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THE MICROSTRUCTURES OF THE ALPI APUANE MARBLES AND THEIR TECTONIC SETTING: A PRELIMINARY NOTE

Abstract - This paper presents some results of an ongoing microstructural investigation of marbles of the Alpi Apuane greenschist facies metamorphic complex in NW Tuscany. In the region, the partitioning of the strain and the distribution of the effect of the peak temperature allowed the preservation of marbles with different microstructures. In particular three groups of marbles are described whose microstructures can be related to the process of static recrystallization (type A), dynamic recrystallization (type B) and twinning (type C) at very low temperatures. Taking into account the relationships with mesoscopic deformational features the relative timing of development of the different microstructures in the overall tectono-metamorphic evolution of the Alpi Apuane complex has been constrained.

Key words - Microstructures, Carrara marble, static and dynamic recrystallization, Alpi Apuane, northern Apennine.

Riassunto - *Microstrutture e contesto tettonico dei marmi nelle Alpi Apuane: una nota preliminare.* In questa nota vengono presentate alcune osservazioni sulle caratteristiche microstrutturali dei marmi delle Alpi Apuane e sulla loro relazione con l'assetto tettonico della regione. I marmi delle Alpi Apuane, e in particolare il marmo di Carrara (cioè la varietà bianca più o meno omogenea), sono comunemente considerati, dal punto di vista microscopico, come un esempio di materiale naturale che ha subito un completo processo di «annealing» cioè di ricristallizzazione statica post-deformazione. A questo processo è collegabile la tipica microstruttura granoblastica poligonale con debole o assente orientazione cristallografica preferenziale che caratterizza molti dei marmi apuani. All'interno di questo tipo di fabric microscopico, tuttavia, è possibile evidenziare una variabilità, notata già da Zaccagna (1832) e dagli autori successivi, collegata ad un aumento nella granulometria media che passa da 80-100 μm nelle porzioni orientali e centrali a 150-300 μm nelle porzioni più occidentali del complesso metamorfico. Le granulometrie medie maggiori si ritrovano, in particolare, nel settore adiacente al contatto tettonico con l'unità di Massa. La variabilità granulometrica è associata, come sottolineato da Di Pisa *et al.* (1985), ad un aumento delle temperature calcite/dolomite che passano da 340-360° nelle porzioni orientali a 430-450° in quelle più occidentali (Carrarese).
Un secondo tipo di microstrutture, mai precedentemente segnalato, è invece collegabile a processi deformativi e di ricristallizzazione dinamica. Queste microstrutture sono caratterizzate da cristalli di calcite con orientazioni di forma, riduzione granulometrica associata a fenomeni di rotazione e migrazione del limite dei granuli, e forti orientazioni cristallografiche preferenziali. Esse sono associate a distinti gruppi di strutture deformative mesoscopiche e collegate direttamente ai diversi stadi dell'evoluzione tettono-metamorfica delle Alpi Apuane. In particolare, sono state riconosciute microstrutture prodotte da fenomeni di ricristallizzazione dinamica associabili agli stadi tardivi dell'evento deformativo principale D1 e microstrutture associate a zone di taglio e pieghe collegate con l'evento D2. Un terzo gruppo microstrutturale di marmi (tipo C) è caratterizzato da fenomeni di geminazione meccanica prodotti per deformazione a temperature molto basse e collegati agli stadi tardivi dell'evento D2.
I caratteri microstrutturali e termometrici nei marmi di tipo A (microstrutture di «annealing») sottolineano la differente posizione geometrica dei settori crostali (orientale ed occidentale) al momento della ricristallizzazione statica dei marmi ed enfatizzano il ruolo di raccorciamenti crostali (post-picco termico) responsabili dell'attuale assetto geometrico. Le microstrutture di ricristallizzazione dinamica (tipo B1), osservabili in domini ad alta deformazione ripiegati da strutture attribuibili all'evento deformativo D2, possono rappresentare le zone di movimento lungo le quali si è realizzato questo raccorciamento tardo D1.
Microstrutture (tipo B2) di ricristallizzazione dinamica successive (sin-D2) sono collegate a zone di taglio discrete (da millimetriche a metriche) nel Carrarese, mentre si ritrovano in volumi più rilevanti ed associati a strutture plicative megascopiche nelle porzioni orientali del complesso metamorfico (Arni). Nel sistema accrezionale le aree orientali hanno rappresentato zone più profonde rispetto a quelle occidentali, sia al termine dell'evento deformativo D1 che durante l'evento tardivo D2; questo può spiegare oltre al diverso tipo di sviluppo nelle rielaborazioni microstrutturali sin-D2, anche il fatto che localmente (Boana) si possano essere mantenute condizioni termiche sufficienti per produrre fenomeni di «annealing» tardo-D2.

Parole chiave - microstrutture, marmi di Carrara, ricristallizzazione statica e dinamica, Alpi Apuane, Appennino settentrionale.

INTRODUCTION

The Alpi Apuane marble and in particular the white pure variety called Carrara marble is commonly considered as an example of «annealed material» since, from the microscopic point of view, it is known as a homogeneous coarse grained (150-250 μm), granoblastic, untextured rock-type (Ramez and Murrel, 1964, Rutter, 1972; Kern, 1977; Casey *and al.*, 1978; Schmid *and al.*, 1980). However, recent analyses following previous studies (Zaccagna, 1932; Bonatti, 1938, Crisci *et al.* 1975, Di Pisa *et al.*, 1985, Coli, 1989) have allowed us to verify the presence of a

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microstructural variability that can be traced directly back to the tectono-metamorphic evolution in different parts of the polyphase structural building of the Alpi Apuane metamorphic complex.
The existence of a close relationship between the microfabric (microstructure and texture) and the physical properties of the material calls for a complete quantitative characterization of the different marble types as the first step for more detailed studies on the link between microfabric and weathering processes. On the other hand, the study of marble microstructures provides a key to further unravel the tectono-metamorphic history of the region.
This paper introduces some preliminary results of an ongoing project focusing on these topics.

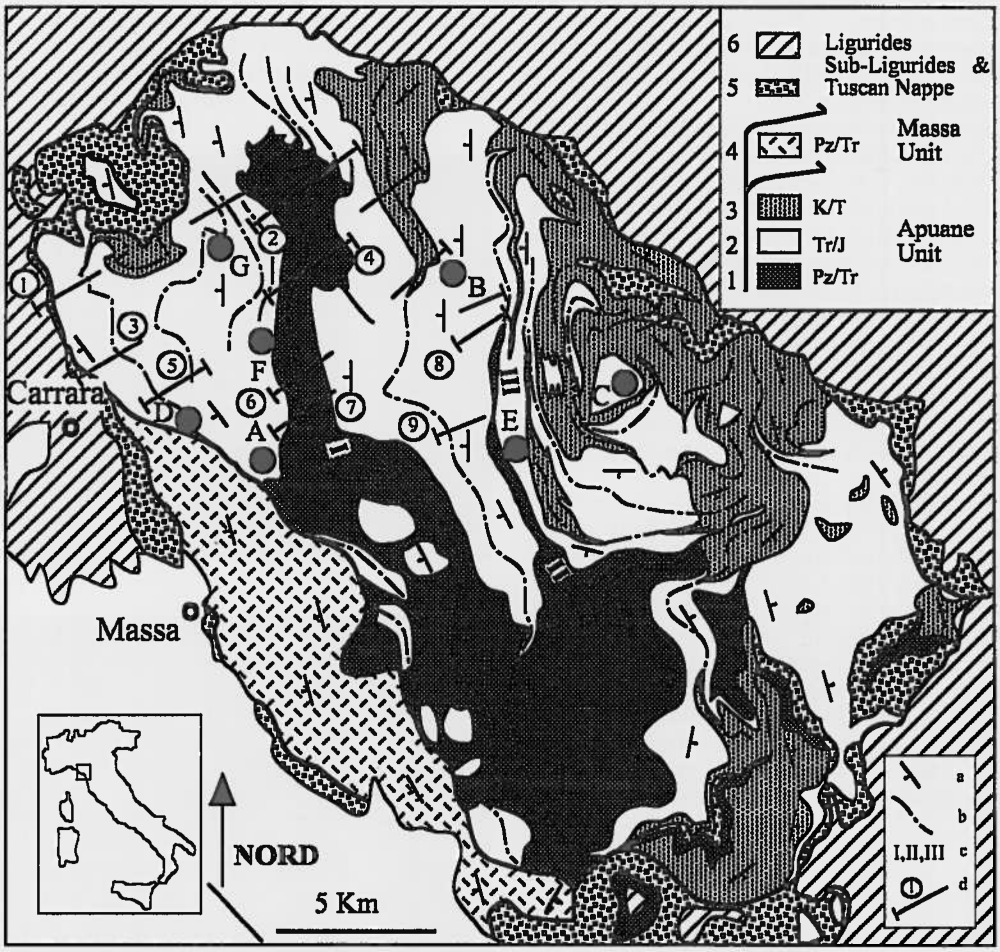
Geological setting

In the Alpi Apuane region the lowermost tectonic units of the inner side of the Northern Apennine fold and thrust belt are exposed (Fig. 1). According to classical interpretations (Elter, 1975; Carmignani *et al.*, 1978 and reference therein) the following tectonic units can be recognized from top to bottom:
– the Liguride and sub-Liguride Units characterized by ophiolites and deep-water sediments representing the former Mesozoic Ligurian ocean, the sedimentary covers of the ocean-continent transitional area and parts of an accretional wedge system related to the closure of the ocean itself. These units show anchimetamorphic to very low grade metamorphic conditions (Reutter *et al.*, 1980; Cerrina Feroni *et al.*, 1983);
– the Tuscan Nappe, a continental-derived unit formed by Late Triassic to Aquitanian sedimentary sequences (Baldacci *et al.*, 1992) detached from their original basement and characterized by a polyphasic deformation associated with a very low grade metamorphism;
– the Massa Unit, formed by a pre-Mesozoic basement and a well developed metasedimentary Middle Triassic to Late Triassic sequence associated with Middle Triassic metavolcanics (Elter *et al.*, 1966);
– a lowermost Apuane Unit made up by a Hercynian basement unconformably overlain by a Triassic to Oligocene (?) metasedimentary sequence.
The large scale deformational history of the Northern Apennine involves northeastward nappe transport and a progressive deformation of the westernmost sector of the Adriatic continental margin. This history began after the Paleocene in the inner and originally westernmost units (Ligurides and sub-Ligurides) and followed in the Late Oligocene-Miocene in the lowermost continental-derived (Tuscan, Massa and Apuane) units.
Several workers suggested that starting from the late Early Miocene the deep levels of the thrust belt were affected by an extensional process followed by a regional extension related to the Tyrrhenian sea opening (Coli, 1989; Carmignani and Kligfield, 1990; Storti, 1995).
Within the lower units (Massa and Apuane) two main polyphasic tectono-metamorphic events can be recognized (cfr. Carmignani & Kligfield, 1990). During D1 nappe building and emplacement occured, whereas during D2 the previously formed structures associated with the main regional schistosity were deformed under retrograde metamorphic conditions. Both D1 and D2 events are associated with different fold and shear zone generations producing a heterogeneous strain pattern (Molli and Meccheri, 1997 and submitted). The latest stages of D2 deformation are also associated with a polyphase brittle deformation tectonics.
In the Apuane unit the metamorphic conditions recorded by mineral assemblage are typical of the chlorite and biotite zones of the greenschist facies (Giglia, 1967; Carmignani *et al.*, 1978), or based on Al-silicates of the pyrophillite+quartz zone (Franceschelli *et al.*, 1986; 1997) indicating maximum temperature between 300-450°C and pressure at the peak of metamorphism around 5-6 Kbar (Di Pisa *et al.*, 1985; Schultz, 1996, Franceschelli *et al.*, 1997). The thermal peak of metamorphism was attained after D1 and during the development (early stage?) of D2 (Boccaletti e Gosso, 1980; Carmignani and Kligfield, 1990, Franceschelli *et al.*, 1997).
Radiometric K/Ar, $^{40}Ar/^{39}Ar$ data suggest that D1 occured at approximately 27 Ma with subsequent early D2 ending by 10-8 Ma (Giglia and Radicati di Brozolo, 1975; Kligfield *et al.*, 1986). Cooling through 100-120°C temperature can be constrained by fission tracks data ranging from 6 to 2 Ma (Abbate *et al.*, 1994).

MARBLE-TYPES AND THEIR MICROSTRUCTURES

Broadly speaking, in the Alpi Apuane three main groups of marbles can be distinguished according to their mesoscopic features: the white massive marbles (with or without light grey to dark «veins», lenses or spots), breccias (monogenic or polygenic, «in situ», clast or matrix supported) and grey marbles (called bardiglio and nuvolato). These three main groups encompass more than fifty different commercial varieties quarried in the Alpi Apuane region (ERTAG, 1980).
According to published studies (Crisci *et al.*, 1975;

Fig. 1 - a) Schematic structural map of the Alpi Apuane region from Carmignani and Kligfield (1990) modified.; 1) Paleozoic to Triassic: metavolcanics (Porphyroids), phyllites, quarzites and conglomerates; 2) Upper Triassic to Liassic carbonate platform deposits, mainly metadolostones, marbles and cherty metalimestones; 3) Cretaceous to Tertiary phyllites and metasandstones; 4) breccias and cataclasites largely derived from Triassic evaporites («Calcare Cavernoso») base of the Tuscan Nappe; 5) Tuscan nappe, subLiguride and Liguride units. a) strike and dip of the main regional schistosity; b) axial plane traces of major D1 structures; c) I «Vinca-Forno anticline», II «M. Tambura anticline», III M. Tambura thrust. Locations of specimen A to F are indicated; b) composite down-plunge projected cross-section across the northern part of the Alpi Apuane region. Modified from Carmignani *et al.* (1993).


6 Ligurides
Sub-Ligurides &
5 Tuscan Nappe
4 Pz/Tr Massa Unit
3 K/T
2 Tr/J
1 Pz/Tr
Apuane Unit
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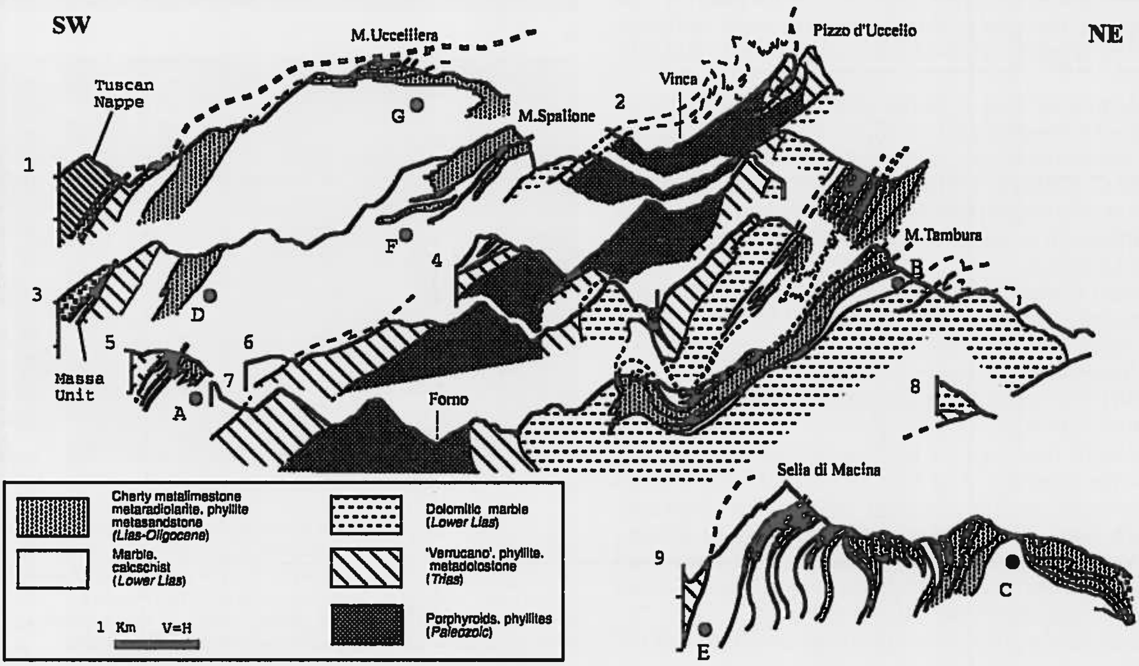
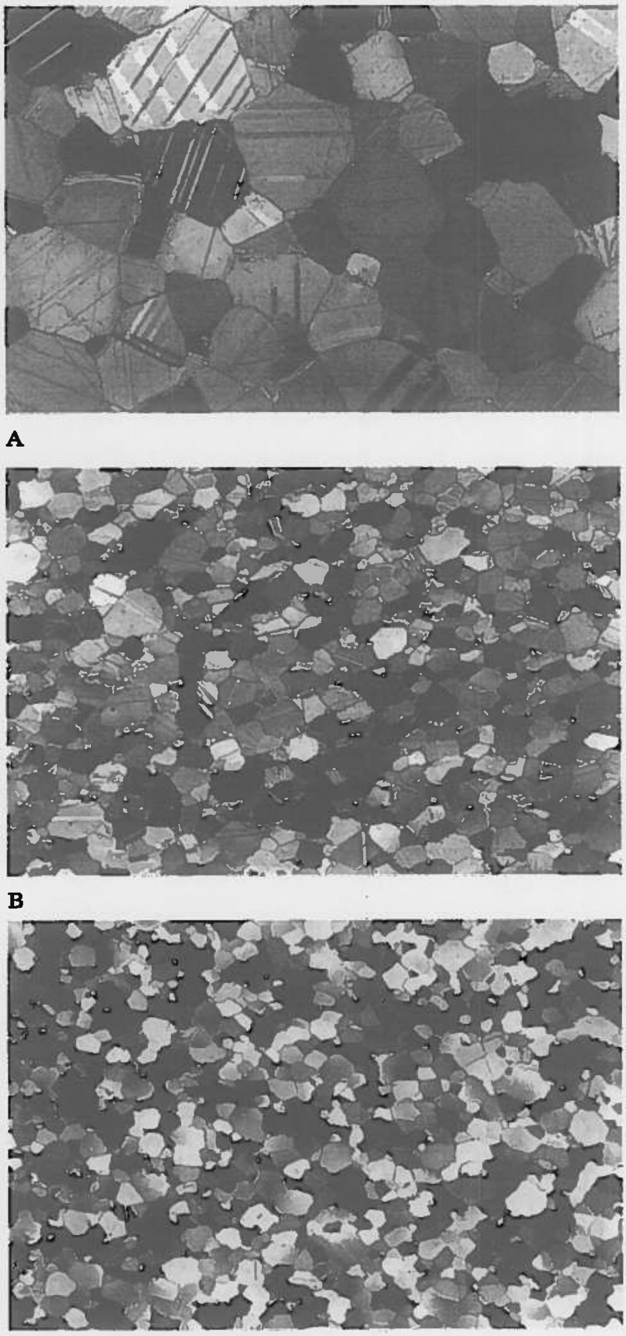

SW
NE
M.Uccelliera
Pizzo d'Uccello
Vinca
M.Spallone
Tuscan Nappe
M.Tambura
Massa Unit
Forno
Sella di Macina
Cherty metalimestone metaradiolarite, phyllite metasandstone (Lias-Oligocene)
Marble, calcschist (Lower Lias)
Dolomitic marble (Lower Lias)
'Verrucano', phyllite, metadolostone (Trias)
Porphyroids, phyllites (Paleozoic)
1 Km V=H

Coli, 1989, Coli e Fazzuoli, 1992), the main differences in the marble-types can be related to their former position and evolution within the Rhetian and then Liassic carbonatic platform.
The only recent papers dealing with microstructures and tectonics in the Alpi Apuane marbles are Di Pisa *et al.* (1985), where a relationship between grain size in marble and the peak of temperature estimated with calcite/dolomite thermometry is suggested, and Coli (1989), where a general theoretical evolution of the marble microstructures is presented.
The present study focuses on Carrara marbles (white pure variety, commercially called «marmo ordinario») collected in areas in which the quarry activity is either still ongoing or was present in the last decades. Samples distributed in the different geometrical and structural levels of the Alpi Apuane (Fig. 1) have been considered.
Taking into account their main microstructural features and relationships with mesoscopic field structures (foliations, folds and shear zones) we have been able to divide the analyzed marbles into three main group-types whose microstructures are interpreted respectively as the product of static recrystallization (type A), of dynamic recrystallization (type B, further subdivided into B1 and B2 types); and of the reworking during the late stage of deformation (type C). These distinctions represent the end-member of a wide range of transitional types which in some cases can be observed superimposed one to the other.

Type A

The common microstructure of this group (Fig. 2) consists of an aggregate of equigranular polygonal grains (granoblastic or «foam» microstructure). No optical evidence of crystal-plastic deformation can be observed, the grain boundaries are well defined, straight to slightly curved and only rarely slightly dentate.
The presence of thin e-twins characterizes some of the studied samples and is to be considered as the product of a late stage of deformation (see microfabric type C below). Universal stage measurements show no crystallographic preferred orientation of the c-axis although a weak texture seems to be present in some samples.
The overall features and their presence in rocks that were strongly deformed as witnessed by tight folds (Fig. 3) (and also refolded folds) in layering, call for a static recrystallization microstructure (Tullis and Yund, 1981; Covey-Crump and Rutter, 1989; Passchier and Trouw, 1996).
Marbles with this type of microstructure can be observed in the western (A in Fig. 2), central (B in Fig. 2) and eastern (C in Fig. 2) parts of the Alpi Apuane. The grain size, however, clearly allowed to distinguish the westernmost (grain size ranging from 300 to 150 μm) from the central and easternmost ones (grain size ranging from 100 to 80 μm).
New calcite/dolomite investigations confirm the results of Di Pisa *et al.*, (1985) yielding temperatures increasing from 360-390°C in the eastern and central part to 430-450°C in the western part of the Alpi Apuane (Molli and Giorgetti unpublished). Thus,



A

B

C

Fig. 2 - Micrographs of thin and ultrathin sections of static recrystallized Carrara marbles. Sample A (see also Fig. 3) comes from the west (La Rocchetta); Sample B from the central (Passo Focolaccia) and sample C from the eastern area (Boana).
All the pictures refer to XZ plane, length of micrograph 1,6 mm scale applies to all the samples; cross polarized light.

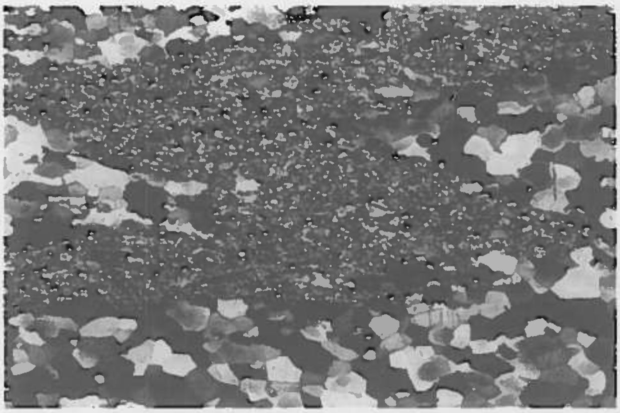


Fig. 3 - Micrograph of millimetric scale isoclinal fold, defined by a layer of fine grained calcite, phyllosilicates and dolomites. Note the coarse grained granoblastic polygonal microstructure testifying the static recrystallization after deformation (sample D, Belgia). Ultrathin section of XZ plane, length of micrography 4,2 mm cross polarized light.

Fig. 4 - Micrograph of ultrathin section of dynamic recrystallized Carrara marble (microstructure type B1, sample E, Arni). The grain shape define the main foliation in the outcrop (a differentiated crenulation cleavage in pelitic layers). XZ plane, length of micrograph 1,6 mm cross polarized light.

assuming that the measured peak temperatures were attained during the static recrystallization (annealing), a clear increasing trend in temperature toward the overlying higher grade Massa unit (kyanite+quartz zone according to Franceschelli *et al.*, 1986) appears to be present at least in the northern cross-section of the Alpi Apuane metamorphic complex.
Although the presence of an evident grain shape preferred orientation is not the rule, the samples we have analyzed always show a statistic orientation in the long axes of particles (anisotropy ratio short axis/long axis of 0.8 to 0.7), which appears to be parallel to the expected trace of the axial plane cleavage of large scale structures [1]. If confirmed in further analyses, this might point to the survival of a memory of the deformational geometries throughout the annealing and therefore to some kind of relation between the annealed microstructures and the pre-annealing shape preferred orientation (cfr. Covey-Crump, 1997).

Type B

This group comprises two different kinds of microfabrics whose general features can be related to the dynamic recrystallization process.
Fig. 4 shows an example of type B1 microstructure, whose main features are a relatively coarse grain size (around 200-100 μm), the presence of an evident grain shape preferred orientation (anisotropy ratio short axis/long axis of 0.6 to 0.5), grain boundary shapes from slightly curved, embayed to lobate and a strong crystallographic preferred orientation of c-axes showing a maximum near the normal to the foliation plane. This microstructural type came from the base of the M. Tambura fault (Fig. 1), an important tectonic discontinuity bounding the lower inverted limb of a major fold-nappe, the «Tambura anticline» (Carmignani, 1985).
The shape preferred orientation of long particle axis is from subparallel to a low angle with respect to the main regional schistosity (in this area a well developed crenulation cleavage), this foliation can be observed as refolded by a large scale post-main phase structure, the Arni-Arnetola back-fold, (D2 according to Carmignani and Kligfield, 1990 and references therein) therefore the foliation and its microstructural features seem to be referable to a late stage of D1 deformation.
A second example of dynamic recrystallized microstructure (type B2 in Fig. 5) is characterized by a polymodal grain size distribution with larger grains (150-200 μm) to be considered as relicts of previous microfabrics associated with a second generation of recrystallized fine grained (20-50 μm) calcite. Mechanical twinning, bulge nucleation as well as grain boundary and twin boundary migration can be observed. Both bulging and subgrain rotation appear to be present.
This microstructural type can be found in the western Carrara area in association with localized millimetric to decimetric wide shear zones reworking the main regional foliation (Molli *et al.*, 1997; Molli and Meccheri, 1997); in some cases the transition from lower to higher strain mylonitic areas and their progressive microstructural variation can be observed. These shear zones are responsible for the presence in still active Carrara quarries of marbles with microstructures similar to that in Fig. 5. These marbles show the best geotechnical properties and are less prone to weathering processes (Barsotelli *et al.*

[1] Taking this into account, between the western-central marbles and the eastern ones a major difference seems to emerge. In the first the statistical shape preferred orientation defined by the particle long axes coincides with the expected trace of the axial plane clevage of large scale structures belonging to the main phase of deformation (D1) whereas the easternmost sample seem show the same features in relationship with a large scale structure (D2) deforming the main regional schistosity.

Fig. 5 - Micrograph of ultrathin sections of dynamic recrystallized Carrara marble (microstructure type B2, sample F, Colonnata). Transition between weekly reworked annealed microfabric to mylonic marble. Although the latter were only observed in millimetric to decimetric wide shear zones, microstructures similar to the locally affected huge marble bodies. Micrograph XZ plane, length of micrograph 1,6 mm cross polarized light.

in press). A similar microstructure can be observed in huge volumes of rocks in the deeper eastern marble levels, where it is possible to relate it to the post-main phase large scale folding described in that area (the Arni and Arnetola D2 fold of Carmignani and Kligfield, 1990; Carmignani *et al.*, 1994).

Type C

Altough this marble-type cannot be properly considered as a microstructural type on its own, it is worth quoting because its study can supply information related to a later stage of the tectonic evolution of the Alpi Apuane complex. It is characterized by the presence of thin rectilinear e-twins (Fig. 6) whose general character points to their development at low

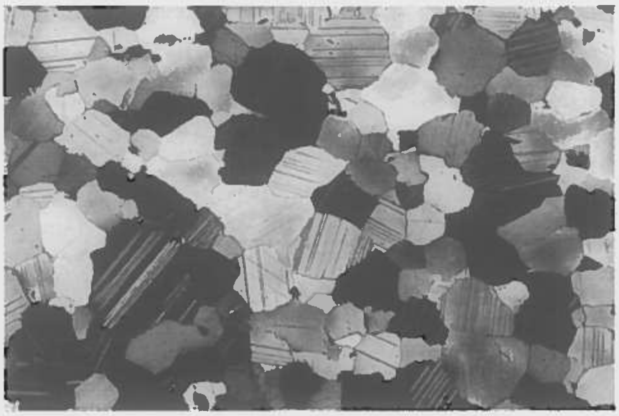


Fig. 6 - Micrograph of granoblastic polygonal marble (cfr. type A), thin e-twins related with late stage of deformation can be observed (Type C microstructure, sample G, Foce di Pianza), XZ plane, length of micrograph 1,6 mm cross polarized light.

temperatures, minor than 200°C according to Ferril (1991); Burkard (1993). Preliminary results of analyses performed with the Dietrich and Song (1984) method are coherent with the interpretation of their association with the recent exhumation of the metamorphic complex. This deformation is present, though with different intensity, in all marble levels of the Alpi Apuane.

Discussion

In the Alpi Apuane marbles and also in the white pure variety called «Carrara marble» a wide range of microstructural types can be observed.
A first kind of variability can be found in the granoblastic polygonal type A marble in which the grain size increases from the eastern-central to western areas, which can be related to the peak of temperature associated with the static recrystallization process.
A second kind of variability is associated with the presence of microstructures testifying dynamic recrystallization. Taking into account the mesoscopic scale geometry of deformation it is possible to recognize microstructures (type B1) related with the main phase foliation and therefore formed during the polyphasic D1 deformation, as well as microstructures (type B2) deforming the main regional foliation and the thermal peak microfabric and associated with the D2 post main deformation event. Though in different ways all the previous microstructural types can be affected by a late stage of deformation in very low temperature conditions (minor than 200°C) producing thin e-twins (type C microstructure).
The microstructures and thermometric data of type A marbles (static recrystallized) point out the different geometrical position of the marble-levels now represented in the eastern, central and western part of the Alpi Apuane and suggest the important role of post-thermal peak shortening (late D1) producing the present stacking.
Type B1 microstructures, refolded in large scale D2 structures, can be possibly related with these late D1 movement zones.
Type B2 microstructures, associated with D2 deformation, can be observed in the western part (i.e. Carrara area) in discrete millimetric to metric wide shear zones whereas they affect huge marble bodies and are associated with large scale D2 folds in the eastern part of the Alpi Apuane (i.e. Arni area). The different types of deformational features (discrete shear zones in the west as opposed to large scale close folding in the east) and the different development of type B2 microstructures can be directly related with the geometrical position of the two areas during D2 deformation, when the eastern part of the Alpi Apuane was at least 2,5-3 Km deeper than the western part (Carrara area) (Cfr. Fig. 3 Carmignani and Kligfield, 1990). This is likely to be the reason of the preservation of sufficient temperature conditions responsible for the locally developed late-D2 annealed microstructures (i.e. Boana).

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