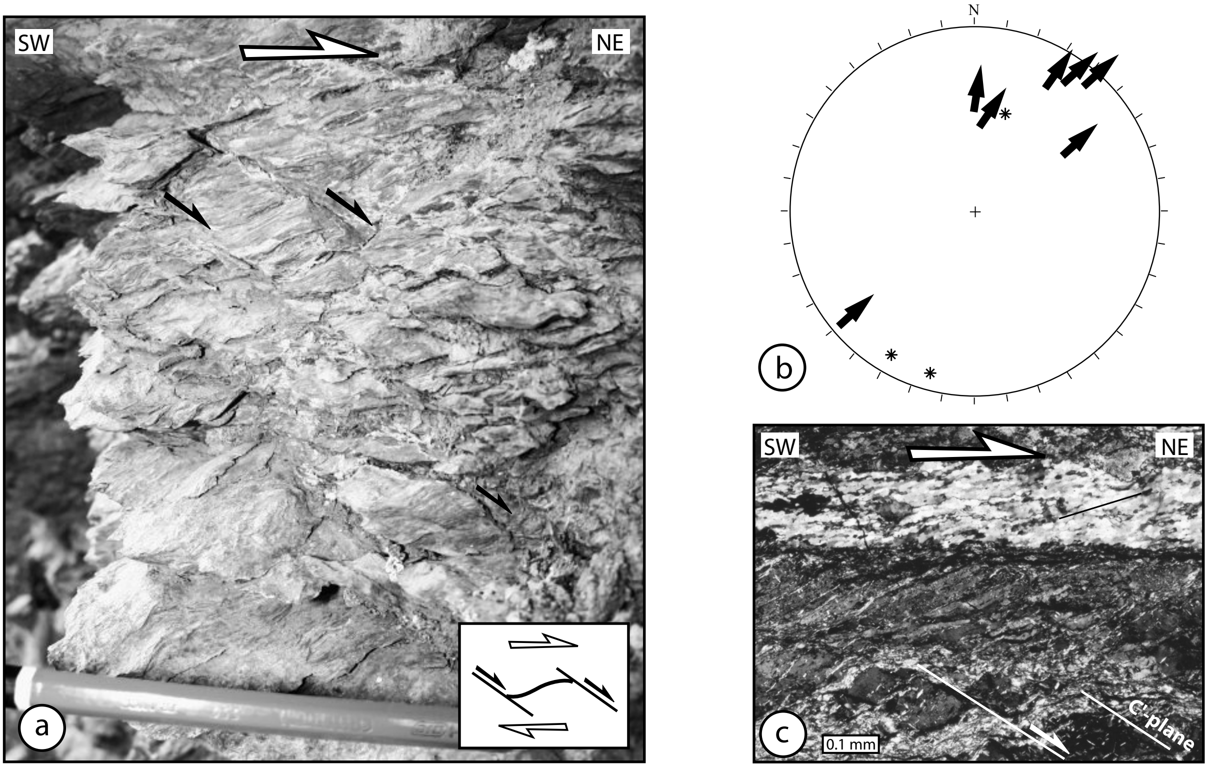

Cardeto
C
D
?
Punta d'Atò
Roccaforte del Greco
A
A'
B
B'
C'
D'
F. Valanidi
Al
Sill-Ms zone
St-And zone
Grt zone
Bt zone
Chl zone
Bt zone
F. Pietre Bianche
F. Tuccio
F. San Pietro
F. di Amendolea
Bagaladi
Fo
SLz
Co
Ch
Mb
0
2km
N
N = 15
Main normal faults
DA2 stretching lineation
Detachment
SU / AU tectonic contact
Chl zone Metamorphic zoning
Unconformable deposits
Alluvial deposits
Post SCOF deposits
Stilo-Capo d'Orlando Formation (SCOF)
Calabride Complex
Stilo Unit (SU)
Aspromonte Unit (AU)

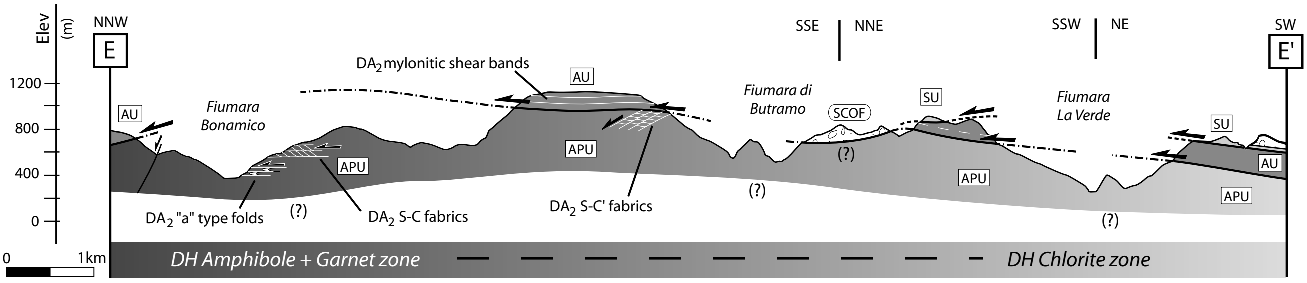

3
2
1
MdP
Biotite + Garnet Zone
AV
Chlorite Zone
2 km



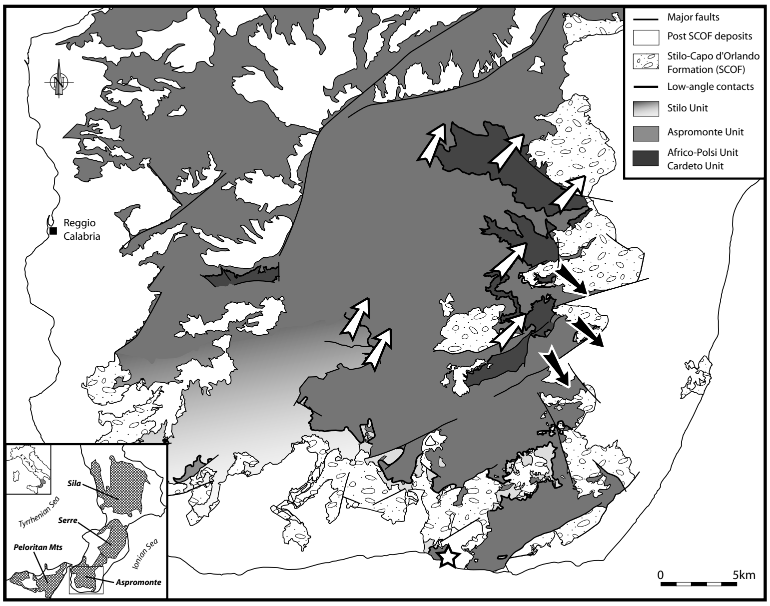
N
S
D
D'
Df
Punta d'Atò
Elev (m)
1200
1000
800
600
400
400m
Granite (Punta d'Atò)
Paragneiss and micaschist
Orthogneiss
Lower Unit (Cardeto)
Augen felsic metavolcanics
Phyllitic series
Various psammitic series
Metamorphic zoning
Detachment fault
Thrust fault
Plio-Quaternary
Stilo - Capo d'Orlando formation (SCOF)
C
C'
Sil-Ms zone
St-And zone
Grt zone
Bt zone
Chl zone
Bagaladi
Chorio
?
Tf
200
A
A'
Fiumara di Valanidi
B
B'
Fossato
Montebello Ionico

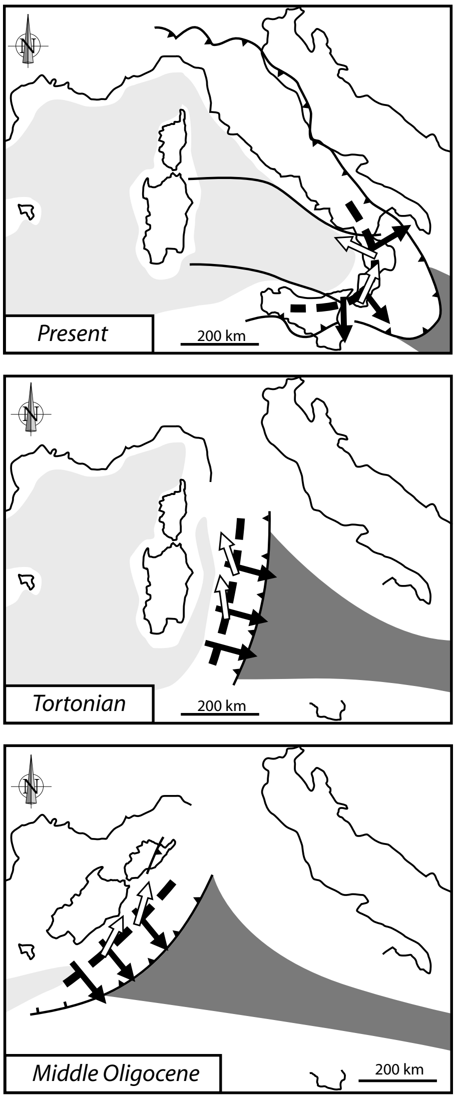

SW
Punta d'Atò granite
Df
NE
Stilo Unit
Aspromonte
Unit
S
N
S
N


SW
NE
a
N
b
SW
NE
0.1 mm
C'-plane
c



Elev (m)
1200
800
400
0
0
1km
NNW
E
SSE
NNE
SSW
NE
SW
E'
AU
Fiumara Bonamico
DA2 mylonitic shear bands
AU
APU
APU
Fiumara di Butramo
SCOF
SU
Fiumara La Verde
SU
AU
APU
APU
DA2 "a" type folds
(?)
DA2 S-C fabrics
DA2 S-C' fabrics
(?)
(?)
(?)
DH Amphibole + Garnet zone
DH Chlorite zone


Major faults
Post SCOF deposits
Stilo-Capo d'Orlando Formation (SCOF)
Low-angle contacts
Stilo Unit
Aspromonte Unit
Africo-Polsi Unit
Cardeto Unit
Reggio Calabria
ITALY
Sila
Tyrrhenian Sea
Serre
Peloritan Mts
Ionian Sea
Aspromonte
0
5km


N
Present
200 km
N
Tortonian
200 km
N
Middle Oligocene
200 km