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GEOLOGICAL STRUCTURES AFFECTING THE MARBLE MINING IN THE APUAN ALPS (NORTHERN APENNINES)

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EXTENDED ABSTRACT

La finestra tettonica delle Alpi Apuane costituisce la porzione geometricamente più bassa, nota in affioramento, dell'edificio a falde dell'Appennino Settentrionale. In quest'area affiorano sia i terreni metamorfici profondi della catena (Unità di Massa e Unità delle Alpi Apuane), sia le unità tettoniche più superficiali rappresentate dall'alto verso il basso dalle Unità Liguri *s.l.*, Sub-liguri e dalla Falda Toscana. Le Alpi Apuane sono costituite da rocce metamorfiche di medio-basso grado, con età compresa fra il Cambriano Inferiore e il Miocene Inferiore, appartenenti all'unità tettonica dell'"Autoctono" *Auctt.* (recentemente rinominata Unità delle Alpi Apuane). Tale unità tettono-metamorfica è caratterizzata dalla presenza di un basamento continentale di età paleozoica, sopra al quale affiora, in discordanza, una copertura costituita da una successione metasedimentaria di età compresa fra il Triassico Superiore ed il Miocene Inferiore. L'evoluzione tettonica del Complesso Metamorfico Apuano è polifasica ed è caratterizzata da una deformazione da duttile a fragile, legata all'evoluzione tettono-metamorfica terziaria del cuneo orogenico che costituisce l'Appennino settentrionale. Secondo le interpretazioni divenute ormai classiche la strutturazione di questo settore di catena, si è realizzato secondo due fasi regionali principali, indicate in letteratura come D1 e D2, sviluppatesi in condizioni metamorfiche di basso grado (facies scisti verdi), ed un evento D3, recentemente ipotizzato, e tuttora in fase di studio, evoluto in condizioni da tardo-metamorfiche a post-metamorfiche. L'evento D1, sviluppato in regime tettonico compressivo, ha prodotto sovrascorrimenti e pieghe isoclinali in vario grado non cilindriche, spesso a guaina, caratterizzate da una vergenza verso Nord-Est, ed una scistosità sin-metamorfica di piano assiale associata ad una pronunciata lineazione di estensione orientata circa Nord Est - Sud Ovest ben sviluppata in quasi tutte le formazioni metamorfiche. L'evento D2, sviluppato in regime tettonico estensionale, si è realizzato mediante zone di taglio duttili inclinate verso Sud Ovest lungo il fianco Sud occidentale del Complesso Metamorfico ed inclinate verso Nord Est lungo il fianco Nord orientale. L'opposto senso di movimento delle zone di taglio distensive sui due versanti del Complesso Metamorfico Apuano ha determinato la sovrapposizione di pieghe sin - D2 Sud Ovest vergenti su pieghe sin - D1 Nord Est vergenti lungo il versante occidentale e di pieghe sin - D2 su pieghe sin - D1 con la stessa vergenza verso Nord Est sul versante orientale.

L'evento D3 complica ulteriormente il quadro deformativo sopra descritto, esso si imposta sulle precedenti strutture mediante zone di taglio a basso angolo e faglie ad alto angolo sia "top-Sud Ovest" sia "top-Nord Est". Tali zone di taglio e faglie dirette a basso angolo sono associate a complicati sistemi di trasferimento sia destri che sinistri che complessivamente determinano l'immersione assiale verso Nord Est e verso Sud Ovest del complesso metamorfico delle Alpi Apuane. Questi sistemi di faglie e zone di taglio rappresentano un elemento di novità nel panorama geologico delle Alpi Apuane, e derivano da nuove informazioni acquisite attraverso tradizionali rilevamenti geologico-strutturali di campagna e da attività di foto-interpretazione di dati derivati da LIDAR aereo ed optical proximal sensing. Queste particolari strutture e la loro architettura tridimensionale condizionano la geometria dei giacimenti di pietre ornamentali e quindi anche la programmazione delle attività estrattive a medio e lungo termine. Gli effetti della deformazione da fragile/duttile a duttile che caratterizza il Complesso Metamorfico Apuano, ha portato allo sviluppo di zone di taglio con marmi milonitici i quali sono caratterizzai da eccellenti caratteristiche fisiche e meccaniche. Molti delle più famose varietà merceologiche di marmo si trovano lungo questi importanti sistemi di zone di taglio e sono caratterizzati da miloniti e metabrecce a clasti appiattiti e allungati, come alcune tipologie marmo Bianco, Bardiglio, Nuvolato e Arabescato. Le loro proprietà fisiche e meccaniche uniche, note già in antichità, sono da mettere in relazione alla loro significativa variabilità micro-strutturale legata allo sviluppo di zone di taglio durante le fasi finali dell'esumazione del Complesso Metamorfico Apuano. L'identificazione e lo studio ancora in corso di queste importanti zone di taglio è quindi di fondamentale importanza per la pianificazione e lo sfruttamento dei giacimenti marmiferi, caratterizzati da un alto valore commerciale ed estetico.

ABSTRACT

The still ongoing studies on the geology of the Apuan Alps show the presence of a deformational event which is developed in the late-metamorphic to post-metamorphic conditions (D3), that has occurred on the previous structures and has created the low-angle shear zones and high-angle faults, associated with both right hand and left hand complicated movement systems. These shear zones represent a new element in the geological landscape of the Apuan Alps, and our knowledge about them is deducted from the information obtained from the traditional geological-structural surveys and photo-interpretation of data derived from aerial LIDAR and optical proximal sensing. The effects of brittle/ductile to ductile deformation which characterizes the Apuan Metamorphic Complex, has established the development of shear zones consisting the mylonitic marbles, such as the specific types of Bianco, Bardiglio, Nuvolato and Arabescato marbles, which are distinguished by their excellent physical and mechanical characteristics, as well as having high commercial and aesthetic value. These particular structures and their three-dimensional architecture affect the geometry of the deposits of ornamental stones and as the consequence, also on the planning of medium and long-term mining activities.

Key words: *shear zone, mylonite, marble, Apuan Alps*

INTRODUCTION

The marbles of the Apuan Alps, for several years, have been the subject of studies, since they represent the best known stone materials and are commonly used by designers, architects and artists to decorate and embellish the various cities throughout the world. In particular, in recent years, the marble of the Apuan Alps are the subject of detailed geological and structural studies to identify its deformational microscopic and mesoscopic characteristics.

According to the different lithological, mineralogical and microstructural characteristics, the marbles can be divided into the marbles with tectonic-derived origination and those with stratigraphic-derived origination. The former consists of many types of Arabescato, Fantastico and some types of Bianco, Bardiglio and Nuvolato marbles, and corresponds to the zones of lamination and/or ductile tectonic-interdigitation which may be originated to very high transposition phenomena related to syn-metamorphic (D1 and D2) and post-metamorphic (D3) deformational events. These rock types are found primarily in the hinge region of narrow or isoclinal folds, along the inverted flanks of the large anticlinal structures of laminating or along the shear zones that are developed during the exhumation of the Apuan Metamorphic Core. Rather, the latter is represented by merceological types, such as Ordinario, Venato, Bianco, gray marbles and breccia, which represent the result of the tectono-metamorphic transformations of carbonate rocks, mainly of Triassic-Liassic carbonate platform.

GEOLOGICAL SETTING OF THE APUAN ALPS

The northern Apennines are characterized by a pile of thrust-sheets derived from the distal part of the Adriatic continental margin (Tuscan Domain) currently lying below the oceanic Ligurian and sub-Ligurian accretionary wedge units (Elter, 1975; Carmignani & Kligfield, 1990; Liotta, 2002; Molli, 2008 and references therein). The Apuan Alps represents the largest tectonic window in the inner northern Apennines where the deepest levels (Tuscan Metamorphic Units) of the belt are exposed.

The tectono-metamorphic complex is composed of two major units which are traditionally distinguished in Massa unit and the Apuan unit ("Autochthon" *Auctt.*) Fig. 1). The former is well exposed in the westernmost part of the Apuan Alps and consists of a Paleozoic basement and an Upper Permian–Upper Triassic sedimentary succession that have registered a metamorphic imprint of a higher grade than that of the Apuan unit (kyanite and chloritoid in metapelites; Molli *et alii*, 2000, 2002 and references therein). Our study focusses on the Apuan unit whose litho-stratigraphic sequence is made up of a Paleozoic basement which with an unconformity has been laid under the Upper Triassic–Oligocene metasedimentary sequence. The Mesozoic cover rocks consist of thin Triassic continental to shallow water deposits which refer to the typical "Verrucano" formation, followed by Upper Triassic–Liassic carbonate platform metasediments that include dolomites (Grezzoni formation), dolomitic marbles and marbles (worldwide known as "Carrara marbles"). These are laid under the Middle Liassic–Lower Cretaceous cherty meta-limestones, cherts and calcschists, and under the Lower Cretaceous–Lower Oligocene sericitic phyllites and calcschists, with the marble interlayers, which are related to deep-water sedimentation during the drowning of the former carbonate platform. Oligocene sedimentation of turbiditic metasandstones (Pseudomacigno formation) closes the sedimentary history of the external Tuscan Domain.

The regional tectonic setting of the Apuan Alps is the result of two main tectono-metamorphic events (D1 and D2 phases of Carmignani & Kligfield, 1990) which are regarded as recording progressive deformation of the distal Adriatic continental margin during the continental subduction and the syn- to post-contractional exhumation (Molli & Meccheri, 2000; Molli *et alii*, 2002; Molli & Vaselli, 2006; Molli & Meccheri, 2012).

The ductile compressional D1 event was due to the Tertiary continental collision between the Sardinia–Corsica block and the Adria plate, and was followed by the D2 and D3 extensional events that resulted an isostatic rebalance (Carmignani & Kligfield, 1990). During the D1 event, which can be associated

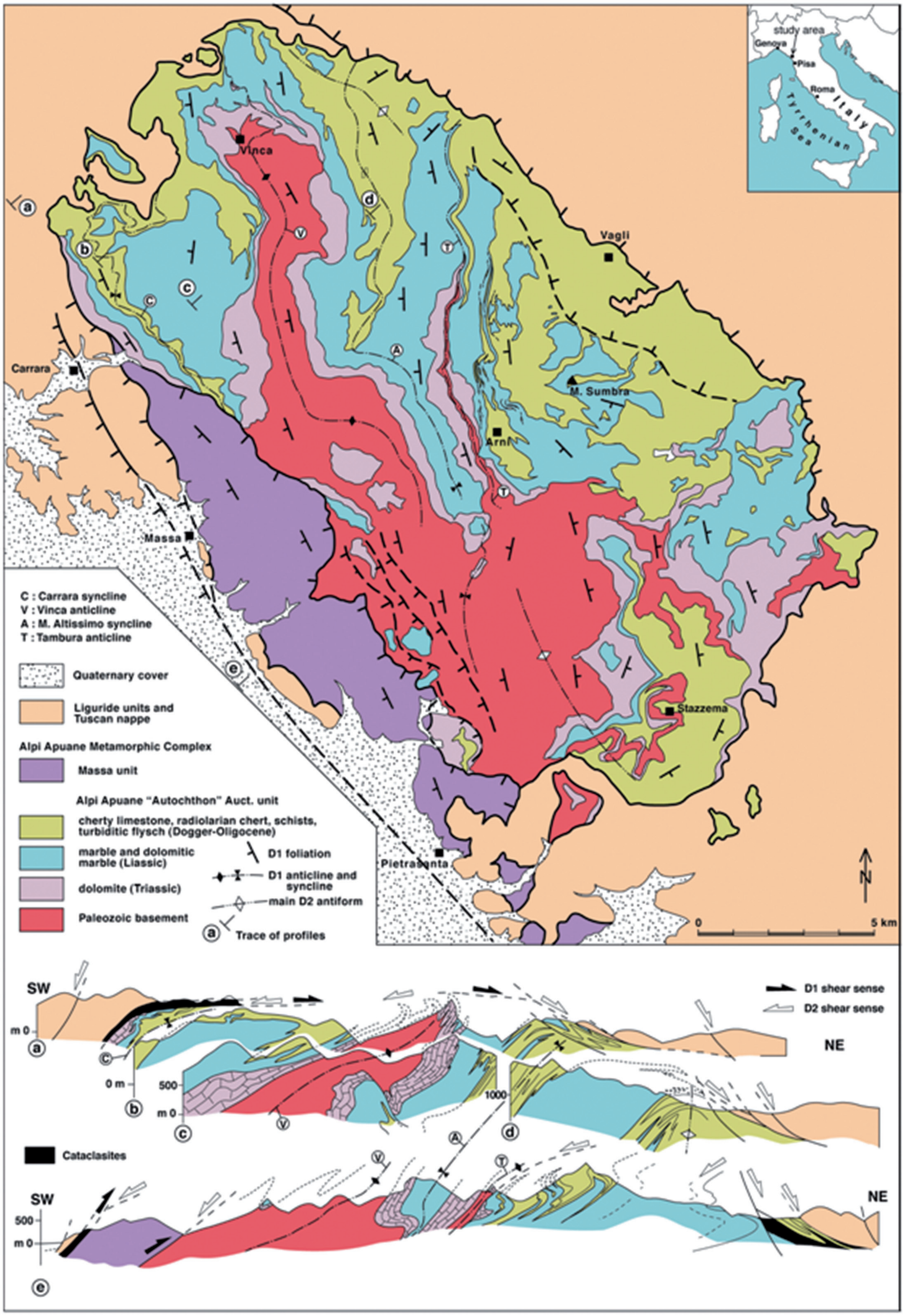

Fig. 1 - Tectonic sketch map of Apuan Alps (from Conti *et alii, 2004).*

with underplating, the stacking took place of the tectonic units belonging to the Tuscan and Ligurian domains, with development of a progressive deformation in two stages (Molli & Meccheri, 2000), which their main one is represented by greenschist foliation (Sp) that is axial plane of isoclinal micrometric to kilometric scaled folds. This foliation, which characterizes most of the metamorphic rocks of the Apuan Alps, is associated with a stretching lineation of SW–NE trend, interpreted as the main transport direction of the inner northern Apennines (Carmignani *et alii*, 1978; Molli, 2008). During the D2 event, the previously formed structures were reworked and developed by different generations of folds and along high strain zones associated with exhumation and vertical movement of the metamorphic unit within the inner portion of the northern Apenninic wedge (Molli & Vaselli, 2006; Molli, 2012). The result of this second deformative phase is a complex mega-antiform with the axis of Apennines-trend (NW–SE) (Carmignani & Kligfield, 1990). This trend is associated with non-cylindrical parasitic folds with sub-horizontal axial planar crenulations that involve the transportation to the east on the eastern and to the west on the western limbs of the antiform (Carmignani & Kligfield, 1990; Carmignani *et alii*, 1993).

The D3 phase is set on previous D1 and D2 structures, and is developed through the metamorphic complex, as well as its overlaying units, by low-angle shear zones and high-angle faults with "top-SW" and "top-NE" dip directions as in the classic scheme of Carmignani & Kligfield (1990). These low-angle shear zones and high-angle normal faults are associated with complicated systems of transfer both right-hand and left-hand which together determine the dip direction towards the NE of the metamorphic complex in the North and the SW in the southern Apuan Alps.

Late stages of D3 are characterized by the development of semi-brittle and brittle structures (low- and high angle faults, joint systems) associated with the final exhumation and uplift of the metamorphic units in a frame of late to post-orogenic regional extension of the inner part of the northern Apennine (Ottria & Molli, 2000; Corti *et alii*, 2006; Molli *et alii*, 2010 and references therein).

According to Molli *et alii* (2000, 2002), Molli & Vaselli (2006), Fellin *et alii* (2007, and references therein), the peak of metamorphism has occurred in the Early Miocene (approximately at 27 Ma; Kligfield *et alii*, 1986), during the early D1 phase, at the temperature around 300-450°C and the pressure approximately 0.3-0.8 GPa (Di Pisa *et alii*, 1985; Kligfield *et alii*, 1986; Franceschelli *et alii*, 1986; Jolivet *et alii*, 1998; Franceschelli & Memmi, 1999; Molli *et alii*, 2000, 2002). The early stage of the D2 phase the syn-metamorphic D2 structures have developed at a T higher than 250°C and according to zircon fission-track ages of Fellin *et alii* (2007) are dated 11 Ma.

DEFORMATIONAL AND MICROSTRUCTURAL CHARACTERISTICS OF THE MARBLE OF APUAN ALPS

The Apuan marbles have played a key role in the crustal deformation of the Apennine chain. In fact, carbonate rocks are able to accommodate large amounts of strain and plastically deform even under the conditionsof low pressure and temperature. In many orogenic chains, such as the Alps, with the consequent development of mylonites the main shear zones develop within carbonate rocks. Hence, the study of textural and microstructural characteristics of carbonate rocks which are ductilely deformed lets us to acquire plentiful information about them, such as the regime of stress and strain, the kinematics, the regime of deformation within these shear zones and their evolution over time, as well as representing the rock types which have superb physico-mechanical characteristics. For these reasons and because of their particular composition (these rocks consist of almost only calcite), the marble of the Apuan Alps has been the subject to numerous geological studies for their mineralogical and petrographic characteristics (Zaccagna, 1932; Bonatti, 1938; D'Albissin, 1963; Crisci *et alii*, 1975; Di Sabatino *et alii*, 1977; Di Pisa *et alii*, 1985; Coli, 1989; Coli & Fazzuoli, 1992; Cortecci *et alii*, 1999; Molli & Heilbronner, 1999; Molli *et alii*, 2000a; Leiss & Molli, 2003; Oesterling *et alii*, 2007), and also to many experimental studies of rock deformation (Rutter, 1972, 1995; Casey *et alii*, 1978; Spiers, 1979; Schmid *et alii*, 1980, 1987; Wenk *et alii*, 1987; Fredrich *et alii*, 1989; De Bresser, 1991; Covey Crump, 1997, 1998, 2001; Pieri *et alii*, 2001; 2001a). These marbles, investigated by various authors, come from different stratigraphic horizons of Metamorphic Complex of the Apuan Alps.

Within the marble lithologies of Apuan Unit, the marbles and monogenic or polygenic metabreccia belong either to the Triassic formations, such as Vinca formation, Brecce di Seravezza and Megalodonti Marbles, or to the lower Jurassic formations, such as Marmi Dolomitici, Marmi, and Marmo Zebrino. Yet, the more or less pure marble rock types (e.g. Marmi Cipollini), polygenic metabreccia and schists are present in the Mesozoic-Tertiary cover.

Rather, within the Massa Unit, marble lithologies belong to the Marmi a Crinoidi formations. Furthermore, major deformational events of Apuan Metamorphic Complex have created the systems of folds and shear zones which together make up a very heterogeneous deformation pattern. Therefore, Apuan marbles have undergone a geometric deformation, which in very simple cases, has caused the duplication or narrowing their original thickness.

As previously mentioned, of the Apuan Alps marble have been used for various experimental studies of the rock deformation, and this is because from the microscopic point of view, they are commonly considered as an example of a natural material that has undergone a complete annealing process or, in other words, a complete static post-deformation recrystallization. This process develops the typical polygonal granoblastic texture (foam microstructure) with a weak or absent crystallographic preferred orientation (CPO). Within this microscopic fabric a certain variability of particle size may be noticed. As it is already remarked by Zaccagna (1932) and by later authors (Crisci *et alii*, 1975; Di Pisa *et alii*, 1985; Coli, 1989; Molli *et alii*, 2000a), the average size of the calcite crystals, increases from 80-100 µm in the eastern and central zones of the Apuan Alps to 150-300 µm in their western parts. According to Di Pisa *et alii* (1985); Molli *et alii* (2000a); and Oesterling *et alii* (2007), this granulometric variability is associated with an incensement of calcite-dolomite temperatures from 340-360°C in the eastern parts to 430-450°C in the West. Recent investigations (Molli & Heilbronner, 1999; Molli *et alii*, 2000a; Leiss & Molli, 2003; Oesterling *et alii*, 2007), within the Apuan Alps marble, have highlighted the presence of microstructures that can be correlated to deformation processes and dynamic recrystallization. Within the Apuan Alps marbles, Molli *et alii* (2000a) have recognized three main microstructures: (1) microfabric Type-A, characterized by granoblastic texture resulting from static recrystallization processes, with equidimensional grains (foam microstructure) and straight grain boarders which converge in triple junctions, where form angles of 120°; (2) Type-B microfabric, characterized by microstructures of syntectonic dynamic recrystallization. In this microfabric, two main end members are recognizable: Type-B1 that consists of a well-developed orientation of the preferred form, large size of the lobated calcite crystals; and Type-B2 which is characterized by a strong orientation of the preferred form, small crystals of calcite with straight granular edges; and (3) microfabric Type-C, represented by a late crystal gemination, characterized by fine straight twinning superimposed upon both Type-A and Type-B microfabrics. These three main microfabrics represent the extreme terms of a wide range of intermediate types, sometimes observable with explicit overlapping relations on one another. This microstructural variability has been associated with geological structures, such as folds and shear zones (Oesterling *et alii*, 2007), and placed into an evolutionary tectonic model (Molli *et alii*, 2000a) (Fig. 2).

During the D1 deformation phase different tectonic units have laid over each other, resulting the development of dynamic microfabric (Type-B) and the main metamorphic foliation (Fig. 2a). After the early stages of deformation, following the thermal balance within the accretionary prism and/or decrement in the strain rate, static recrystallization phenomena have developed the Type-A microfabric in Apuan marbles (Molli *et alii*, 2000a) (Fig. 2b). During the final stages of the D1 phase (Fig. 2c), there is the development of shear zones, with dimensions ranging from one to few meters, which has developed the dynamic type microfabric and partially reworked the previous static microstructures (Molli *et alii*, 2000a; Oesterling *et alii*, 2007). These structures are probably linked to the initial exhumation and transporting the deeper structural levels of the West northeastwards, namely toward more superficial structural levels.

The D2 deformation phase is associated with the progressive exhumation and retrograde metamorphism of Apuan Metamorphic Complex. In particular, within the shear zones of main folded structures of D2, still the lower temperatures of recrystallization produce dynamic recrystallization processes are associated with the development of a new generation of mylonites in the marble with microfabric of Type-B (Oesterling *et alii*, 2007) (Fig. 2d). The temperature variation during the D2 event, 380°C in the eastern sectors and 340°C in the West, can be explained by considering the deeper structural position of the eastern areas in the early stages of the mentioned phase (Molli *et alii*, 2000a).

THE COMMERCIAL VARIETY OF THE APUAN ALPS MARBLES

The first modern representation of the mining of the Apuan Alps marble is a manuscript map (scale 1: 25,000) of the area of Carrara (D. Zaccagna) (Fig. 3) which according to the content and style of the design can be dated back to the late nineteenth and early twentieth centuries. The new thematic map of stone materials of the Apuan marble field appear in the mid-1970s, under the project of "Progetto marmi". The results of these studies are presented in the Geological-Structural Map of Metamorphic Complex of the Apuan Alps ("Foglio Nord", Carmignani, 1985) and in the catalog of merceological variety of Apuan marbles (ERTAG, 1980). Subsequently, detailed maps have been made for the north-eastern marble quarries of Orto di Donna (Coli *et alii*, 1987) and of Boana (Coli, 1992), to the basin of Carrara (Meccheri, 1996; Meccheri *et alii*, 2004; 2004a) and the eastern center of Monte Altissimo (Meccheri *et alii*, 2007). In these maps, different marble varieties are described and mapped according to geological and stratigraphic criteria, that is, the different types of marble are interpreted as primary lithostratigraphic variations related to different depositional environments within the Jurassic Carbonate Platform. The lithological, mineralogical and stratigraphic characteristics of commercial varieties are therefore considered not only for classification purposes, but also in order to define a stratigraphic succession of them.

This approach, though correct in principle, have some limitations to apply for Apuan marbles, due to the following factors: 1) The origin of the marbles: the majority of the extracted stone materials in the Apuan Alps, except for some types of metabreccia and schists (e.g. Breccia di Seravezza

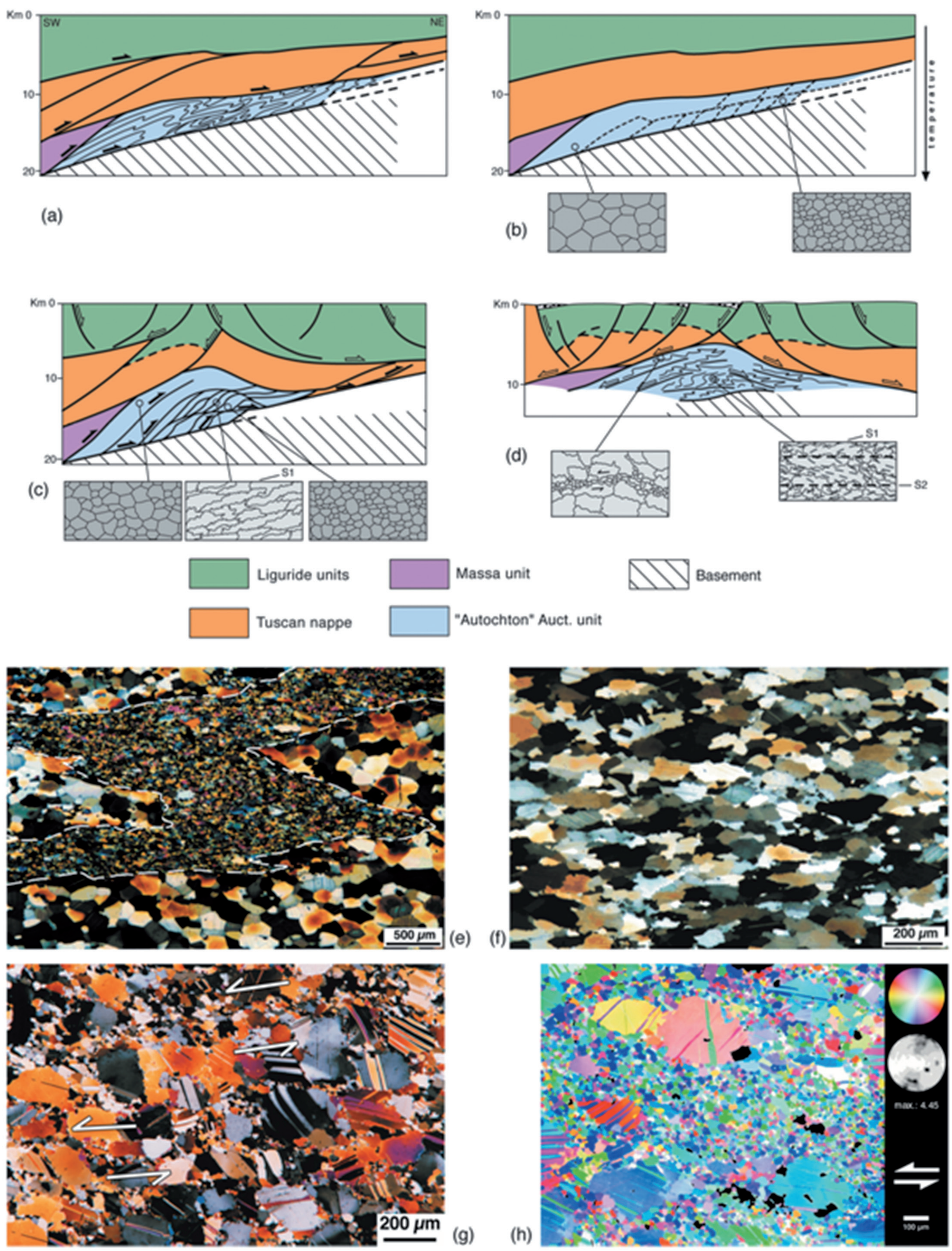

Fig. 2 - Microfabrics in the Apuan Alps marbles (after Molli et alii, 2000a). (a) D1 phase, with the development of main foliation and km-scaled isoclinal folds. (b) After D1 main folding phase annealing occurred, with annealining and complete obliteration of earlier microfabrics. (c) During final D1, NE transport along thrusts, the annealed microstructures are passively transported toward NE or reworked in shear zones along thrusts. (d) D2 deformation has created the folding and shear zones along low angle normal faults. Earlier microstructures are be reworked in D2 shear zones or along D2 fold axial planes. (e) Typical D1 folds, overprinted by annealed microstructure. (f) Shape preferred orientation of grains parallel to axial plane foliation of D2 fold. (g) Dynamically recrystallized microstructures along D2 shear zone. Strain is associated with core-mantle structure, grain size reduction and rotation recristallization. (h) C-axes orientations image revealed by computer-aided microscopy (Heilbronner Panozzo & Pauli, 1993). The thin section image is colour coded according to its c-axis orientation and a stereographic Colour Look-up Table. The thin section shows a strong crystallographic preferred orientation oriented normal to the shear zone boundary

and Cipollini) are derived from lower Lias carbonate platform sediments of Tuscan Domain. This geological-stratigraphic setting characterizes the Carrara marble basin, where all the extracted commercial varieties (e.g. Ordinario, Statuario, Venato, Arabescato, etc.) come from the Marmi formation (Lower Lias). Instead, the extracted stone materials from other marble basins (such as M. Corchia, Forno, Arni, Arnetola, Orto di Donna, etc.) are not only from the Marmi formation, but also from the formations above or below it, like the Marmi Megalodonti and Marmi Dolomitici formations. The two latter, which in many cases show the lithological characteristics (lithotype, color, etc.) very similar to those of the formation of the Marmi, are identified in the trade with the same product name, apart from the geological and stratigraphic significance, though; 2) The story of marble deformation: the Apuan marble during its tectono-metamorphic evolution has undergone the recrystallization processes that obliterated many original features of the sedimentary protolith. Additionally, as a result of the three main deformational events of D1, D2 and D3, they are characterized by a complex geometrical deformation that is associated with the transposition of the sedimentary and/or metamorphic layering from their origins to the deformational zones (shear zones) and to the interferential structures between different fold systems. Such geological-structural settings,

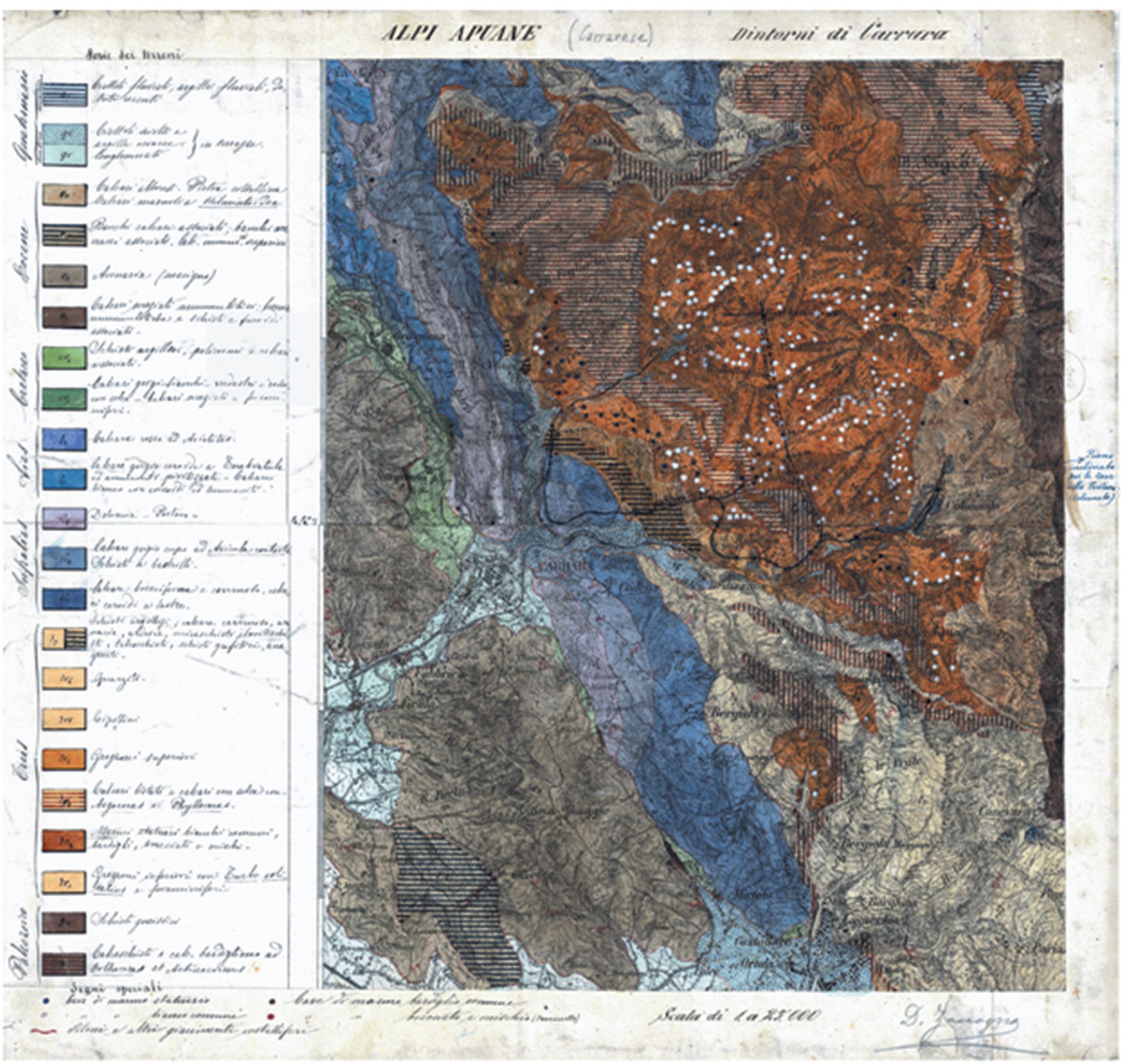

Fig. 3 - Geological map of the area NE of Carrara by Donenico Zaccagna (realisation age unknown, from the library colletion of the Servizio Geologico Italiano, Roma). Note the indications of marble commercial varieties and marble quarries locations

in some cases, can be related to the main features of the extracted material (e.g. Fantastico, Nuvolato and some types of Arabescato); 3) The origin of commercial types: the famous commercial types are born in response of the need to identify the different types of present marbles. The terms which today are in use (Arabescato, Calacatta, etc.) have their origins in the centuries-old history of the extraction and trade of the material, and have been coded independent of the geological and structural-stratigraphic implication of these materials.

In order to define a legend of commercial varieties of the marble, valid for the entire Apuan marble zone, Carmignani *et alii* (2007) consider a commercial variety as an "informal lithostratigraphic unit" which represents a distinguishable rock body and in function of a general lithological homogeneity and also for the presence of other particular characteristics, for instance their utility or economic concern, is separable from the adjacent ones. Therefore, a commercial marble can be comprehensively described and separated from adjacent ones based on characters that are either just lithological (metalimestone, metabreccia, calcschist, etc.) or properly commercial and aesthetic (e.g. color and design), regardless of its stratigraphic-structural significance. The direct consequence of this is that the same type of marble can be recognized and mapped in different stratigraphic and/or structural positions within the metamorphic Apuan succession (Fig. 4). The lithological characters which are taken into account in determining the commercial types are the result of a range of observations of the outcrop and the optical microscope analysis and they concern: I) the predominant lithotype (marble, monogenic or polygenic impure marble metabreccia, calcschist etc.); II) the rock structure (e.g. homogenous or heterogeneous rock); III) the average size of the crystals of calcite (fine grained <150 µm, medium grain 150-350 µm, coarse grained >350 µm); IV) the mineralogical composition; V) in the case

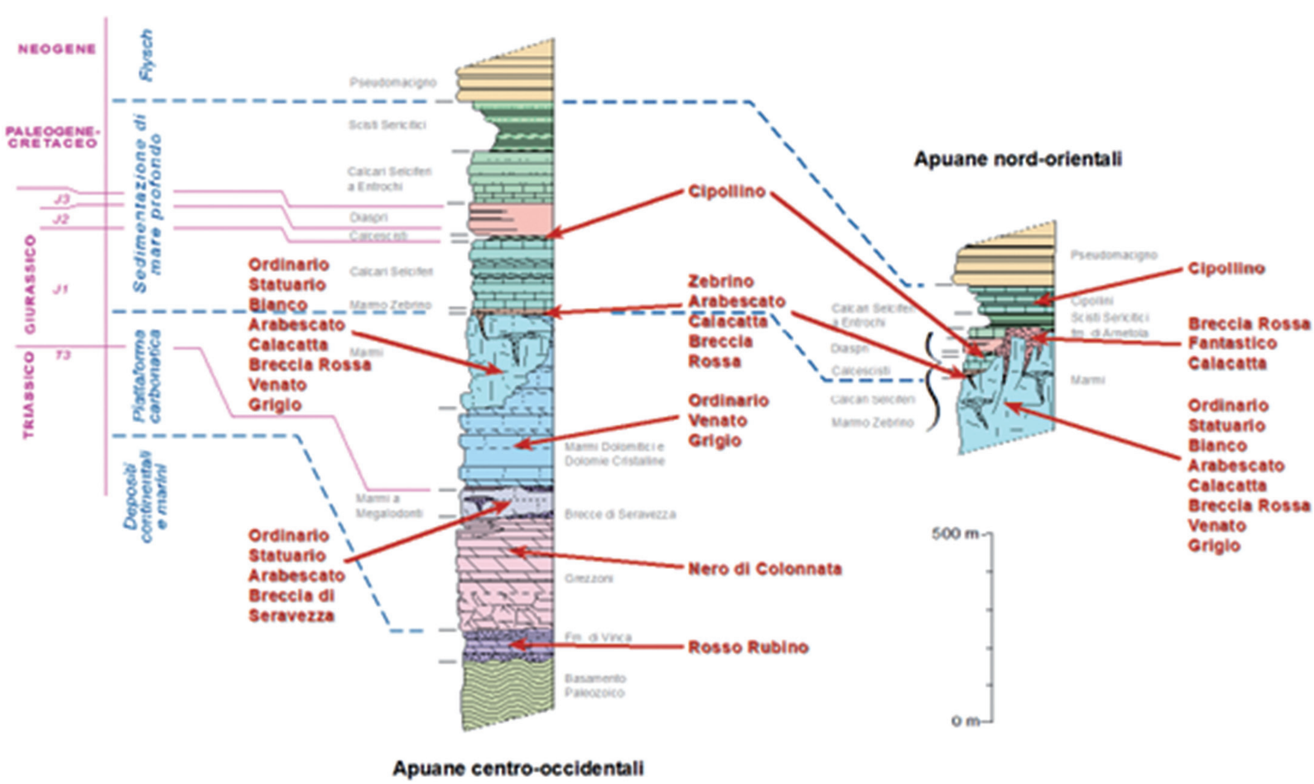

Fig. 4 - The merceological variety of marbles (in red) in the metamorphic sequence of the Apuan Alps. Paleozoic Basement: phyllite, porphyroids, porphyritic schists, dolomite, graphitic phyllites and schists (?Cambrian - ?Devonian); Vinca formation: phyllites, quartzites and metaconglomerates alternating with dolomite, marble, dolomitic marble, and polygenic metabreccia (Carnian - ?Norian); Grezzoni: dolomite, dolomite breccia and blacks marbles alternating with dolomite (Norian); Megalodonti Marbles, Brecce di Seravezza: marbles, polygenic metabreccia and chloritoid schist; Dolomitic Marbles: marbles, dolomitic marble and dolomite (Lower Lias); Marbles: marbles and monogenic metabreccia (Lower Lias); Zebrino Marble: marble, metabreccia and schists (Lower Lias - ?Middle); Cherty Limestone: metalimestone with lists and nodules of cherts (Middle - Upper Lias); Calcschists: schists and carbonate phyllites (Upper Lias); Jaspers: metaradiolarite and quarzitic phyllites (Malm); Entrochi Cherty Limestone: metalimestone with lists and white chert nodules (Upper Tithonian - Lower Cretaceous); Sericitic Schists: phyllites with interbedded limestones and metaradiolarite (Lower Cretaceous - Paleogene); Cipollini: calcschists and chloritic marbles (?Eocene - Oligocene); Pseudomacigno: metasandstones and phyllites (Upper Oligocene - ?Lower Miocene). (from Carmignani et alii, 2007)

of metabreccia, the relationship between the clasts and matrix (textures of clastic content or matrix content). The taken into account a esthetic parameters are represented by color and design. The color is often a decisive factor and, in marble, is usually due to the presence of microcrystals of hematite (from pink to bright red in color), manganese oxides (from dark red to purple), iron hydroxides (from orange to yellow), chlorite (shades of green), etc., evenly spread within the rock or concentrated in the matrix. The design is defined by the size, shape, orientation and relative disposition of the elements that substitute the material (for example, shape of the clasts of a metabreccia, spatial arrangement of the veins).

Based on the above mentioned criteria, Carmignani *et alii* (2007) identified 14 informal lithostratigraphic units, representing the different product varieties present in the marble quarries of the Apuan Alps (Tab. 1). According to their general characteristics, these 14 commercial varieties are divided to 5 groups: Brecciated, White, Gray and Veined, Cipollino, and Historical marbles.

THE STORY OF DEFORMATION AND PRODUCT VARIETY

The recent geological-structural surveys of the Apuan Metamorphic Complex have allowed us to describe the event D3 deformation better, which in the past have been investigated in terms of microstructures and mesostructures, but ignored or underestimated in terms of large mappable structures.

The D3 deformational event has occurred on previous D1 and D2 structures and develops the areas of direct shear zones and normal faults to the lower or higher angle (Carmignani *et alii*, 2015). These structures have the dip direction toward NE and SW, respectively towards the north-eastern and south-western slopes of the metamorphic core. These extensional structures with variable directions between N-S and NW-SE to NW-SE and NE-SW, activate the mechanisms of transfer both right-hand and left-hand with strong direct element, which control the dip direction to either NW or SE of metamorphic core. Finally, this feature that forms the ellipsoidal shape of metamorphic core, already mentioned since early geological works on Apuan area ("Ellissoide Apuano", Savi, 1863), has been determined precisely by the geometry of the structures of D3 phase. The strike-slip structures often cut the folds of D2 phase on higher angle, so that there creation of the trend of two-dimensional traces of the axial planes of these folds throughout the metamorphic complex is only possible when the strike-slip faults of the D3 phase are recognized and restored.

Among all the analyzed and attributed structures of D3, there are two major shear zones "top-E" of several hundred meters thickness, which mainly through the Mesozoic carbonate formations, and in particular the Marmi formation. The first shear zone starts from near to the Gorfigliano and with a N-S direction continues along the anticline of Monte Tambura and above all the marbles of its overturned side, until the proximity of the high valley of Arni. Here, by a NW-SE direction, goes to the right and crosses through the overturned anticline of Monte Tambura, and finally, toward more to the south-east, completely cuts the synform of Monte Corchia and with the same direction continues through the Pania della Croce complex. The most western shear bands of this zone completely cut the syncline of Orto di Donna-Monte Altissimo from the normal flank to the overturned one.

Type of Marble	MERCEOLOGICAL VARIETY
WHITE MARBLES	ORDINARIO
	STATUARIO
	BIANCO
GRAY AND VEINED	GRIGIO
	VENATO
	ZEBRINO
BRECCIATED MARBLE	ARABESCATO
	CALACATTA
	BRECCIA ROSSA
	FANTASTICO
CIPOLLINO MARBLE	CIPOLLINO
HISTORICAL MARBLES	BRECCIA DI SERAVEZZA
	ROSSO RUBINO
	NERO DI COLONNATA

Tab. 1 - Types of marble and merceological variety of the Apuan Alps marble. The names used to identify the merceological varieties derived from the terms commonly used in the trade.(from Carmignani *et alii, 2007)*

The second shear zone, with a N–S trend and a "top-W" shear trend follows the phyllitic core of the Vinca Anticline and the contact of the Grezzoni-Marmi on its direct side.

These main shear zones, are locally associated with minor shear zones of normal cut direction with right and left trending elements, such as those characterize the entire southern closure of the syncline of Monte Altissimo (Fig. 5).

These shear zones, with a variable wideness from few meters to several tens of meters, are present on the surface and are characterized by a pervasive mylonitic foliation to that is often associated with a mineralogical lineation that indicates

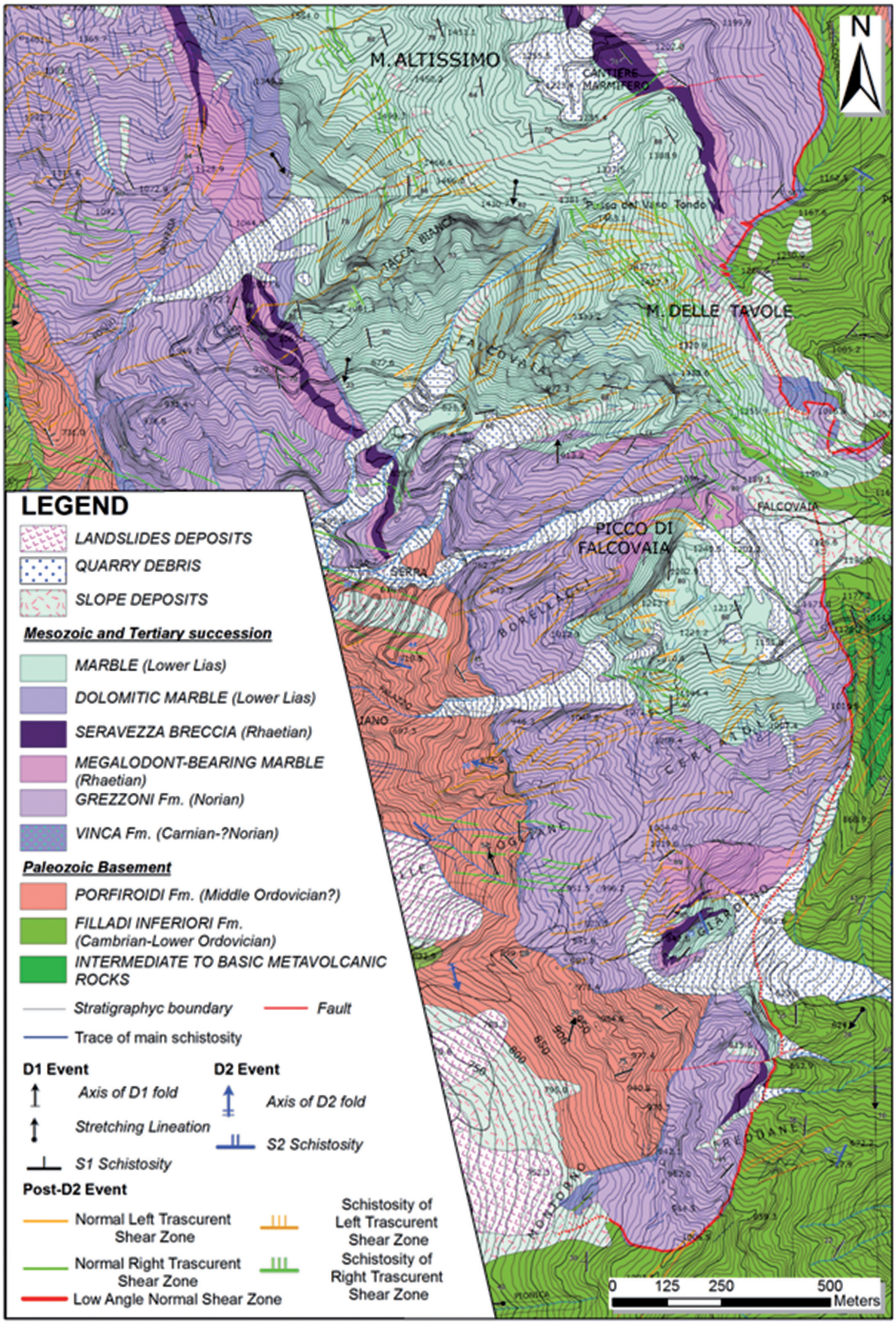

Fig. 5 - Geological-structural map of southern closure of Altissimo syncline

Fig. 6 - D3 right trascurrent shear zone, marked by s-c structure, with mylonitic white marble (Bianco) near the Monte dei Ronchi (Central Apuan Alps)

the possible direction of movement. Along these shear zones is commonly possible to find different kinematic indicators, such as s-c structure (Fig. 6), drag folds, bookshelf structure (Fig. 7) and rare porphyroclasts.

All these dextral strike-slip faults are newer than the sinistral ones which are related to the "top-NE" normal faults of metamorphic core. These structures, and their three-dimensional architecture, determines the geometry of some marble deposits and specifies their exploitation during the extraction phase.

The marbles that characterize these important shear zones are constituted of particular product quality and the type of great value, due to both aesthetic characteristics of color and orientation of main foliation ("verso di macchia"), and good physical-mechanical characteristics that distinguish these marbles from all those of the rest of the Apuan Metamorphic Complex.

The main common varieties which are found in the whole of these late shear zones are of many types of Arabescato, some types of Bianco, Bardiglio and Nuvolato marbles that reflect the deformation regime from ductile to brittle/ductile, where these varieties have originated within.

In particular, the Arabescato marbles are clast-consisted metabreccia with multimetric-scaled marble elements in the matrix of varying color from gray/brown to dark green, and clasts from light gray to white in color. Depending on the size of the clasts, and their relative arrangement with respect to the surrounding matrix, a wide range of aspects and ornamentations, usually well exposed in the various quarry cuts, are created.

In many cases, in the cuts of the quarry, the intercepting contact of Ordinario marbles and Arabescato marble, shows the gradual transition from the original protolith (Ordinario marble), damage zones characterized by high fracturing, where it is still possible to recognize the fragments of the original protolith even until to get to the heart of the shear zone characterized by a fully brecciated rock, which represents a "dyke" ("corso") of Arabescato marble. During the progressive exhumation of the Apuan Metamorphic Complex, the clasts of this breccia could be stretched and compressed due to a mylonitic foliation related to the development of dextral or sinistral strike-slip shear zones that superimpose on the previous structures. During this deformation event, from the micro-structural point of view, there is a slight recrystallization on the mylonitic foliation of white mica, dolomite and calcite.

The Bianco and Nuvaloto marbles that develop within these late shear zones, have aesthetic features such as color and the particular orientation of main foliation ("verso di macchia") very similar to the same varieties found around the Apuan massif. The difference, however, is taking place at the micro-structural level.

Fig. 7 - D3 right trascurrent shear zone, marked by bookshelf structure and asimmetric boudinage, with mylonitic marble (Nuvolato) near the Monte Sumbra (Central Apuan Alps)

CONCLUSIONS

Although, the D3 has formerly been studied in terms of microstructures and mesostructures, but it has been ignored or significantly underestimated in the level of the large-scaled structures. The present geological-structural investigation,carried out on the Apuan Metamorphic Complex, leads us to hypothesize the D3 deformational event more explicitly and also to see its role better from the commercial aspect of the Apuan marbles.

As it comes from its name, the D3 has taken place after the previously occurred D1 and D2 phases and has developed a set of the low-angle shear zones and high-angle normal faults which, with a major direct component, have activated the strike-slip movements both right-hand and left-hand. All these effects of ductile and brittle/ductile late tectonism have created a mylonitic marble that is individual for its outstanding physical and mechanical properties. Of these kind of marbles, some types of Arabescato, Bianco, Bardiglio and Nuvolato can be mentioned as the most typical ones.

The unique physical and mechanical properties of the aforementioned marbles are due to the microstructural variability of the shear zones which have been formed during the final stage of the exhumation of the Apuan Metamorphic Complex.

The geometrical and spatial characteristics of these structures determine the geometry of the mining of ornamental stones, during the early as well as the advanced planning, and also the direction of the development of the mining.

Therefore, the identification and study of these important shear zones is of fundamental importance for the planning and the exploitation of the marble deposits, characterized by great economical value and excellent commercial quality.

REFERENCES

Bonatti S. (1938) - *Studio petrografico delle Alpi Apuane*. Mem. Descr. Carta Geologica d'Italia, **26**: 1-116.

Carmignani L., Giglia G. & Kligfield R. (1978) - *Structural evolution of the Apuane Alps: an example of continental margin deformation in the Northern Apennines, Italy*. Journal of Structural Geology, **86**: 487-504.

Carmignani L. (1985) - *Carta geologico-strutturale del Complesso Metamorfico delle Alpi Apuane, Foglio Nord, 1:25.000*. Litografia Artistica Cartografica, Firenze.

Carmignani L. & Kligfield R. (1990) - *Crustal extension in the Northern Apennines: the transition from compression to extension in the Alpi Apuane core complex*. Tectonics, **9** (6): 1275-1303.

Carmignani L., Fantozzi P. L., Giglia G. & Meccheri M. (1993) - *Pieghe associate alla distensione duttile del Complesso Metamorfico Apuano*. Mem. Soc. Geol. It., **49**: 99-124.

Carmignani L., Conti P., Fantozzi P. L., Mancini S., Massa G., Molli G. & Vaselli L. (2007) - *I marmi delle Alpi Apuane (Toscana settentrionale)*. Geoitalia, **21**: Novembre 2007.

Carmignani L., Massa G., Salvini R., Pieruccioni D., Tufarolo E., Conti P., Mancini S. & Lorenzoni V. (2015) - *Acquisition of morpho-structural data by the use of aerial lidar and proximalsensing in the southern end of Monte Altissimo syncline (Apuan Alps, Italy)*. Rend. Online Soc. Geol. It., **35** (2): 18.

Casey M.S., Rutter E.H., Schmid S.M., Siddans A.W.B. & Whalley J.S. (1978) - *Texture development in experimentally deformed calcite rocks*. In Proceedings 5th International Conference on Textures of Materials. A cura di Gottstein G. & Lücke K., SpringerVerlag, Berlin, 231-240.

Coli M., Grandini G. & Matteini L. (1987) - *Carta Strutturale del bacino marmifero di Orto di Donna (Alpi Apuane), 1:5.000*. SELCA, Firenze.

Coli M. (1989) - *Litho-structural assemblage and deformation history of "Carrara marble"*. Boll. Soc. Geol. It., **108**: 581-590.

Coli M.(1992) - *Carta Strutturale del Bacino Marmifero di Boana (Alpi Apuane), 1:5.000*. SELCA, Firenze.

Coli M. & Fazzuoli M. (1992) - *Evoluzione sedimentaria dell'area apuana nel Triassico- Liassico*. Studi Geologici Camerti, Vol. Spec. CROP 1-1A, 193-201.

Conti P., Carmignani L., Giglia G., Meccheri M. & Fantozzi P.L. (2004) - *Evolution of geological intepretations in the Alpi Apuane metamorphic complex, and their relevance for the geology of the northern Apennines*. In: Morini D. & Bruni P. (Eds.). The "Regione Toscana" project of geological mapping case histories and data acquisition, 241-262.

Cortecci G., Dinelli E., Indrizzi M.C., Susini C. & Adorni Braccesi A. (1999) - *The Apuane Alps metamorphic complex, Northern Tuscany: chemical and isotopic features of Grezzoni and Marmi Dolomitici*. Atti Soc. Tosc. Sci. Nat., Mem., Ser. A, **CVI**: 79-89.

Corti G., Serena L., Bonini M., Sani F. & Mazzarini F. (2006) - *Interaction between normal faults and pre-existing thrust systems in analogue models*. In: Buiter S.J.H. & Schreurs G. (Eds.). *Analogue and numerical modeling of crustal-scale processes.* Geol. Soc. Lond. Spec. Publ., **253**: 65-78.

Covey Crump S.J. (1997) - *The high temperature static recovery and recrystallization behaviour of cold-worked Carrara marble*. Journal of Structural Geology, **XIX**: 225-241.

Covey Crump S.J. (1998) - *Evolution of mechanical state in Carrara marble during deformation at 400°C to 700°C*. Journal of Geophysical Research, **CIII**: 29781-29794.

Covey Crump S.J. (2001) - *Variation of the exponential and power law creep parameters with strain for Carrara marble deformed at 120°C to 400°C*. Geophysical Research Letters, **XXVIII**: 2301-2304.

Crisci G.M., Leoni L. & Sbrana A. (1975) - *La formazione dei marmi delle Alpi Apuane (Toscana); studio petrografico, mineralogico e chimico*. Atti Soc. Tosc. Sci. Nat., Mem., Serie A, **82**: 199-236.

D'Albissin M. (1963) - *Les traces de la déformationdans les rochescalcaires*. Revue de géogr. physique et de géologie dynamique (fascicule supplementaire), 174.

De Bresser J.H.P. (1991) - *Intracristalline deformation of calcite*. Geologica Ultraiectina, **LXXIX**: 1-191.

Di Pisa A., Franceschelli M., Leoni L. & Meccheri M. (1985) - *Regional variation of the metamorphic temperatures across the Tuscanid Unit and its implications on the alpine metamorphism (Apuane Alps, N-Tuscany)*. Neues Jahrb. Mineral. Abhandl., **151**: 197-211.

Di Sabatino B., Giampaolo C. & Negretti G. (1977) - *Metamorfismo di "verylow grade" ad altissima pressione nell'Unità delle Panie*. Periodico di mineralogia, **46**: 79-89.

Elter P. (1975) - *Introduction à la géologie de l'Apennin septentrional*. Bull. Soc. Geol. Fr., **7**: 956-962.

ERTAG (1980) - *I Marmi Apuani*. Nuova Grafica Fiorentina, Firenze, 126.

Fellin M.G., Reiners P.W., Brandon M.T., Wuthrich E., Balestrieri M.L. & Molli G. (2007) - *Thermocronologic evidence for the exhumational history of the AlpiApuane metamorphic core complex, Northern Apennines, Italy.* Tectonics, **26**: 6015-6036.

Franceschelli M., Leoni L., Memmi I. & Puxeddu M. (1986) - *Regional destribution of Al-silicates and metamorphic zonation in the low-grade Verrucano metasediments from the Northern Apennine, Italy*. Journal of Metamorphic Geology, **4**: 309-321.

Franceschelli M. & Memmi I. (1999) – *Zoning of chloritoid from kyanite-facies metapsammites, AlpiApuane, Italy*. Mineralogical Magazine, **63**: 105-110.

Fredrich J.T., Evans B. & Wong T.F. (1989) - *Micromechanics of the brittle to plastic transition in Carrara Marble*. Journal of Geophysical Research, **XCIV**: 4129-4145.

Heilbronner Panozzo R. & Pauli C. (1993) - *Integrated spatial and orientation analysis of quartz c-axis by computer-aided microscopy.* J. Struct. Geol., **13**: 369-382.

Jolivet L., Faccenna C., Goffè B., Mattei M., Rossetti F., Brunet C., Storti F., Funicello R., Cadet J.P., D'agostino N. & Parra T. (1998) - *Midcrustal shear zone in post-orogenicextension: example from Northern Tirrenyan Sea*. Journal of Geophysical Research, **103**: 12123-12160.

Kligfield R., Hunziker J., Dallmeyer R.D. & Schamel S. (1986) - *Dating of deformational phases using K–Ar and 40Ar/39Ar techniques: results from the Northern Appennines*. J. Struct. Geol. **8**: 781-798. http://dx.doi.org/10.1016/0191-8141(86)90025-8

Leiss B. & Molli G. (2003) - *"High-temperature" texture in naturally deformed Carrara marble from the AlpiApuane, Italy*. Journal of Structural Geology. **25**: 649-658.

Liotta D. (2002) - *D2 asymmetric folds and their vergence meaning in the Montagnola Senese metamorphic rocks (inner northern Apennines, central Italy)*. Journal of Structural Geology, **24**: 1479-1490.

Meccheri M. (1996) - *Carta Geologico-Strutturale delle Varietà Merceologiche dei Marmi del Carrararese, 1:10.000*. Dipartimento di Scienze della Terra, Università di Siena, Siena.

Meccheri M., Massa G., Notini P., Carmignani L. & Conti P. (2004) - *Carta giacimentologica dei marmi delle Alpi Apuane. Sezione n249060 - Gragnana*. Centro di GeoTecnologie, Università di Siena.

Meccheri M., Massa G., Bigoni G., Carmignani L. & Conti P. (2004a) - *Carta giacimentologica dei marmi delle Alpi Apuane. Sezione n249100 - Carrara*. Centro di GeoTecnologie, Università di Siena.

Meccheri M., Bellagotti E., Berretti G., Conti P., Dumas F., Mancini S. & Molli G. (2007) - *The Mt. Altissimo marbles (Apuane Alps, Tuscany): commercial types and structural setting.* Boll. Soc. Geol. It., **126** (1): 25.

Molli G. & Heilbronner P.R. (1999) - *Microstructures associated with static and dynamic recrystallization of Carrara marble (AlpiApuane, NW Tuscany Italy)*. Geologieen Mijnbouw, **78**, 119-126.

Molli G., Giorgetti G. & Meccheri M. (2000) - *Structural and petrological constrains on the tectono-metamorphic evolution of the Massa Unit (AlpiApuane, NW Tuscany, Italy)*. Geological Journal, **35**: 251-264.

Molli G., Conti P., Giorgetti G., Meccheri M. & Oesterling N. (2000a) - *Microfabric study on the deformational and thermal history of the AlpiApuane marbles (Carrara marbles), Italy*. Journal of Structural Geology, **22**: 1809-1825.

Molli G. & Meccheri M. (2000) - *Geometrie di deformazione nell'alta valle di Colonnata: un esempio di deformazione polifasica e composita nelle Alpi Apuane*. Boll. Soc. Geol. It., **119**: 379-394.

Molli G., Giorgetti G. & Meccheri M. (2002) - *Tectono-metamorphic evolution of the Alpi Apuane Metamorphic Complex: new data and constraints for geodynamic models*. Boll. Soc. Geol. It., **1**: 789-900.

Molli G. & Vaselli L. (2006) - *Structures, interference patterns and strain regime during mid-crustal deformation in the AlpiApuane (Northern Apennines, Italy)*. In: Mazzoli S. & Butler R. (Eds.). *Styles of continental contraction.* Geological Society of America Special Papers, **414**: 79-93.

Molli G., Cortecci G., Vaselli L., Ottria G., Cortopassi A., Dinelli E., Mussi M. & Barbieri M. (2010) - *Fault zone structure and fluid-rock interaction of a high angle normal fault in Carrara marble (NW Tuscany, Italy)*. J. Struct. Geol. **32**: 1334-1348.

Molli G. (2008) - *Northern Apennine-Corsica orogenic system: an updated review*. In: Siegesmund S., Fügenschuh B. & Froitzheim N. (Eds.). *Tectonic aspects of the Alpine-Dinaride-Carpathian System.* Geological Society of London Special Publication, **298**: 413-442.

Molli G. (2012) - *Deformation and fluid flow during underplating and exhumation of the Adria Continental margin: a one-dayfield trip in the AlpiApuane (northern Apennines, Italy)*. In: Vannucchi P. & Fisher D. (Eds.). *Deformation, fluid flow and mass transfer in the forearc of convergent margins: field guides to the Northern Apennines in Emilia and the Apuan Alps (Italy), **28***. The Geological Society of America, Boulder, Colorado, USA, 35–48, http://dx.doi.org/10.1130/2012.0028(02).

Molli G. & Meccheri M. (2012) - *Structural inheritance and style of reactivation at mid-crustal levels: A case study from the AlpiApuane (Tuscany, Italy)*. Tectonophysics, **579**: 74-87. Doi:10.1016/j.tecto.2012.06.044.

Oesterling N., Heilbronner R., Stünitz H., Barnhoorn A. & Molli G. (2007) - *Strain dependent variation of microstructure and texture in naturally deformed Carrara marble*. Journal of Structural Geology, **29**: 681-696.

Ottria G. & Molli G. (2000) - *Superimposed brittle structures in the late orogenic extension of the northern Apennine: results from Carrara area (AlpiApuane, NW Tuscany)*. Terra Nova, **12**: 1-8.

Pieri M., L. Burlini L., Kunze K., Stretton I. & Olgaard D.L. (2001) - *Rheological and microstructural evolution of Carrara marble with high shear strain: results from high temperature torsion experiments*. Journal of Structural Geology, **XXIII**: 1393-1413.

Pieri M., Kunze K., Burlini L., Stretton I., Olgaard D.L., Burg J.P. &Wenk H.R. (2001a) - *Texture development of calcite by deformation and dynamic recrystallization at 1000°K during torsion experiments of marble to large strains*. Tectonophysics, **CCCXXX**: 119-140.

Rutter E.H. (1972) - *The influence of interstitial water on the rheological behaviour of calcite rocks*. Tectonophysics, **XIV**: 13-33.

Rutter E.H. (1995) - *Experimental study of the influence of stress, temperature, and strain on the dynamic recrystallization of Carrara marble*. Journal of

Geophysical Research, **C**: 24651-24663.

Savi P. (1863) - *Sulla costituzione geologica dell'ellissoide della catena metallifera ed in particolare di quella delle Alpi Apuane*. Memoria estratta dal Nuovo Cimento, **18**, Fasc. di Luglio-Agosto-Settembre e Ottobre 1863. Tipografia Pieraccini, Pisa, 49 pp.

Schmid S.M., Paterson M.S. & Bolan D.J.N. (1980) - *High temperature flow and dynamic recrystallization in Carrara marble*. Tectonophysics, **LXV**: 245-280.

Schmid S.M., Panozzo R. & Bauer S. (1987) - *Simple shear experiments on calcite rocks: rheology and microfabric*. Journal of Structural Geology, **IX**: 747-778.

Spiers C.J. (1979) - *Fabric development in calcite polycrystals deformed at 400°C*. Bulletin de Minéralogie, **CII**: 282-289.

Wenk H.R., Takeshita T., Bechler, Erskine B.G. & Matthies S. (1987) - *Pure shear and simple shear calcite textures. Comparision of experimental, theoretical and natural data*. Journal of Structural Geology, **IX**: 731-745.

Zaccagna D. (1932) - *Descrizione Geologica delle Alpi Apuane*. Memorie Descrittive della Carta Geologica d'Italia, **XXV**: 1-440.

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