Available online at www.sciencedirect.com
SCIENCE DIRECT®
C. R. Geoscience 337 (2005) 861–871
COMPTES RENDUS GEOSCIENCE
http://france.elsevier.com/direct/CRAS2A/

Tectonics / Tectonique

Syn-orogenic extension in the Peloritani Alpine Thrust Belt (NE Sicily, Italy): Evidence from the Alì Unit

Roberta Somma [a], Antonia Messina [a,*], Stefano Mazzoli [b]

[a] *Dipartimento di Scienze della Terra, Università degli Studi di Messina, Sant'Agata, 98166 Messina, Italy*
[b] *Dipartimento di Scienze della Terra, Università degli Studi di Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy*

Received 28 September 2004; accepted after revision 7 March 2005

Available online 22 June 2005

Presented by Michel Durand-Delga

Abstract

Structural and petrological analyses on the Alì Unit, in the Peloritani Thrust Belt, document the first evidence for Alpine exhumation associated with syn-orogenic extension in this part of the Calabria-Peloritani Arc. The Alì Unit displays ductile structures occurred during three Alpine deformation phases (D_{a1}, D_{a2}, D_{a3}). D_{a1} and D_{a3} developed in a contractional context, whereas D_{a2} was generated in an extensional regime. The present-day tectonic contact between the Alì Unit and the overlying Mandanici Unit is interpreted as a low-angle extensional detachment responsible for the metamorphic break between the two units. Structural overprinting relationships indicate that the development of D_{a2} structures and related tectonic exhumation occurred during syn-convergence extension, and were followed by further nappe stacking in the Peloritani Belt. ***To cite this article: R. Somma et al., C. R. Geoscience 337 (2005).***

Résumé

Extension synorogénique dans la chaîne alpine péloritaine (Nord-Est de la Sicile, Italie) : l'exemple de l'unité d'Alì. L'étude de l'évolution tectono-métamorphique de l'unité d'Alì (monts Péloritains) apporte la première indication de l'exhumation alpine par extension synorogénique dans cette partie de l'arc Calabro-Péloritain. L'unité d'Alì montre des structures ductiles développées durant trois phases de déformation alpines (D_{a1}, D_{a2}, D_{a3}). D_{a1} et D_{a3} se sont développées dans un contexte compressif, alors que D_{a2} s'est formée dans un régime extensif. Le contact tectonique entre l'unité d'Alì et l'unité superposée de Mandanici est représenté par des failles extensives, responsables de l'omission métamorphique et stratigraphique entre les deux unités. Les rapports structuraux indiquent que les structures D_{a2} et l'exhumation associée se sont produites au cours d'une extension synorogénique, suivie par l'empilement des nappes de la chaîne péloritaine. ***Pour citer cet article : R. Somma et al., C. R. Geoscience 337 (2005).***

* Corresponding author.
E-mail address: antonia.messina@tiscalinet.it (A. Messina).

1631-0713/$ – see front matter © 2005 Académie des sciences. Published by Elsevier SAS. All rights reserved.
doi:10.1016/j.crte.2005.03.004

Keywords: Structural analysis; Syn-orogenic extension; Exhumation

Mots-clés : Analyse structurale ; Extension synorogénique ; Exhumation

Version française abrégée

1. Introduction

L'exhumation des roches métamorphiques peut se produire, soit par compression, soit par extension, qui peut être elle-même, soit post-orogénique, soit synorogénique [13].

Dans ce travail, nous exposons les données qui apportent la première preuve d'exhumation par extension synorogénique dans la chaîne péloritaine (arc Calabro-Péloritain). Ces données fournissent de nouvelles contraintes pour la reconstruction de l'évolution tectono-métamorphique de la chaîne Péloritaine.

2. Rappel géologique

L'unité d'Alì (UA) appartient à la chaîne Péloritaine, un édifice tectonique d'âge Oligo-Miocène formé par des nappes de croûte continentale amincie. Cette unité, composée par un substratum varisque (Paléozoïque) revêtu d'une couverture mésozoïque, a subi un métamorphisme alpin de faible degré [9]. L'UA s'étend le long de la côte ionienne. Elle est recouverte tectoniquement par les roches épimétamorphiques, d'âge Varisque, de l'unité de Mandanici (Fig. 1). Ce contact tectonique a été interprété comme un chevauchement alpin. Le contact tectonique inférieur n'affleure pas, mais l'étude régionale de la chaîne Péloritaine indique que l'UA est probablement superposée à l'unité de Fondachelli.

3. Données structurales

Les analyses méso- et microstructurales nous ont permis de reconnaître trois phases de déformation ductiles alpines. La première et la troisième phases se sont développées dans un régime compressif, alors que la deuxième s'est produite dans un contexte d'extension (synorogénique). L'analyse microstructurale indique que les deux premières phases ont aussi été accompagnées par un métamorphisme.

La première déformation alpine (D_{a1}), associée à un raccourcissement sub-horizontal, produit des structures compressives représentées par : (*i*) un plissement alpin F_{a1} avec plans axiaux à fort pendage, (*ii*) une foliation de plan axial S_{a1} sub-vertical pénétrative (Fig. 2).

La deuxième phase alpine (D_{a2}), liée à un raccourcissement vertical, est responsable de la formation de structures d'extension représentées par : (*i*) un système de plissement F_{a2} avec plans axiaux sub-horizontaux, (*ii*) un clivage espacé de plan axial S_{a2}, sub-horizontal et peu pénétratif (Figs. 3–5).

La troisième déformation alpine (D_{a3}), qui n'est pas accompagnée de métamorphisme, est associée à un nouveau raccourcissement sub-horizontal. Elle forme des structures compressives, avec une foliation de crénulation S_{a3} et des linéations de gaufrage locales (Figs. 4c et 6).

Un saut métamorphique caractérise le contact tectonique entre l'UA, métamorphisée durant l'événement alpin, et l'unité de Mandanici sus-jacente, une nappe composée par un substratum varisque sans métamorphisme alpin. L'analyse structurale de ce contact tectonique révèle la présence de zones de cisaillement extensif à faible angle. Les indicateurs cinématiques (structures S–C et S′–C) suggèrent un sens de cisaillement normal vers le nord.

4. Discussion et conclusion

Les données pétrologiques de l'unité d'Alì indiquent la présence de deux stades métamorphiques alpins : le stade D_{a1} à $P = 0{,}3–0{,}4$ GPa et $T = 330 \pm 20\,°C$; le stade D_{a2}, en conditions de P et T plus basses.

Vers la fin de la phase D_{a1}, des sur-charriages se sont produits, déterminant un épaississement crustal dans la chaîne Péloritaine.

L'extension synorogénique, mise en évidence par l'analyse de la déformation interne de l'UA et par la reconnaissance de zones de cisaillement extensif, est probablement responsable du saut métamorphique entre ces unités et de l'amincissement de la pile de nappes, en causant l'élimination de la surcharge et l'exhumation de certaines portions de la chaîne. La déformation interne de l'UA permet d'attribuer une part considérable de la déformation finie coaxiale et de l'amincissement des terrains étudiés, au raccourcissement vertical. En revanche, une omission tectonique substantielle, au niveau du contact entre les unités de Mandanici et d'Alì, est vraisemblable, compte tenu des données pétrologiques qui indiquent un saut de pression de sens normal.

Pendant l'orogenèse alpine, l'UA était recouverte par une épaisseur considérable de roches, conservée seulement en partie dans la chaîne actuelle. La tectonique liée, vraisemblablement, à l'extension synorogénique a exhumé cette unité de portions plus profondes de la chaîne. Le fait que l'unité tectonique structuralement sous-jacente à l'UA, c'est-à-dire l'unité de Fondachelli, n'ait pas été métamorphisée durant l'orogenèse alpine suggère que l'exhumation s'est produite avant l'emplacement de l'UA et des unités sus-jacentes sur l'unité de Fondachelli (Fig. 7). Ainsi, la phase D_{a2} et l'exhumation de l'unité métamorphique se seraient développées dans le contexte d'une déformation syn-convergence, suivi par un raccourcissement crustal ultérieur.

L'analyse tectono-métamorphique précédente révèle que, dans l'arc Calabro-Péloritain, de la même façon que dans d'autres orogènes, des épisodes d'extension syn-convergence ont accompagné l'empilement des nappes et le raccourcissement crustal.

1. Introduction

Exhumation of metamorphic rocks may occur as a result of different mechanisms, including crustal shortening (accompanied by substantial erosion [3]), rock buoyancy in a subduction channel [15], or crustal/lithospheric extension [14]. Both syn- and post-orogenic extension may occur in orogens. Syn-orogenic extension is contemporaneous with the build up of the belt and it is restricted only to the upper crust [7]. Post-orogenic extension occurs once tectonic building stops, affecting the whole lithosphere [13], and so it contributes (with erosion) to the erasing of the chain. The occurrence of both syn- and post-orogenic extension has been widely documented in the Mediterranean area [2,14] including the Calabria–Peloritani Arc [20–23].

In this paper, meso- and microstructural data are reported, documenting the first evidence for Alpine exhumation associated with syn-orogenic extension in the Peloritani Thrust Belt (Southern Sector of the Calabria–Peloritani Arc). These data provide new elements for the reconstruction of the tectono-metamorphic evolution of the Peloritani Thrust Belt.

2. The Peloritani Thrust Belt

The Alì Unit (AU) belongs to the Peloritani Thrust Belt, which belt is formed by thin continental crust nappes emplaced during the Upper Oligocene–Aquitanian time span and postdated by Burdigalian wedge-top basin deposits. The belt includes, from base to top: the Longi–Taormina, Fondachelli, Alì, Mandanici, Piraino, Mela and Aspromonte Units [18]. The Aspromonte Unit records three metamorphic (Pre-Variscan, Variscan and Alpine) and two plutonic (Pre- and Late-Variscan) events. The other units include Palaeozoic successions affected by Variscan metamorphism showing peculiar characteristics. The Mela and Alì Units exhibit a more complex tectonic evolution, with Eo-Variscan eclogite relics in the former and an Alpine overprint in the latter [18]. The Meso-Cenozoic cover is lacking only in the Aspromonte and Mela Units.

In the Aspromonte Unit [18], the Alpine metamorphism ranges from the Barrovian-type garnet zone of the greenschist facies (first stage D_{a1} – $P = 0.7$–0.9 GPa, $T = 380 \pm 10\,°C$) to the oligoclase zone of the amphibolite facies (second stage D_{a2} and D_{a3} – $P < 0.5$ GPa, $T \geqslant 550\,°C$; 22 Ma).

3. The Alì Unit

The AU is made up of a Palaeozoic (Upper Carboniferous–Lower Devonian) succession, affected by a low-grade Variscan metamorphism, and a Mesozoic cover, both interested by a very low-grade Alpine metamorphism [9]. The AU crops out on the Ionian coast, near the Alì village, with a thickness of 300–450 m (Fig. 1). It is tectonically overlain by the Variscan epimetamorphites of the Mandanici Unit.

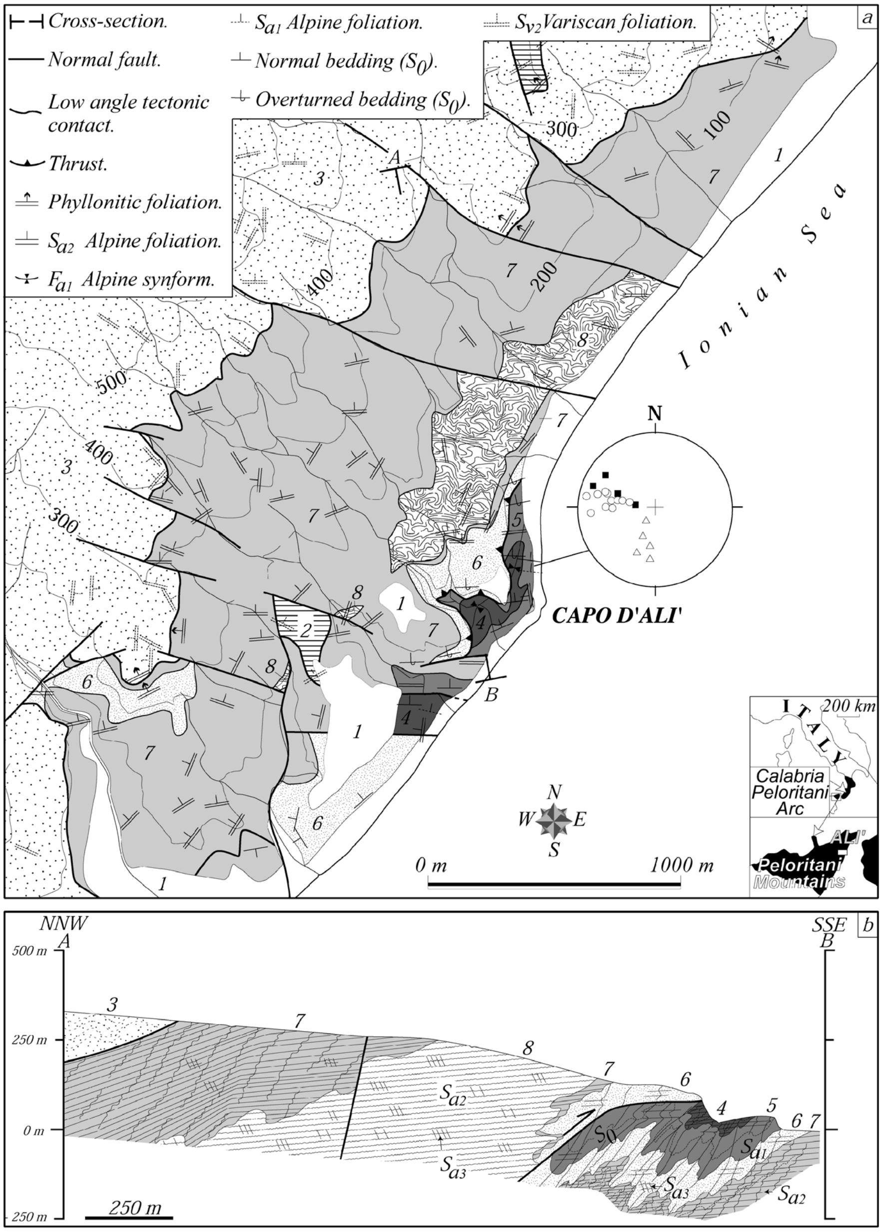

Fig. 1. Geological map (**a**) and cross section (**b**) of the Alì area. Lower hemisphere, equal area projection shows F_{a1} fold hinges (dots), $L_{a1} = S_0/S_{a1}$ intersection lineation (squares) and poles to axial surfaces (triangles). Legend: **1**, Quaternary cover; **2**, Aspromonte Unit; **3**, Mandanici Unit. Alì Unit–Mesozoic cover: **4**, metamarls (Lower Cretaceous?–Jurassic); **5**, metamarly-limestones (*Medolo*-type, Domerian); **6**, meta(?)-dolomites, meta-limestones, *cargneules* (Norian-Carnian?); **7**, *Verrucano*-type (Upper–Middle Triassic?); **8**, Palaeozoic basement (*Scisti a piante*, Upper Carboniferous–Lower Devonian).

Fig. 1. Carte (**a**) et coupe géologique (**b**) de la région d'Alì. La projection équivalente de Schmidt, hémisphère inférieur, montre les charnières de pli F_{a1} (points), les linéations d'intersection $L_{a1} = S_0/S_{a1}$ (carrés) et les pôles de plans axiaux (triangles). Légende : **1**, dépôts quaternaires ; **2**, unité de l'Aspromonte ; **3**, unité de Mandanici. Unité d'Alì–couverture mésozoïque : **4**, métamarnes (Crétacé inférieur ?–Jurassique) ; **5**, métacalcaires marneux (de type *Medolo*, Domérien) ; **6**, méta(?)-dolomies, méta-calcaires, cargneules (Carnian–Norien ?) ; **7**, *Verrucano* (Trias supérieur–moyen ?) ; **8**, substratum paléozoïque (*Schistes à plantes*, Carbonifère supérieur–Dévonien inférieur).

Locally, the AU is overlain by reworked, cataclastic meso-catametamorphites (Modderino klippe). The upper boundary of the AU is commonly interpreted as an Alpine overthrust. The lower tectonic contact does not crop out. According to regional analyses on the belt, the AU probably overthrusts the Fondachelli Unit.

The AU stratigraphic succession, strongly deformed by Alpine tectonics, has been reconstructed based on lithostratigraphic observations. It is characterised, from top to base, by:

– a *Mesozoic cover*: variegated siliceous metamarls with intercalations of grey centimetre-thick calcarenites and microbreccia (Lower Cretaceous?–Jurassic), grey to bluish cherty metamarly limestones (*Medolo*-type, Domerian), grey to yellowish meta(?)-dolomites, black meta-limestones (Norian?), strongly cataclastic pinkish to yellowish *cargneules* (Carnian?), reddish to yellowish *Verrucano*-type metapelites, metasiltites, metarenites and metaconglomerates (Upper-Middle Triassic?);
– a *Palaeozoic basement*: polymetamorphic dark graphite, metapelites, metasiltites, metarenites and metaconglomerates with plant rests (*Scisti neri a piante* – Upper Carboniferous–Lower Devonian).

According to most authors [1,5,6,24], the Alì Mesozoic rocks and some other Peloritani Alpine overprinted rocks belong to the cover of the Mandanici Unit. Our data on the Mandanici Unit, also near the tectonic contact with the Alì rocks, indicate that this unit is not affected by an Alpine metamorphic overprint. Moreover, the AU preserves a Palaeozoic basement not recognised by previous studies.

4. Structural and petrological data

4.1. Internal deformation and metamorphism of the Alì Unit

Structural analyses and kinematic reconstructions on the AU [5,11] did not point out the occurrence of syn-orogenic extensional structures. Cirrincione and Pezzino [5] recognised, both in the Mesozoic succession of the Alì area and in the terrains ascribed to the Mandanici Unit, two Alpine deformation cycles. Four Alpine ductile deformation phases were identified by Giunta and Somma [11]. These authors reconstructed a very complex structure characterised by two structural sets. The structurally uppermost group was formed by several tectonic slices and the lowermost one numerous duplexes. The related kinematic model, characterised by a piggy-back thrust sequence with a south-wards tectonic transport direction, would have involved first the uppermost set of slices, and then the duplex level.

New meso- and microstructural investigations on the AU allowed us to recognise three main ductile deformation phases. The first and third phases developed in a contractional regime, the second generated in an extensional context (syn-orogenic extension). Microstructural analyses indicate that the first two phases were also accompanied by metamorphism.

The *first Alpine deformation* (D_{a1}), syn-metamorphic and associated with sub-horizontal shortening, generated pervasive contractional structures represented by: (*i*) an Alpine polyharmonic F_{a1} fold system with steeply dipping axial surfaces, and (*ii*) a steeply dipping S_{a1} axial plane foliation.

D_{a1} is responsible for the dominant macroscopic structural setting of AU rocks. Along the Ionian coast, an overturned tight syncline with a 100-m wavelength preserves the variegated metamarls in the core (Fig. 1).

F_{a1} folds consist of S–SSW-vergent tight buckle folds showing wavelengths of tens of metres to a few metres, east–west to WNW–ESE axial trends (Fig. 2a) and axial surfaces dipping towards N–NNE with angles of 55° (Figs. 1 and 3a–b). F_{a1} folds show different styles both in the various formations of the AU multilayer and within the same formation, depending on the lithotype. In metamarly limestones, parasitic, close buckle folds with rounded hinge zones (Fig. 3a–d) evolve, along the axial surface, to open kinks in the range of a few metres. Cuspate-lobate folds are also common along the interface between limestone/marly beds with different pelite contents. Moreover, in the *Medolo* and variegated metamarls, fold limbs often present *boudin*-like structures, originating pinch and swell structures with the long axis parallel to F_{a1} fold axes.

The S_{a1} foliation (Figs. 3c–f and 4a–b) occurs as axial plane foliation to F_{a1} folds (Fig. 3c–d). It is well recognisable both at the micro- and the mesoscale.

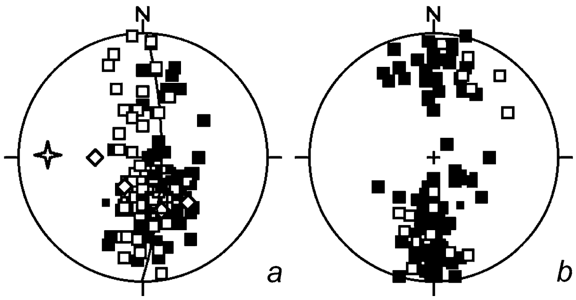

Fig. 2. Orientation data for D_{a1}-related Alpine mesoscopic fabrics (lower hemisphere, Schmidt equal area projections). (**a**) Poles to bedding (198 data) and pole to the best fit great circle of bedding poles (the mean π fold axis is 270/15). (**b**) Poles to S_{a1} Alpine foliation (123 data). Symbols: empty squares = metamarls; large solid squares = *Medolo*; small solid squares = *Verrucano*; rhombs = Palaeozoic basement.

Fig. 2. Stéréogrammes des éléments structuraux associés à la déformation alpine D_{a1} (projection équivalente de Schmidt, hémisphère inférieur). (**a**) Pôles de stratification (198 données) et pôle de meilleur ajustement avec la stratification (meilleur axe = 270/15). (**b**) Pôles de foliation de première phase alpine (123 données). Symboles : carrés vides = métamarnes ; carrés pleins de grande taille = *Medolo* ; carrés pleins de petite taille = *Verrucano* ; losanges = substratum paléozoïque.

It forms convergent (in competent beds) and divergent (in less competent units) cleavage fans typical of buckle folds. The foliation dips towards north and south (because of both cleavage refraction and later deformation phases), showing a wide range of dip values (Fig. 2b). The intersection lineation $L_{a1} = S_0/S_{a1}$ roughly lies sub-parallel to F_{a1} axes (stereonet in Fig. 1a). In the pelitic rocks (Fig. 4b), S_{a1} consists of a slaty cleavage defined by Alpine syn-kinematic phengitic white mica (3.3 to 3.25 Si content − p.f.u.) or paragonite + chlorite + quartz + hematite + graphite + magnetite ± pyrophyllite. Quartz shows irregular grain boundaries in response to grain boundary migration recrystallisation. In the *Verrucano* metapelites, white mica grew at the expense of previous albite (paragonite) and biotite (phengite). Relict clastic materials consist of white mica, hematite, quartz and chloritised biotite (pennine). In the calcareous levels, S_{a1} is spaced and consists of an anastomosing foliation marked by wriggly to stylolitic cleavage domains mainly defined by hematite. In the Variscan basement, S_{a1} is observable only at the microscale. S_{a1} appears to produce an intensification of the Variscan foliation and is accompanied by phengite (3.3 Si content – p.f.u.) + chlorite + quartz + hematite + graphite + magnetite.

The *second Alpine deformation* (D_{a2}), syn-metamorphic and associated with vertical shortening, is responsible for the development of structures represented by: (*i*) a F_{a2} fold system with moderately dipping to sub-horizontal axial surfaces, and (*ii*) a sub-horizontal S_{a2} axial plane foliation.

D_{a1} structures are deformed by cascade F_{a2} folds (Figs. 3c–d and 5) showing both rounded and angular hinges, weakly plunging towards the west. In the metamarls, folds are widespread and present centimetric to millimetric wavelengths. Differently, F_{a2} folds in the *Medolo*-type rocks are not common and are generally represented by kink bands, only few centimetres wide, deforming the previous S_{a1} fabric. Fold hinges are also very rare to observe in the *Verrucano* layers.

The S_{a2} fabric (Fig. 5a), well recognisable both at micro- and mesoscale (Figs. 3e–f and 4), occurs as a crenulation cleavage associated with F_{a2} folds. S_{a2} anisotropy surfaces display dominant gentle north dips, steepening towards the structurally uppermost portion of the unit. The intersection lineation $L_{a2} = S_{a1}/S_{a2}$ is oriented consistently with F_{a2} axial trends. A further $L_{a2} = S_0/S_{a2}$ lineation is easily observable on bedding surfaces. In the pelitic rocks, S_{a2} is represented by a pronounced, parallel to anastomosing crenulation cleavage (Fig. 4b), defined by crystallisation of the same minerals forming the S_{a1}, with strain fringes rimming clastic quartz. During D_{a2}, quartz polycrystalline microlithons also originated irregular grain boundaries. S_{a2} is represented by a zonal crenulation cleavage, locally of discrete type, with rough to smooth cleavage domains and with symmetric microfolds deforming the S_{a1} fabric. In the *Medolo*-type carbonate level, S_{a2} shows features analogous to those described above, but it is only incipiently developed. In the *Verrucano*, S_{a2} crenulation cleavage is mainly of discrete type and is associated with open, asymmetric microfolds. The S_{a2} foliation is pervasive only in the Palaeozoic basement (Fig. 4c), and is represented by a crenulation cleavage with symmetric microfolds deforming the S_{a1} foliation. S_{a2} is defined by the same S_{a1} mineral assemblage.

The *third Alpine deformation* (D_{a3}), not accompanied by metamorphism, is again associated with sub-horizontal shortening. It locally originated contrac-

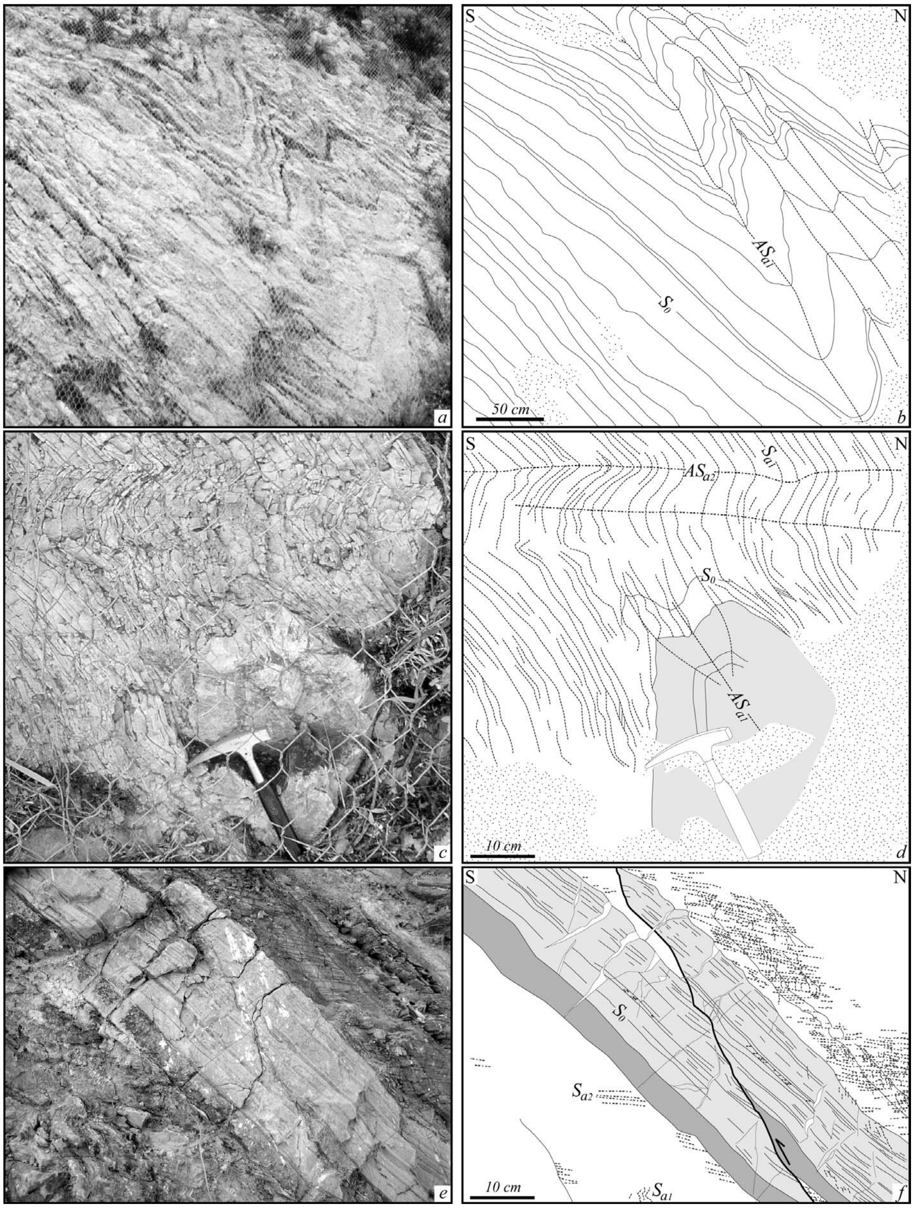

Fig. 3. Photographs (**a**, **c**) and lines drawing (**b**, **d**) of mesoscopic structures in the AU *Medolo*-type metamarly limestones. Photograph (**e**) and line drawing (**f**) of mesoscopic structures in the AU metamarls.

Fig. 3. Photographies (**a**, **c**) et dessins (**b**, **d**) des structures mésoscopiques dans les calcaires métamarneux de type *Medolo* de l'UA. Photographie (**e**) et dessin (**f**) des structures mésoscopiques dans les métamarnes de l'UA.

tional deformation features mainly represented by a steeply dipping S_{a3} crenulation cleavage.

The S_{a3} cleavage, recognisable both at micro- and mesoscale, was observed mainly in the Palaeozoic basement (Fig. 4c). The S_{a3} fabric displays southward dips of about 45° (Fig. 6a). A crenulation lineation $L_{a3} = S_{a2}/S_{a3}$ trends mainly WNW–ESE (Fig. 6b). S_{a3} is characterised by a zonal crenulation cleavage, locally

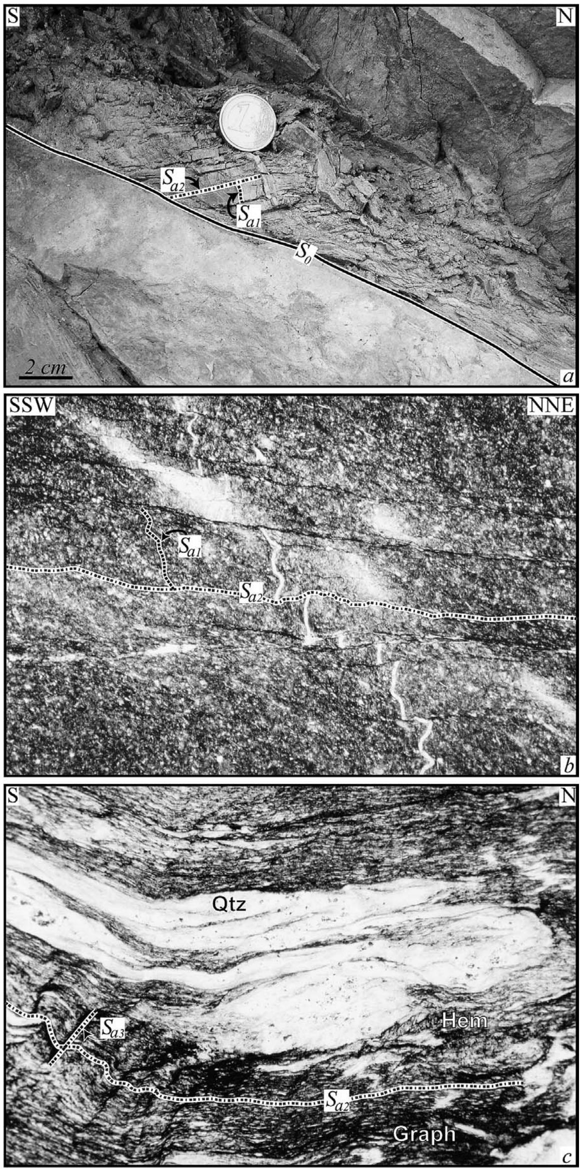

Fig. 4. (**a**) Photograph of mesoscopic structures in the AU *Medolo*-type metamarly limestones. (**b**) Photomicrograph of structures in the AU variegated metamarls (P.P.L., 2.5×). (**c**) Photomicrograph of structures in the AU Palaeozoic basement (P.P.L., 4×). Graph = graphite; Qtz = quartz; Wm = white mica; Hem = hematite.

Fig. 4. (**a**) Photographie des structures mésoscopiques dans les calcaires métamarneux de type *Medolo* de l'UA. (**b**) Microphotographie des structures dans les métamarnes de l'UA. (**c**) Microphotographie des structures dans le substratum paléozoïque de l'UA. Graph = graphite ; Qtz = quartz ; Wm = mica blanc ; Hem = hématite.

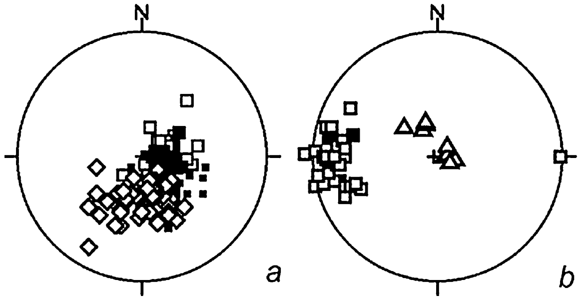

Fig. 5. Orientation data (lower hemisphere, equal area projections) for D_{a2}-related Alpine mesoscopic fabrics. (**a**) Poles to S_{a2} Alpine foliation (174 data). (**b**) F_{a2} Alpine fold hinges (32 data), $L_{a2} = S_{a1}/S_{a2}$ intersection lineations (14 data), and poles to F_{a2} axial surfaces (10 data). Symbols as in Fig. 2, triangles = poles to axial surfaces.

Fig. 5. Stéréogrammes des éléments structuraux associés à la déformation alpine D_{a2} (projection équivalente de Schmidt, hémisphère inférieur). (**a**) Pôles de foliation de deuxième phase alpine (174 données). (**b**) Charnières de plis alpins F_{a2} (32 données), linéations d'intersection $L_{a2} = S_{a1}/S_{a2}$ (14 données), et pôles de plans axiaux F_{a2} (10 données). Symboles comme sur la Fig. 2, triangles = pôles de plans axiaux.

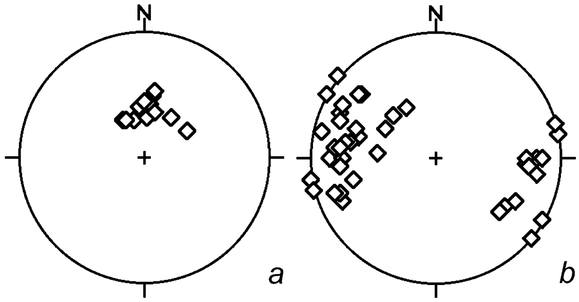

Fig. 6. Orientation data (lower hemisphere, equal area projections) for D_{a3}-related Alpine mesoscopic fabrics. (**a**) Poles to S_{a3} Alpine foliation (11 data). (**b**) F_{a3} Alpine crenulation microfold hinges (40 data). Symbols as in Fig. 2.

Fig. 6. Stéréogrammes des éléments structuraux associés à la déformation alpine D_{a3} (projection équivalente de Schmidt, hémisphère inférieur). (**a**) Pôles de foliation de troisième phase alpine (11 données). (**b**) Linéations de gaufrage alpines F_{a3} (40 données). Symboles comme sur la Fig. 2.

of discrete type with a thin foliation marked by transposition of hematite and graphite. S_{a3} rough to smooth domains with asymmetric kink microfolds deform the pre-existing S_{a2} fabric.

4.2. Structural relationships between the Alì Unit and the overlying terrains

The Mandanici Unit tectonically overlying the AU is composed of a Palaeozoic succession showing exclusively prograde Variscan metamorphism, from the chlorite zone of the greenschist facies to the beginning of the oligoclase + almandine zone of the amphibolite facies.

A metamorphic break characterises the tectonic contact between the Alpine AU and the Variscan terrains of Mandanici Unit, a nappe not affected by Alpine metamorphism. The contact dips towards the northwest (with a dip angle of about 35–40°, Fig. 1). Locally the AU is also overlain by a few tens of metre-thick cataclastic breccia (Modderino klippe) formed by reworked meso-catametamorphics of the Aspromonte and Mela Units. Structural analysis of these tectonic contacts reveals the presence of low-angle extensional shear zones, marked by phyllonitic to cataclastic levels, accompanied by a foliation exhibiting the same attitude as the S_{a2} fabric. Where (rarely) observed, kinematic indicators such as S–C fabrics and shear bands suggest a general top-down-to-the-north sense of shear. Shear zones are characterised by grain-size reduction and retrogressive processes.

5. Discussion and concluding remarks

The *second Alpine deformation* (D_{a2}) of the Alì Unit, syn-metamorphic and associated with vertical shortening, is best interpreted as a result of horizontal extension leading to ductile thinning of the unit, as well as to the development of low-angle normal faults marked by phyllonitic to cataclastic levels between the AU and the overlying Mandanici Unit.

Petrological data from Al-rich rock types of the AU indicate the occurrence of two Alpine metamorphic stages. The early stage, related to D_{a1}, developed under pressures around 0.3–0.4 GPa and temperatures between 300 and 350 °C – phengite (3.3 to 3.25 Si content ar p.f.u.) or paragonite + chlorite + quartz + hematite + graphite ± pyrophyllite assemblage. Temperatures are in good agreement with those indicated by previous authors [9], whereas pressures are higher then those envisaged by previous authors. The second stage, related to D_{a2}, took place at lower P and T conditions with respect to the first stage.

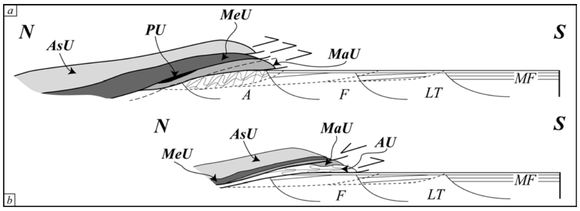

Fig. 7. Model of the Alpine tectonic evolution for the Alì area (not to scale). (**a**) Nappe stacking during D_{a1}. (**b**) Syn-convergence extension during D_{a2}. Abbreviations: AsU = Aspromonte Unit; MeU = Mela Unit; PU = Piraino Unit; MaU = Mandanici Unit; A = Alì domain; F = Fondachelli domain; LT = Longi–Taormina domain; MF = Maghrebid Flysch domain; AU = Alì Unit.

Fig. 7. Modèle de l'évolution tectonique alpine dans la région d'Alì (sans échelle). (**a**) Empilement des nappes pendant la phase D_{a1}. (**b**) Extension syn-convergente pendant la phase D_{a2}.

During the late D_{a1}, i.e. following early buckle folding (F_{a1}), overthrusting occurred, producing crustal thickening in the Peloritani Belt (Fig. 7a).

Syn-orogenic extension, pointed out by the analysis of the internal deformation of the AU and by recognition of a phyllonitic to cataclastic extensional detachment, is responsible for the metamorphic break between the units and for significant thinning of the original nappe pile, causing removing of overburden and related exhumation. Although an analysis of the relative importance of bulk, distributed strain vs localised shear zone deformation has not been carried out in this study, internal deformation features of the AU suggest a significant component of nearly coaxial strain and nappe thinning by vertical shortening. On the other hand, a substantial tectonic omission along the contact between the Mandanici and Alì Units is indicated by the petrological data, showing a 'normal-sense' pressure gap.

During Alpine orogenesis, the AU was overthrust by a significant thickness of rocks, only in part preserved in the present-day thrust belt. Syn-orogenic extensional tectonics is likely to have exhumed this unit from deeper portions of the chain. The fact that the tectonic unit structurally underlying the AU (Fondachelli) does not show evidence of Alpine metamorphism suggests that substantial exhumation occurred prior to final emplacement of the AU (and structurally overlying units) onto such footwall (Fig. 7b). This, in turn, indicates that D_{a2} extensional deformation and related tectonic exhumation occurred within the context of syn-convergence deformation, and were followed by further thrusting and crustal shortening.

The analysis of structural and metamorphic patterns in the Calabria-Peloritani Arc reveals that, similarly to what occurs in other thrust belts all over the world and particularly in the western Mediterranean area, repeated episodes of syn-convergence extension accompanied nappe stacking and overall crustal shortening in the chain [21,22]. Tectonic evolution and metamorphic conditions of the AU closely resemble those of the Tizgarine Unit ($P < 0.5$ GPa and $T = 300\,^{\circ}\mathrm{C}$, cookeite + pyrophyllite + phengite assemblage [12]) of the Federico Complex in the Rif (Morocco). In the latter area, an Alpine syn-orogenic extensional detachment produced the direct superposition of non-metamorphic Ghomaride rocks on top of low-grade metasediments of the Tizgarine Unit. Several extensional detachments also occur in the footwall to the Tizgarine Unit, producing significant metamorphic breaks among the different Federico Units.

Taking into account the somewhat similar tectonic evolution of parts of the Betic-Rif and Calabria-Peloritani Arcs [2,14,16,19–23], it may be envisaged that the extensional phase documented in this paper for the AU took place within the framework of a major geodynamic process involving the retreat of the Apennine–Maghrebide subduction boundary and associated back-arc basin development [4,8,10,17].

Acknowledgement

Thoughtful and constructive reviews by Alessandro Iannace and André Michard allowed us to substantially improve the paper.

References

[1] P. Atzori, R. Cirrincione, A. Del Moro, A. Pezzino, Structural metamorphic geochronologic features of the alpine event in the southeastern sector of the Peloritani Mountains (Sicily), Periodico di Mineralogia 63 (1995) 113–125.

[2] J.M. Azañón, V. García-Dueñas, B. Goffé, Exhumation of high-pressure pelites and coeval crustal extension in the Alpujarride Complex (Betic Cordillera), Tectonophysics 285 (1998) 231–252.

[3] R.W.H. Butler, M. Casey, G.E. Lloyd, C.E. Bond, P. McDade, Z. Shipton, R. Jones, Vertical stretching and crustal thickening at Nanga Parbat, Pakistan Himalaya: a model for distributed continental deformation during mountain building, Tectonics 21 (2002) 1027.

[4] A. Chalouan, A. Michard, The Alpine Rif Belt (Morocco): A case of mountain building in a subduction–subduction–transform fault triple junction, Pure Appl. Geophys. 161 (2004) 489–519.

[5] R. Cirrincione, A. Pezzino, Caratteri strutturali dell'evento alpino nella serie mesozoica di Alì e nella unità metamorfica di Mandanici (Peloritani orientali), Mem. Soc. Geol. It. 47 (1991) 263–272.

[6] R. Cirrincione, A. Pezzino, Nuovi dati strutturali sulle successioni mesozoiche metamorfiche dei M. Peloritani orientali, Boll. Soc. Geol. It. 113 (1994) 195–203.

[7] P.-J. Dèzes, J.-C. Vannay, A. Steck, F. Bussy, M. Cosca, Synorogenic extension; quantitative constraints on the age and displacement of the Zanskar shear zone (Northwest Himalaya), Geol. Soc. Am. Bull. 111 3 (1999) 364–374.

[8] C. Doglioni, M. Fernandez, E. Gueguen, F. Sabat, On the interference between the early Apennines–Maghrebides back-arc extension and the Alps-Betics orogen in the Neogene geodynamics of the Western Mediterranean, Boll. Soc. Geol. It. 118 (1999) 75–89.

[9] P. Ferla, E. Azzaro, Il metamorfismo alpino nella serie mesozoica di Alì (M. Peloritani-Sicilia), Boll. Soc. Geol. It. 97 (1978) 775.

[10] D. Frizon de Lamotte, B. Saint Bezar, R. Bracène, E. Mercier, The two main steps of the Atlas building and geodynamics of the west Mediterranean, Tectonics (2000) 740–761.

[11] G. Giunta, R. Somma, Nuove osservazioni sulla struttura dell'Unità di Alì (M. ti Peloritani, Sicilia), Boll. Soc. Geol. It. 115 (1996) 489–500.

[12] B. Goffé, J.M. Azañón, M.L. Bouybaouène, M. Jullien, Metamorphic cookeite in Alpine metapelites from Rif, northern Morocco, and the Betic Chain, southern Spain, Eur. J. Mineral. 8 (1996) 335–348.

[13] L. Jolivet, B. Goffé, Les dômes métamorphiques extensifs dans les chaînes de montagnes. Extension syn-orogénique et post-orogénique, C. R. Acad. Sci. Paris, Ser. IIa 330 (2000) 739–751.

[14] L. Jolivet, B. Goffé, R. Bousquet, R. Oberhänski, A. Michard, The tectono-metamorphic signature of detachments in high pressure mountains belts, Tethyan examples, Earth Planet. Sci. Lett. 160 (1998) 31–47.

[15] L. Jolivet, C. Faccenna, B. Goffé, E. Burov, P. Agard, Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterrenean orogens, Am. J. Sci. 303 (2003) 353–409.

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

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

[18] A. Messina, R. Somma, G. Careri, G. Carbone, E. Macaione, Peloritani continental crust composition (southern Italy): geological and petrochemical evidences, Boll. Soc. Geol. It. 123 (2004) 405–441.

[19] A. Michard, A. Chalouan, H. Feinberg, B. Goffé, R. Montigny, How does the Alpine belt end between Spain and Morocco?, Bull. Soc. géol. France 173 (2002) 3–15.
[20] J.P. Platt, R. Compagnoni, Alpine ductile deformation and metamorphism in a Calabrian basement nappe (Aspromonte, south Italy), Eclog. Geol. Helv. 83 (1990) 41–58.
[21] F. Rossetti, C. Faccenna, B. Goffé, P. Monié, A. Argentieri, R. Funiciello, M. Mattei, Alpine structural and metamorphic signature of the Sila Piccola Massif nappe stack (Calabria, Italy): insights for the tectonic evolution of the Calabrian Arc, Tectonics 20 (2001) 112–133.
[22] S.N. Thomson, 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 (1994) 331–352.
[23] S.R. Wallis, J.P. Platt, S.D. Knott, Recognition of syn-convergence extension in accretionary wedges with examples from the Calabrian Arc and the eastern Alps, Am. J. Sci. 293 (1993) 463.
[24] A. Zuppetta, A. Sava, Nuovi dati sulla geologia dei dintorni di Mandanici (Monti Peloritani–Sicilia), Boll. Soc. Geol. It. 106 (1987) 347–349.