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Tectonics

Ductile shear zones on carbonates: the *calcaires plaquettés* of northern Calabria (Italy)

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Abstract

Field, petrographic and quantitative strain analysis have been performed on highly foliated limestones outcropping in northern Calabria and generally attributed to two distinct units (San Donato and Pollino) on the basis of presence/absence of metamorphism. The deformation, however, is comparable in all the studied outcrops indicating that the widely accepted distinction of units in the area should be revised. Deformation is very localized in narrow ductile shear-zones affecting Tertiary conglomerates and Jurassic oncoidal packstones. The former are more strained because of their closeness to siliciclastic beds. The main deformation mechanism was grain boundary sliding with minor intragranular strain and pressure solution. ***To cite this article: A. Iannace, S. Vitale, C. R. Geoscience 336 (2004).***

Résumé

Les zones de cisaillement dans les carbonates : les « calcaires plaquettés » de la Calabre du Nord (Italie). Une étude de terrain, pétrographique et de la déformation finie a été réalisée sur des calcaires très foliés de la Calabre septentrionale, qui sont généralement attribués à deux unités tectoniques différentes (San Donato et Pollino) sur la base de la présence/absence de métamorphisme. La déformation, au contraire, apparaît comparable dans tous les affleurements étudiés ; ceci démontre que la distinction des unités tectoniques acceptée depuis longtemps doit être révisée. La déformation se localise dans des zones de cisaillement ductiles étroites et affecte des conglomérats tertiaires et des *packstones* jurassiques, ces derniers étant plus déformés du fait de leur proximité des niveaux silicoclastiques. Le mécanisme de déformation dominant a été le *grain boundary sliding*. ***Pour citer cet article : A. Iannace, S. Vitale, C. R. Geoscience 336 (2004).***

Keywords: Southern Apennines; Calabria; shear zones; strain analysis

Mots-clés : Apennin méridional ; Calabre ; zones de cisaillement ; analyse de la déformation

Version française abrégée

En Calabre du Nord (Italie), plusieurs auteurs [3,6, 10] ont décrit des roches carbonatées très déformées (calcaires plaquettés), associées, sans transition claire, à des carbonates de plate-forme non déformés. Dans les travaux les plus récents, ces roches ont été considérées franchement métamorphiques en faciès « schistes verts » [1,2], et donc placées dans une unité (unité de San Donato [1]) tectoniquement séparée par les successions clairement non métamorphiques de plate-

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forme (unité du Pollino [15]). Ces deux unités, à leur tour, sont chevauchées par l'unité de Verbicaro [1,2, 4], pour laquelle on admet un métamorphisme faible ou absent [1]. Ce cadre structural (Fig. 1) n'a jamais été discuté dans les travaux récents qui se sont pourtant attachés à l'important problème de la liaison entre Apennin non métamorphique et arc Calabro-Péloritain cristallin. Nous avons examiné plusieurs affleurements de ces lithologies pour une meilleure caractérisation géologique et structurale, étant donné leur position clé entre les deux chaînes.

Les affleurements analysés (Fig. 1) montrent clairement que la formation des « calcaires plaquettés » est le résultat de l'extrême déformation ductile de conglomérats calcaires tertiaires. Tous les stades de la déformation ont été observés à l'échelle macroscopique (Fig. 2, **1–4**), sur des distances de quelques dizaines de mètres (Campotenese, Monte Ciagola). L'association de ces conglomérats avec des faciès plus marneux et riches en macroforaminifères a démontré aussi leur corrélation avec des formations du Tertiaire appartenant à l'unité de Verbicaro qui les surmonte (*Brecce Poligeniche* et formation de *Colle Trodo* [7,19]). Dans les parties les plus anciennes de la succession (Monte Ciagola, Aieta, Maratea), on a observé aussi une déformation ductile très localisée en bandes, qui intéresse des lithologies oncolitiques de plate-forme (Fig. 2, **5**).

On a réalisé une analyse quantitative bidimensionnelle de la déformation avec la méthode R_f/ϕ [9,13], soit sur les conglomérats, soit sur les *packstones* de plate-forme et à différentes échelles (surfaces macroscopiques polies et lames minces). Les résultats de l'analyse (Figs. 3 et 4) confirment que le degré de déformation pour les faciès de plate-forme est généralement plus faible que celui des conglomérats tertiaires. Sur le plan microscopique et au microscope électronique à balayage (Fig. 2, **6**), en revanche, on a pu remarquer que les cristaux de micrite n'ont pas subi de recristallisation ou de déformation, même dans les échantillons les plus déformés ductilement. Au contraire, les objets spatiques (fragments d'échinides, veines de calcite), bien que non déformés macroscopiquement, montrent souvent en lame mince des phénomènes de gémination et d'extinction onduleuse de la calcite. Ces données indiquent que le mécanisme de déformation dominante à été le *grain boundary sliding* [12,17], qui, dans les matériaux très fins, peut être actif à basse température [15]. Les mécanismes intragranulaires et la pression–solution rend compte d'une part mineure de la déformation totale. La distribution stratigraphique des affleurements étudiés indique que les faciès les plus déformés sont localisés dans la partie la plus haute de la succession, juste au-dessous des faciès silicoclastique du Miocène de type flysch (Fig. 5). La focalisation des fluides pendant la déformation peut donc être envisagée comme la cause de la déformation ductile extrême qui a généré le faciès « calcaires plaquettés ».

Cette étude montre que les calcaires plaquettés peuvent représenter un excellent cas d'étude de l'activation de zones de cisaillement à basse température dans des roches carbonatées. Sur le plan régional, ces résultats préliminaires indiquent que la distinction des unités tectoniques généralement acceptée pour ce secteur de l'Apennin [2] est fausse, parce qu'elle suppose une distinction nette entre carbonates recristallisés, considérés comme métamorphiques, et carbonates non déformés. En revanche, les affleurements étudiés indiquent que toutes les successions carbonatées chevauchées par l'unité de Verbicaro possèdent le même style de déformation et, en même temps, que certaines formations très déformées peuvent être corrélées avec des formations de l'unité de Verbicaro. Il reste néanmoins le problème des rapports de ces carbonates déformés et ceux du reste de l'Apennin calcaire, totalement dépourvu de déformation ductile. Il est évident, donc, qu'une nouvelle distinction des unités tectoniques est nécessaire, qui prenne en considération les détails de la déformation et du métamorphisme, aussi bien que l'étude stratigraphique du protolithe.

1. Introduction

In northern Calabria, mainly within the territory of the Pollino National Park, several metamorphic and non-metamorphic carbonate units crop out. Despite the obvious geodynamic importance of these units, located between the non-metamorphic southern-Apennines fold and thrust belt and the crystalline Calabria–Peloritani Arc, their stratigraphy and deformation mechanisms have never been investigated in detail.

Particularly, the French authors who mapped the areas in the 1960s [3,10] described some highly de-

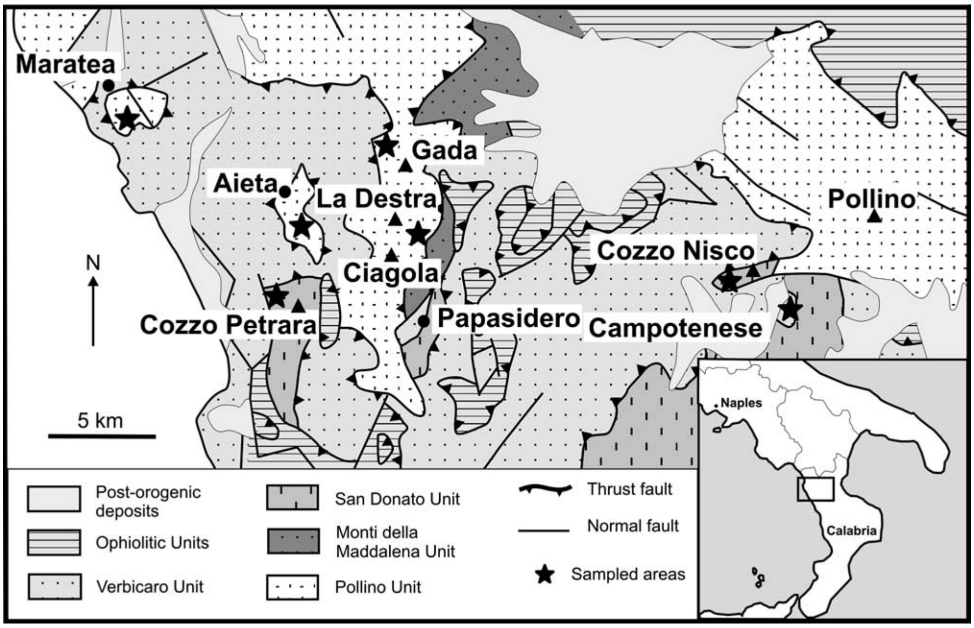

Fig. 1. Structural and location map of the studied area (after [2]).

Fig. 1. Carte structurale et localisation de la zone étudiée (d'après [2]).

formed carbonates, referred to as *calcaires plaquettés,* which apparently made lateral transition to the undeformed Jurassic and Cretaceous platform carbonates of the Pollino Unit. Amodio Morelli et al. [1] considered the *calcaires plaquettés* as a metamorphic lithology and thus attributed them to a tectonic Unit (San Donato) distinct from the non-metamorphic Pollino Unit. Even though the nature of the contact between the two units has never been extensively documented, this distinction has been accepted in all the subsequent papers.

We present here some preliminary results of a more comprehensive project concerned with the stratigraphy and structure of all the carbonate units of northern Calabria. The presented data come from several outcrops which provide excellent documentation of strain localization, from undeformed limestones to highly foliated and stretched rocks (the *calcaires plaquettés*) within the same tectonic Unit. In this respect, the *calcaires plaquettés* represent an interesting case history of strain localization in ductile shear-zones. Moreover, the stratigraphic and structural conclusions resulting from this analysis show that the characterization of the deformation and the metamorphism within all the carbonate units of northern Calabria is the necessary keystone to solve the still-persisting uncertainties about the structure and kinematics of this important sector of the Apennines.

2. Geological setting

The carbonates outcropping in the studied area belong, according to the generally accepted literature, to four tectono-stratigraphic units [1,2]: the Verbicaro Unit [4], the Pollino Unit [15], the Monti della Maddalena Unit [8] and the San Donato Unit [1] (Fig. 1). The studied localities are indicated in Fig. 1. The samples collected in the Campotenese area represent the true *calcaires plaquettés* of Bousquet [3] and should belong to the upper part of the San Donato Unit according to the tectonic scheme of Bigi et al. [2] (Fig. 1). Samples collected northeast of Monte Ciagola, Maratea and Aieta, instead, should belong to the non-metamorphic Pollino Unit. In all these localities, the analysed carbonates are tectonically covered by the Verbicaro Unit Auctt.

3. Geological data

3.1. Campotenese

In the Campotenese area, there are several little hills where the classic *calcaires plaquettés* of Bousquet [3] can be observed. These are represented by strongly laminated, crystalline metalimestones passing upward to calc-schists. In the latter lithologies the main foliation is associated to isoclinal folds ad is refolded and crenulated. In some localities, they overlie dolomites of Upper Triassic age and are overlain by a Langhian flysch [11].

We have analysed in detail two localities, I Campiglioni and Cozzo Nisco, along the road from the highway to the Pollino.

In the first area it is possible to follow, going broadly from west to east, a gradual transition, within a few tens of meters, from the typical highly foliated, crystalline metalimestones to calcareous conglomerates, calcarenites and marly calcarenites (Fig. 2, **1**–**3**). In the top of the succession, both in the clasts and matrix of the conglomerates, as well as in the deformed marly calcarenites, we have recognized *Nummulites sp*. This evidence shows without any doubt that in the Campotenese area, the metaconglomerates (top of *calcaires plaquettés)* represent the strong deformation of not older than Palaeogene calcareous resediments. The presence of oblique foliation or asymmetric mantled porphyroclasts indicates a simple shear component in the deformation.

At Cozzo Nisco, immediately below the tectonic contact with the Norian dolomites of Verbicaro Unit Auctt., the *calcaires plaquettés* make gradual transition to a few metres of calc-schists, containing highly deformed Lower-Miocene macroforaminifers. Again it is possible to recognize that these rocks are the result of the extreme deformation of calcareous conglomerates and of overlying marly calcarenites.

The association of calcareous conglomerates, calcarenites and marly calcarenites with macroforaminifers in all these localities suggests a correlation with Tertiary part of the Verbicaro Unit Auctt. (*Brecce Poligeniche* and *Colle Trodo* Formations [7,19]).

3.2. Monte Ciagola–La Destra–Gada

In the Monte Ciagola area and around the village of Papasidero, Compagnoni and Damiani [6] described and mapped laminated, crystalline limestones referred to as *calcari laminati di Papasidero*.

We recognized the full correspondence between the *calcaires plaquettés* and the *calcari laminati di Papasidero* in Lao River valley and around Monte Ciagola. In the latter area, the metalimestones pass toward the northeast (Monte La Destra) to little strained Cretaceous and Jurassic limestones with intercalations of highly strained calcareous breccias and packstones (Fig. 2, **5**). Also, in the Monte Gada succession, horizons of strained Cretaceous calcareous breccias and oncoidal packstones are found within completely unstrained lithologies.

3.3. Aieta–Maratea

In the area between the Aieta village and Cozzo Petrara, metaconglomerates, foliated metalimestones and calc-schists are found under the Norian dolomites of the Verbicaro Unit Auctt. These rocks stratigraphically follow Jurassic and Cretaceous calcarenites and breccias characterized by little deformation. Similar features can be observed close to Massa di Maratea village, where little strained calcarenites pass toward the top to highly strained calcareous metabreccias and then to foliated metalimestones (Fig. 2, **4**).

4. Strain analysis

To estimate the strain in 2D, we carried out R_f/ϕ analysis [9,13], using aspect ratios and orientations of objects approximate to elliptical shapes in several XZ sections, both on weathered surfaces, polished slabs and thin sections.

To this aim we collected several samples of metapackstones and metaconglomerates. Mineralogically, they mostly consist of calcite with occasionally some dolomite, and quartz; rarely idiomorphic albite is found. In the calc-schists, graphite and oxides, and metamorphic white mica are present.

We determined the object strain ratio R_S by harmonic mean H_m of all aspect ratios of deformed objects comprising breccia pebbles and oncoids in packstones. To determine the XZ plane of the finite strain ellipsoid, we assumed that the lineation corresponds to the maximum elongation axis X, and the foliation to the principal flattening plane XY.

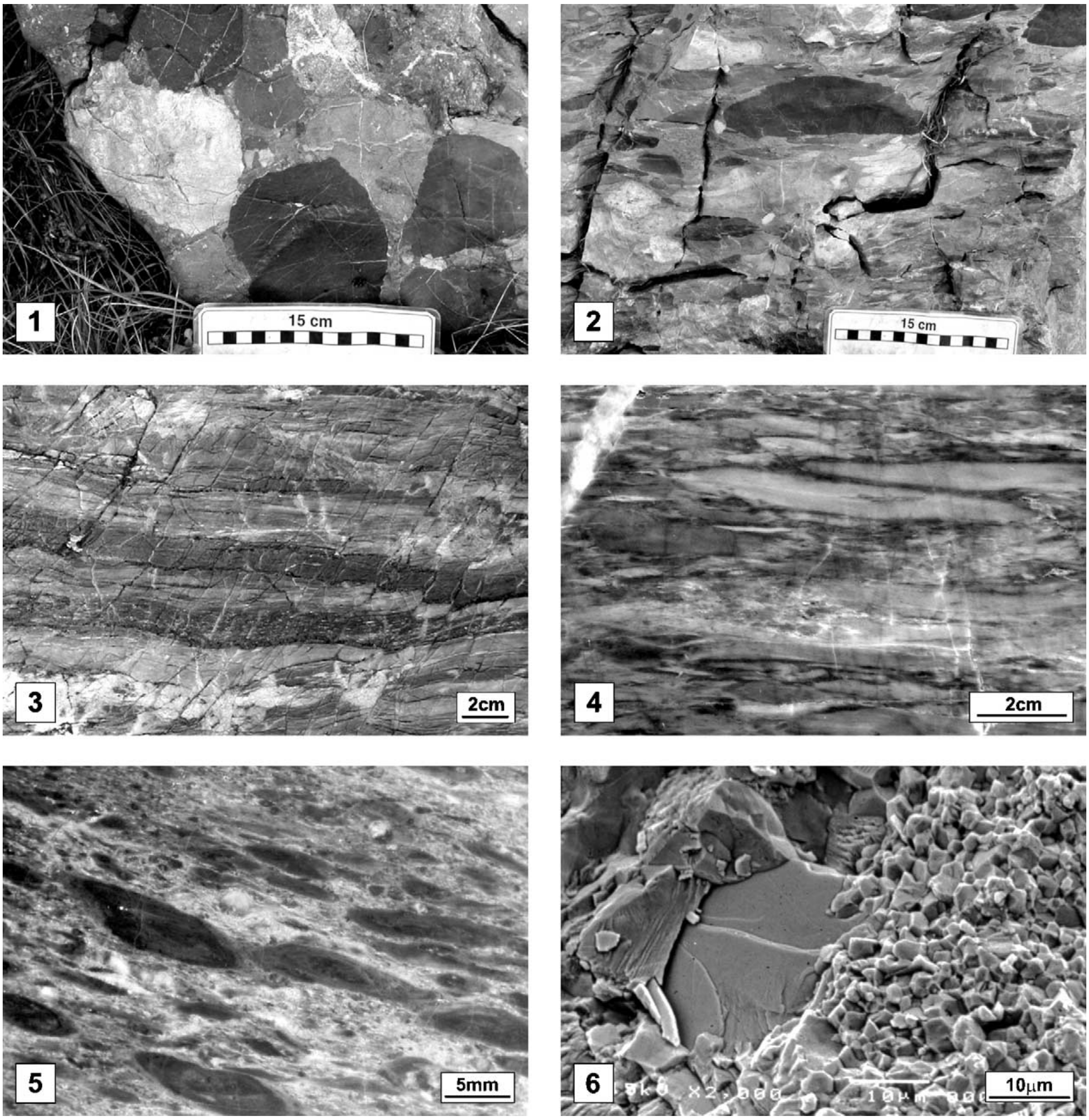

Fig. 2. **1–3.** Tertiary calcareous conglomerates showing increasing degree of strain. Campotenese area. **4.** Polished slab of a strained breccia. Maratea area. **5.** Strained Jurassic oncoidal packstone from Monte Ciagola. **6.** SEM image of the previous sample showing the boundary between micritic and sparry calcites.

Fig. 2. **1–3.** Conglomérats calcaires tertiaires montrant différents degrés de déformation. **4.** Surface polie d'une brèche très déformée. Maratea. **5.** *Packstone* à oncoïdes jurassique déformé du Monte Ciagola. **6.** Image au MEB de l'échantillon précédent, qui montre le contact entre calcites micritique et spatique.

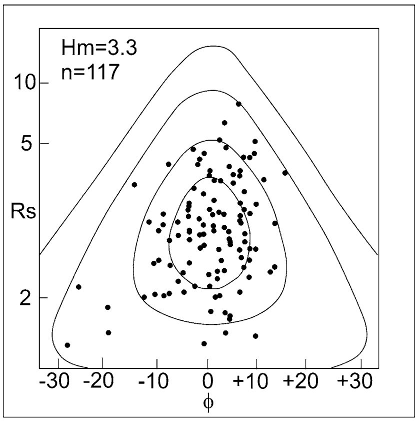

Fig. 3. R_f/ϕ diagram calculated for the sample in Fig. 2. **3.** R_f is the ratio between major and minor axis of any elliptical object; ϕ is the angle between major axes and the mean direction of objects elongation.

Fig. 3. Diagramme R_f/ϕ calculé pour l'échantillon de la Fig. 2. **3.** R_f indique le rapport entre les axes majeur et mineur de chaque objet elliptique ; ϕ indique l'angle entre l'axe majeur et la direction moyenne d'allongement des objets.

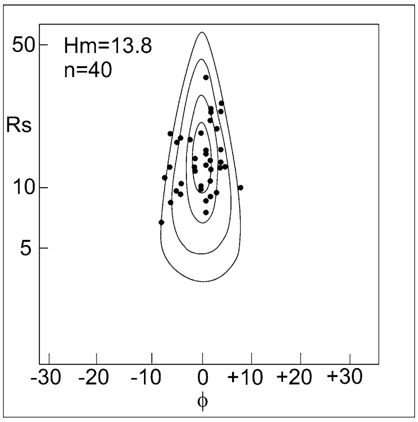

Fig. 4. R_f/ϕ diagram calculated for the sample in Fig. 2 (**5**).

Fig. 4. Diagramme R_f/ϕ calculé pour l'échantillon de la Fig. 2 (**5**).

Figs. 3 and 4 show some examples of the obtained R_f/ϕ diagrams. R_f/ϕ theoretical lines dependent upon original ellipticity R_i of objects ($R_i = 1.5$, 2, 3 and 4) are drawn in the R_f/ϕ diagrams. All distributions have a symmetrical shape, indicating absence of an original preferred orientation of elliptical objects. Some distribution shows a scattered pattern, indicating subsequent deformations.

The analysis in the Campotenese samples gives strain ratio R_{xz} values up to 13.8 (sample in Fig. 2, **3**). It should be remembered that the strain determined by R_f/ϕ analysis (R_s) of objects like pebbles in breccias or oncoids in metapackstones, is generally an underestimate of the whole rock strain [18]. Anyway, the strain ratios are certainly higher in the foliated metalimestones where it is impossible to apply R_f/ϕ method. The strain analysis of Jurassic–Cretaceous metabreccias and metapackstones of the other areas indicates strain ratio values up to 7 (sample in Fig. 2, **5**). The presence in most samples of transgranular and grain-to-grain stylolites indicates that a little part of the total strain has been accommodated by pressure-solution mechanism.

To investigate the deformation mechanism, we observed most of the analysed rocks using a light microscope and a SEM. In all the samples, only the micritic components (oncoids, micritic clasts) are macroscopically deformed, whereas the sparry ones (echinid, veins) preserve their original shape. At the microscopic scale, the micritic crystals of the deformed components still have their isometric shape (Fig. 2, **6**). Echinid calcite crystals, instead, even preserving original shapes, show evidence of intragranular strain (straight, bent or patchy twins, undulose extinction).

These observations suggest a grain-size depending deformation mechanism. In fact, in the case of micrite, the deformation mechanism appears to have been the grain boundary sliding [12,17], which may explain the macroscopic deformation of microscopically undeformed objects. In the case of crystals larger than 10 μm, the main deformation mechanisms are twinning [5] and dislocation gliding [16]. The absence of significant aggrading recrystallization suggests relatively low temperatures. The proposed mechanisms may be active also below 400 °C, when a significant amount of fluids is present [14].

5. Conclusions

A structural study, carried out on some selected outcrops of the carbonate units of northern Calabria, has revealed remarkable examples of strain localization within ductile shear zones. The deformation affects limestones and minor marly limestones belonging to several carbonate successions overthrusted by the Verbicaro Unit Auctt. Immediately below the tec-

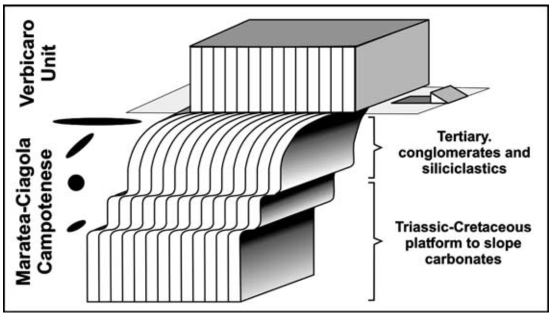

Fig. 5. Schematic diagram showing the relationship between intensity of deformation and structural position of the studied rocks.

Fig. 5. Schéma montrant la relation entre l'intensité de la déformation et la position structurale des roches étudiées.

tonic contact, the strain ratio is extremely elevated and results in the formation of the *calcaires plaquettés* described by former authors. The recognition of the protoliths has proved their stratigraphic equivalence with Tertiary calcareous conglomerates and marls of the overlying Verbicaro Unit Auctt. Within the thick Mesozoic carbonate succession, instead, several shear zones occur at different stratigraphic heights, but finite strain is systematically lower. We imply (Fig. 5) that the higher deformation of the Tertiary conglomerates can be explained by their position immediately below Miocene siliciclastic deposits, a fact that favoured focussing of fluids.

These preliminary data have profound implications on the regional geology of this area that represents the border between the metamorphic Calabrian Arc and the non-metamorphic southern Apennines. In fact, it results that all the carbonates underlying the Verbicaro Unit Auctt. are affected by the same kind of ductile deformation, whose intensity changes over short distances. This indicates that the attribution of Campotenese, Ciagola and Aieta–Maratea outcrops to two different tectono-stratigraphic units (San Donato and Pollino), characterised by markedly different metamorphic character, as widely reported in all the literature starting from Amodio Morelli et al. [1], is untenable. However, it is equally clear that a sharp structural contrast does exist between these deformed carbonates and the calcareous Apennine, including the succession of the nearby Pollino massif, which is totally devoid of any ductile deformation. A new definition of the tectonic units of northern Calabria, based on a close examination of the structural style and the stratigraphic analysis of the protolith, is thus the aim of our ongoing research as a contribution toward a correct understanding of the palaeogeography and kinematics of the area.

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References

[1] L. Amodio Morelli, G. Bonardi, V. Colonna, D. Dietrich, G. Giunta, F. Ippolito, V. Liguori, S. Lorenzoni, A. Paglionico, V. Perrone, G. Piccarreta, M. Russo, P. Scandone, E. Zanettin-Lorenzoni, A. Zuppetta, L'Arco calabro-peloritano nell'orogene appennino-maghrebide, Mem. Soc. Geol. It. 17 (1976) 1–60.

[2] G. Bigi, D. Cosentino, M. Parotto, R. Sartori, P. Scandone, Structural Model of Italy, CNR, Italy, 1991.

[3] J.-C. Bousquet, La tectonique tangentielle des séries calcaréo-dolomitiques du Nord-Est de l'Apennin calabro-lucanien (Italie méridionale), Geol. Romana X (1971) 23–52.

[4] J.-C. Bousquet, C. Grandjacquet, Structure de l'Apennin calabro-lucanien (Italie méridionale), C. R. Acad. Sci. Paris, Ser. D 264 (1969) 204–207.

[5] M. Burkhard, Calcite twins, their geometry, appearance and significance as stress-strain markers and indicators of tectonic regime: a review, J. Struct. Geol. 15 (1993) 351–368.

[6] B. Compagnoni, A.V. Damiani, Note illustrative della Carta Geologica d'Italia, foglio 220 Verbicaro, Servizio geologico d'Italia, 1971.

[7] A.V. Damiani, Osservazioni geologiche in alcune tavolette del F° 220 nella Calabria Settentrionale Nord Occidentale, Parte I. Stratigrafia, Boll. Soc. Geol. It. 89 (1970) 65–80.

[8] B. D'Argenio, T. Pescatore, P. Scandone, Schema Geologico dell'Appennino Meridionale (Campania e Lucania), Quad. Acc. Naz. Lincei 183 (1973) 49–72.

[9] D. Dunnet, A technique of finite strain analysis using elliptical particles, Tectonophysics 7 (1969) 117–136.

[10] C. Grandjacquet, M.-J. Grandjacquet, Géologie de la zone de Diamante–Verbicaro (Calabre), Geol. Romana 1 (1962) 297–312.

[11] E. Patacca, P. Scandone, M. Bellatalia, N. Perilli, U. Santini, The Numidian Sand event in the Southern Apennines, Mem. Sci. Geol. 43 (1992) 297–337.

[12] R. Raj, M.F. Ashby, Grain boundary sliding and diffusional creep, Metall. Trans. 2 (1971) 1113–1127.
[13] J.G. Ramsay, M. Huber, The Techniques of Modern Structural Geology, vol. I, Strain Analysis, Academic Press, London, 1983.
[14] E.H. Rutter, The influence of temperature, strain rate and interstitial water in the experimental deformation of calcite rocks, Tectonophysics 43 (1974) 311–334.
[15] P. Scandone, Studi di geologia lucana: nota illustrativa alla carta dei terreni della serie silico-marnosa, Boll. Soc. Natural. Napoli 81 (1972) 255–300.
[16] S.M. Schmid, Laboratory experiments on rheology and deformation mechanisms in calcite rocks and their application to studies in the field, Mitt. Geol. Inst. ETH & Univ. Zurich 241 (1982) 1–62.
[17] S.M. Schmid, J.N. Boland, M. Paterson, Superplastic flow in fine-grained limestone, Tectonophysics 43 (1977) 257–291.
[18] S.H. Treagus, J.E. Treagus, Studies of strain and rheology of conglomerates, J. Struct. Geol. 24 (2002) 1541–1567.
[19] A. Vallario, G.B. De Medici, Contributo alla conoscenza stratigrafica della Calabria Settentrionale. I: La serie del Collle Trodo, Boll. Soc. Geol. It. 86 (1967) 233–252.