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Article

The Carrara Marbles (Alpi Apuane, Italy): a geological and economical updated review

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Abstract: This paper aims to give an updated overview of the most famous and worldwide known basin of white marbles inland of Carrara. The main commercial marble varieties are described and their stratigraphic and tectonic setting illustrated. The three main microfabric types observable within Carrara Basin are presented altogether with a summary of economic and production data for the different marble types.

Kurzfassung: Der Carrara-Marmor ist seit vielen Jahrhunderten ein weltweit begehrter und außerordentlich gesuchter Werkstein. Ein geologischer und wirtschaftsgeologischer Überblick soll hierzu den aktuellen Stand der Forschung wiedergeben. Daher werden die wichtigsten Gesteinsvarietäten unter kommerziellen Gesichtspunkten besprochen, allerdings unter Berücksichtigung ihrer stratigraphischen und strukturellen Position. Zusätzlich werden die drei wesentlichen Gefügetypen des Carrara-Marmors vorgestellt und zwar hinsichtlich ihrer lagerstättenkundlichen Signifikanz und unter wirtschaftsgeologischen Gesichtspunkten.

Keywords: Carrara Marbles, Alpi Apuane, structural geology, microfabric, economic geology

Schlüsselwörter: Carrara-Marmor, Apuaner Alpen, Strukturgeologie, Gesteinsgefüge, Wirtschaftsgeologie

1. Regional geological overview

The northern Apennines are a fold-and-thrust chain formed during the Tertiary due to the collision of the palaeo-Europe (Corsica-Sardinia block) and the palaeo-Africa (Adria) continental margins (Alpine-Apenninic orogenesis). In the inner northern Apennines, the Alpi Apuane are a known region because of large outcrops of ornamental stones, among which the whitish and variously decorated marbles are the most famous and which were exploited since the first century B.C.; moreover, the Alpi Apuane are an uplifted and severely eroded region (the "Apuane core complex" (Carmignani & Kligfield 1990), in which the regional Apennine structure is best exposed (Fig. 1).

The deepest part consists of the so-called Apuane Metamorphic Complex (AMC) that comprises the metamorphic sequences of the Massa Unit and underlying Apuane Unit (ex Autochthonous Auctorum). Upwards the AMC is followed by unmetamorphosed cover units, which are the Tuscan Nappe, the Canetolo Unit, and some ophiolite-bearing Liguride Units.

Referring to the preorogenetic Tethyan palaeogeography, the AMC units and the Tuscan Nappe derived from the Tuscan Domain, the Canetolo Unit from the Subligurian Domain, and the Liguride Units from the Ligurian Domain. As a whole the lithostratigraphic successions of these tectonic units record a typical sedimentary evolution from rifting (Permian-Triassic) of the old Variscan crust to drifting (from late Jurassic onward) and associated basinal deepening and widening of the Tethys Ocean, up to the Tertiary orogenesis.

Driving attention on the Apuane Unit, to which most of the Apuane ornamental stones belong, its Mesozoic

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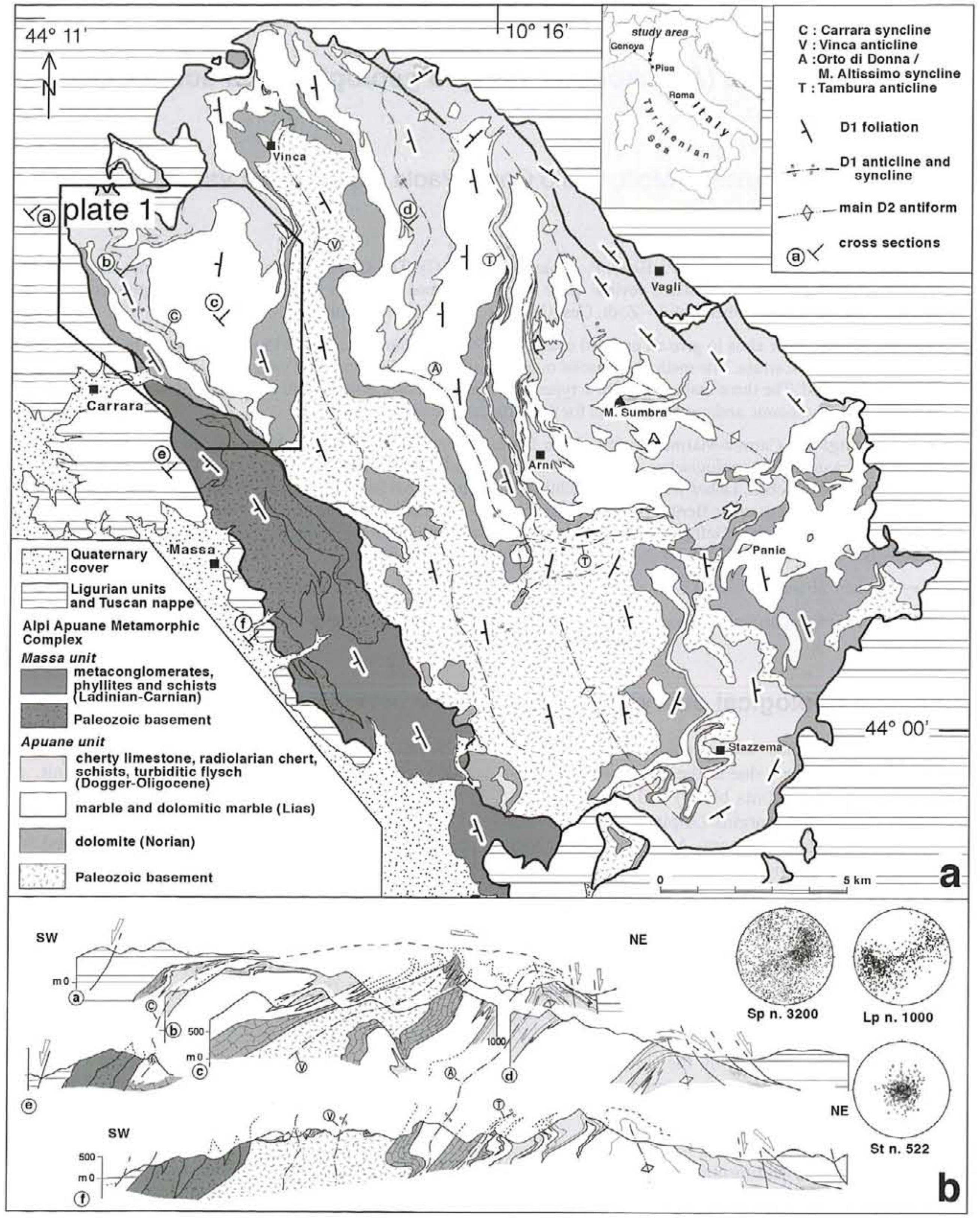


Fig. 1: Structural map of the Alpi Apuane region and composite cross sections. Equal area lower hemisphere stereograms show poles of the main foliation (Sp) and stretching lineation Lp of D1 deformation and the poles of late crenulation cleavage (St) of D2 deformation. Box shows location of Carrara marble basin enlarged in plate 1. (C) = Carrara Syncline; (V) = Vinca-Forno anticline; (A) = Altissimo-Orto di Donna syncline; (T) = Tambura anticline (from Carmignani et al. 1993, modified).

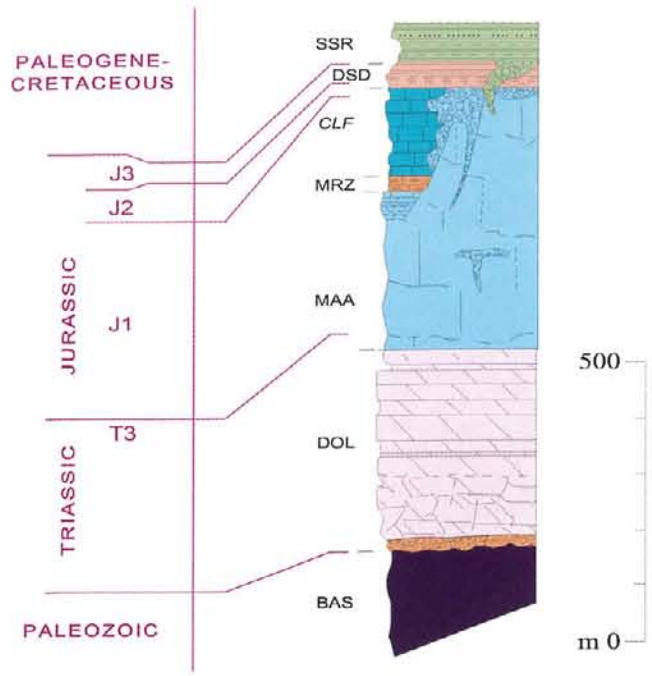


Fig. 2: Stratigraphic detailed column of the metasediments cropping out in the western Alpi Apuane. BAS = Pre-Alpine basement, DOL = siliciclastic deposits, dolostones and dolomitic marble, MAA = marble "Marmi s.s. Auct.", MRZ = calcschists, CLF = cherty limestone "Calcare Selcifero Auct.", DSD = metacherts "Diaspri Auct.", SSR = phyllites and metasiltites "Scisti Sericitici Auct."

lithostratigraphic sequence comprises the following main groups of metasediments (Fig. 2 and Plate 1):

- Middle–Late Triassic to Early Liassic metadolostones (Grezzoni, with basal discontinuous and thin siliciclastic deposits), local dolomitic marbles, and pure marbles sensu stricto;
- Early–Middle Liassic to Early Cretaceous cherty metalimestones (Calcari selciferi Auctorum), metacherts (Diaspri Auctorum) and cherty calcschists (Calcari selciferi a entrochi Auctorum);
- Early Cretaceous to Early Oligocene phyllites and metasiltites (Scisti sericitici Auctorum) locally containing marble interlayers, calcschists, and lenses of metacalcarenites;
- Late Oligocene to very Early(?) Miocene quartz-feldspathic micaceous metasandstone (Pseudomacigno Auctorum).

This sequence deposited over a portion of the palaeo-African margin, and during the Tertiary orogenesis both the Alpine cover and its pre-Alpine basement were affected by two synmetamorphic main tectonic events.

The first deformation (D_1), active at Oligocene/Miocene boundary, was compression-related and caused the above said tectonic units to pile up. The rocks of the Apuane Unit suffered severe deformation through development of a penetrative foliation (S_1) axial planar to NE-verging, sub-millimetric to pluri-kilometric isoclinal folds coeval to a green schist facies metamorphism. The evolution of this phase led to (1) several laminations along the flanks of the folds, (2) widespread elongation lineation parallel to the S_1 (stretching of clasts, fossils, boudinage, linear preferred orientation of metamorphic minerals, pressure shadows, etc.), (3) increasing development of sheath geometry in the fold style passing from WSW to ENE. At the regional scale and along a W–E cross section from the contact with the overlying units (to the West) to the lowermost structural levels (to the East), the main megafolds of the Apuane Unit are the Carrara Syncline, Vinca-Forno Anticline, Orto di Donna-M. Altissimo Syncline, M. Tambura Anticline and many kilometric synclines and anticlines of the Vagli-M. Sumbra sector (Fig. 1).

The following tectonic phase (D_2) began since Early Miocene as a consequence of the tectonic exhumation. This made the piled units to be progressively uplifted in junction since Late Miocene, with the first openings of the northern Tyrrhenian Sea. This uplift resulted in a large-scale positive structure (the Apuane "dome") characterised by a complicated internal geometry and a NW–SE lengthened shape. The most frequent D_2 structures are variously sized folds, with axial planar foliation (S_2) accompanied by a green schist facies retrogression of the former syn-late D_1 imprinting. On the whole, these folds form staircase sets diverging from the main hinge zone of the regional megastructure toward both SW and E–NE along the SW and NE slopes of the "dome". These folds are often associated to several ductile to ductile-brittle shear surfaces whose kinematics match the vergence of the same D_2 folds.

During the final stages of the Apuane uplift, the extensional structures gradually changed from mainly ductile to brittle, that is, high angle normal faults trending both NW–SE and less frequent SW–NE. They were related to the development of the Versilia-Vara, Lunigiana, and Garfagnana-Serchio tectonic depressions bordering the Alpi Apuane high to the SW, NW and NE–E, respectively.

2. Carrara Marbles: commercial varieties

The main compositional and lithological characteristics of the Carrara Marbles are hereafter presented following the names used in the exploitation work.

"Marmo ordinario" (ordinary marble; Fig. 3A): pearl-white to very light grey marble, the bulk rock can be almost homogeneous or spread with more or less large and shaded grey haloes, grey tiny spots and thin, short veins,

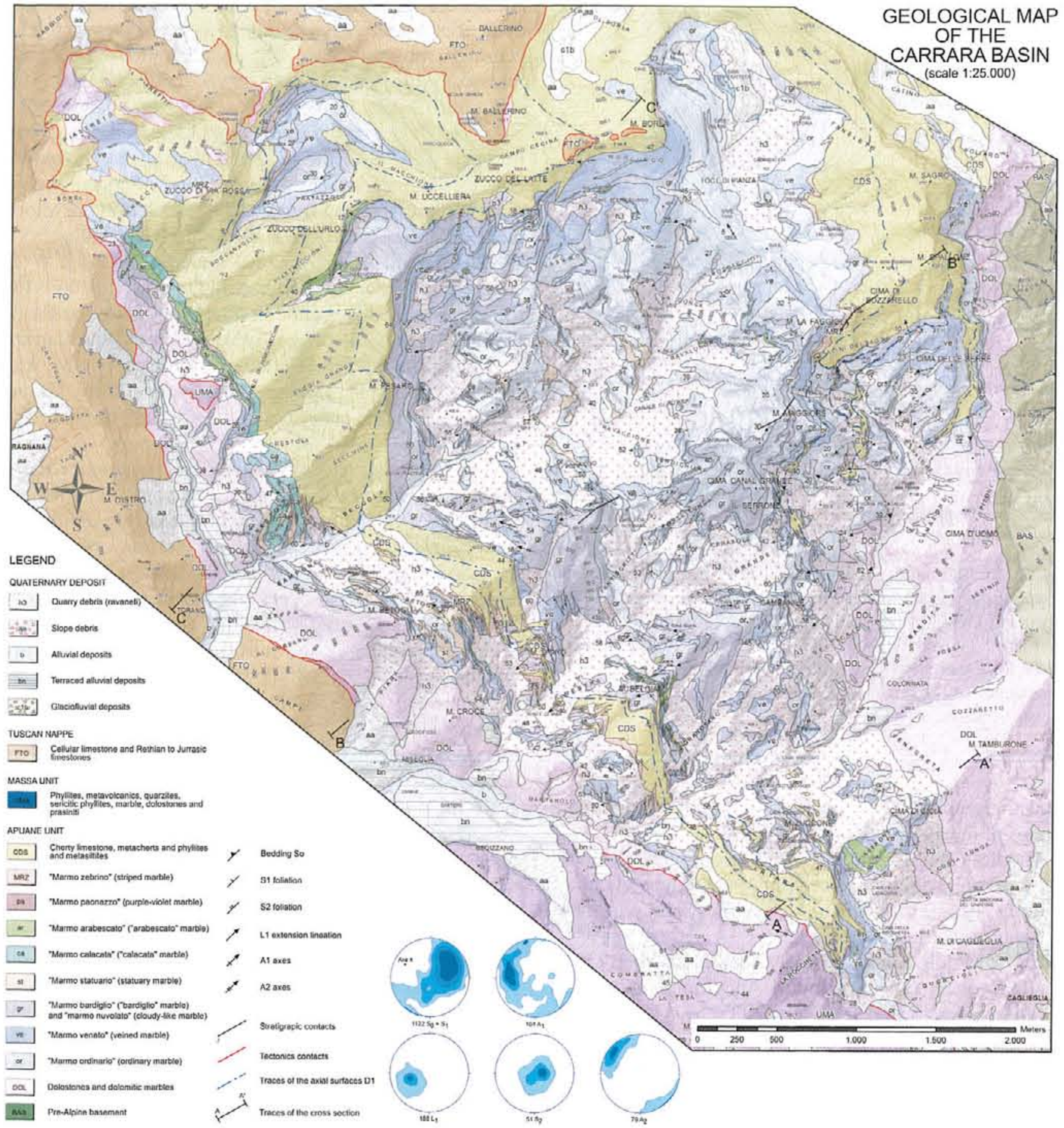


Plate 1: Simplified geological-structural map of the Carrara Syncline and surroundings with the distribution of the main marble types. Map scale is 1:25 000; the scale of the cross sections is 1:20 000 to save details.

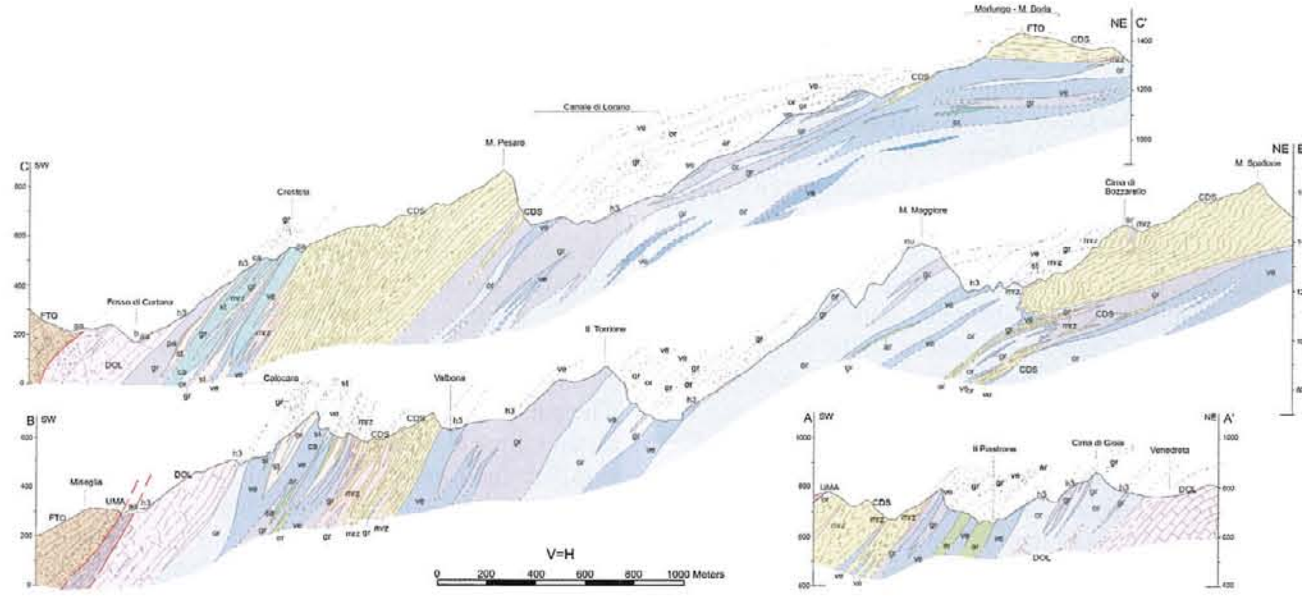


Plate 1. continued.

irregularly distributed and due to local concentrations of pyrite microcrysts. Commonly the mesostructure is free from any orientation of the 0.05–0.3 mm-sized calcite (Di Pisa et al. 1985) and the other very scarce minerals (quartz, dolomite, albite, phyllosilicates), but here and there the impurities, spots and short veins mark a clear foliation (the regional S_1 foliation). The ordinary marble is the most abundant type all over the Carrara basins, but the frequent colour and decoration similarity between it and the veined type makes it difficult to separate the two over even wide places.

"Marmo venato" (veined marble; Fig. 3B): milk- and pearl-white to very light grey marble ornated by many and often dense, light to dark grey veins and thin dykes, meanly 1 mm to 1 cm thick and up to several dm in length, that may be almost straight or (more frequently) form an irregularly branched network everywhere in the rock. Several mm- to cm-sized light grey spots are present as well, which were interpreted as relics of original "fenestrae" filled by different orders of spathic calcite and often by vadose silts (Coli & Fazzuoli 1992).

The bulk composition is about the same of the ordinary type, with a few more abundant accessory minerals; the grain size is similar as well, and the vein network is often parallel–subparallel to the regional S_1 foliation, a setting that was named "Verso di Macchia" by the quarrymen, that is the oriented main attitude of the grey-dark decoration through the light marble volumes.

The principal character of the veined marble is the wide range of aspects due to orientation, persistence, thickness, and spacing of the veins, thus names such as "Venatino" or "Venato forte" are usually adopted to indicate a feeble presence of fine and clear veins, or a heavy system of even thicker grey to dark veins, respectively. Particular types are (1) unreworked metabreccias corresponding to in-situ brecciation of the original light limestone, and (2) metre-thick light marble levels alternating with more or less regular, decimetric to metric grey marble bands resembling the "Nuvolato" type (see later). The latter structure of the veined marble is quite rare and confined to some lengths at the top of the marble s.s. formation; it might represent relics of original bedding.

"Marmo nuvolato" ("cloudy-like" marble; Fig. 3C): grey to light grey marble crossed by numerous light grey to whitish veins and irregular strips, more or less marked and anastomosed. The normal aspect is given by a highly heterogeneous and variegated alternance of cm- to dm-thick irregular beds almost parallel to the regional S_1 ("verso di macchia"), seldom underlined by dolomitic layers and lenses; local bodies of "Bardiglio" marble and metabreccias resembling the "Arabescato" type are present as well. The grey colour is given by microcrystalline pyrite more or less regularly spread within the dominant calcite; however, the accessory minerals (pyrite, dolomite, quartz, etc.) reach a few higher amounts (up to 1.5 %) and this reflects on a little minor size of the calcite crystals. When present, tiny muscovite and chlorite patches appear typically distributed along the S_{1a} surfaces (see later).

According to Coli (1989) and Coli & Fazzuoli (1992), this marble is the product of Tertiary deformation: D_1 phase ultra-syncline cores of the cherty grey metalimestone formation (stratigraphically resting atop the marbles) would have been uprooted and deeply transposed inside the marbles, with diffuse shearing and a kind of amalgamation up to the development of the veined grey "Nuvolato" type (quartzite-free, however). We think that this might be the case for some "Nuvolato" levels close to the top of the marble s.s. formation, but not for all the volumes of this variety, especially for those placed in the central and lower parts, which might have kept their primary location in the lower Liassic carbonates.

The "Nuvolato" marble forms volumes roughly comparable to those of the ordinary and veined marbles, but at present its exploitation is almost dismissed due to drop of commercial demand.

"Marmo Arabescato" (arabesque-like marble; Fig. 3D): clast-supported metabreccia with heterometric clasts and boulders referable to almost all the commercial types here mentioned, in particular ordinary, veined and "Nuvolato" marbles; the by far minor matrix has in turn a calcitic composition and is grey-coloured due to the usual presence of pyrite microcrysts and the other accessory minerals (phyllosilicates, dolomite, quartz, albite).

The interfingering of the two components gives rise to highly irregular decorations that recall the arabesque fashion of Arabian origin, from what the name was coined. The range of draws and ornaments is larger than for all the other marbles, depending on clast size, colour, distribution, and the matrix setting.

In fact, the matrix may form every arrangement between (1) nets of thin, branched grey veins (that is, an aspect very similar to the veined marble), and (2) irregular veins and levels some centimetres thick and a few metres persistent.

In the first case the scarcity of the matrix allows the restoration of the original unbroken continuum, which means negligible dislocations of the fragments developed through an in-situ brecciation along syn-sedimentary fracture belts. Conversely, in the other pattern the pieces can be no way refitted each other suggesting even important reworking of the fractured primary limestone, possibly in a depositional manner: such a genesis is inferred for several neptunian dykes that crosscut the present attitude of the primary bedding (e.g. Boccaletti et al. 1981; Fig. 3E).

The "Arabescati" of the second type are the most decorated but, due to the severe D_1 deformation, the clasts of all these metabreccias were strongly flattened and stretched on the S_1 surfaces, giving a real image of the finite strain ellipsoid associated to this tectonic phase.

The particular shapes of the clasts give rise to quite different aspects and draws exposed in the quarry cuts:

- The cuts parallel to the XZ principal plane of the finite strain ellipsoid (normal to S_1 and parallel to L_1 lineation) are characterised by whitish "strips", a few centimetre thick and several metres long, that correspond to the primary clasts separated by films or very thin matrix levels (Fig. 3F; a setting which strongly recalls a very regular veined type);
- on the contrary, the metabreccia conformation is more and more evident as the cuts progressively approach the no-longitudinal strain sections of the finite strain ellipsoid (Fig. 3F).

The last cuts allow to obtain the lowest deformation fabric with negligible clast orientation, that results in the best ornamental features of the "Arabescato" marble, the so-called "fiorito" (flowered) aspect of the operators and quarrymen and the most appreciated in about all the decorative and building applications.

A valuable "Arabescato" sub-type is named "Bianco Brouillé" (brouillé white; Fig. 3G), crops out only near the Colonnata village (Cima di Gioia-La Rocchetta Quar-

Fig. 3: Illustrations of the outcrop-scale decoration and structure characteristics of the main commercial types in the Carrara Basin marbles.

A: Ordinary to feeble veined marble in the lower portion of the Ortensia Quarry north of Colonnata, in the high left cut note some boudinaged dolomitic layers (ochre-yellowish) within a "Nuvolato" level.

B: Normal to heavy veined marble from the Ponti di Vara area.

C: "Nuvolato" marble close to the Morlungo abandoned quarries, passing upwards to a veined type rich in ochre-brown dolomite levels.

D: "Arabescato" marble from the Cardellino Quarry in the lower Colonnata Valley.

E: Neptunian dyke crosscutting the S_1 foliation along the contact marble s.s. – "Calcare selcifero Auct." at the Piastriccioni Quarry, north of Torano.

F: Two different decoration aspects of the same "Arabescato" as D depending on the cut orientations. The cut to the right is nearly parallel to the XZ principal plane of the finite strain ellipsoid; the left cut is close to the no-longitudinal strain section of the same ellipsoid providing the best "fiorito" aspect of this marble type.

G: The usual aspect of the "Brouillé" subtype of "Arabescato" marble.

H: Fractured veined statuary from the Poggio Silvestre Quarry, M. Betogli northern slope.

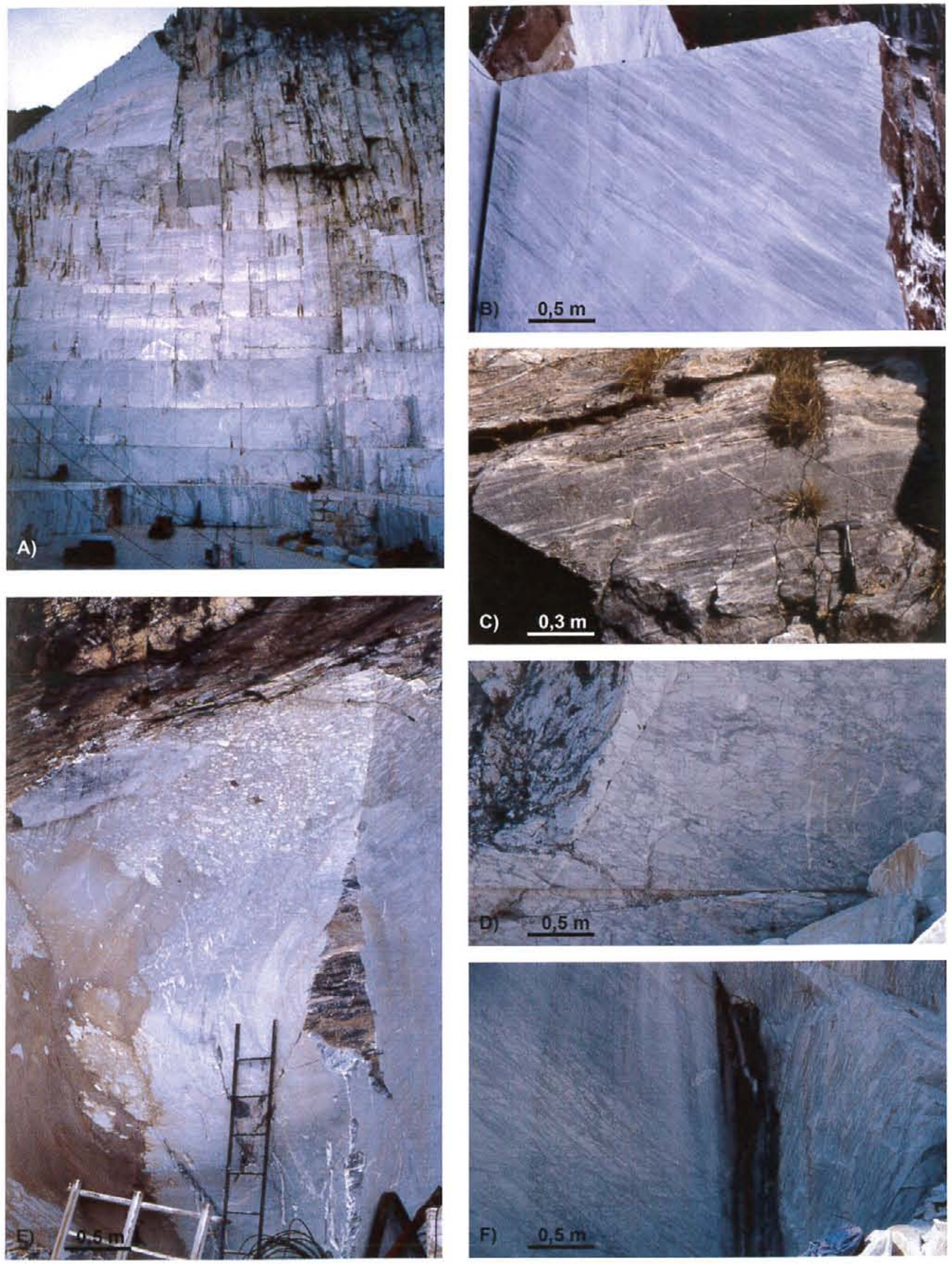
I: Calacata "Macchia Oro" marble from Calacata valley north of Torano.

J: The lens of "Bardiglio" marble at the top of the La Rocchetta Quarry, south of Colonnata.

K: A small block of "Paonazzo" marble from an unmappable layer associated to the statuary-Calacata levels in the northern slopes of M. Betogli.

L: The "Zebrino" marble striped structure involved in metre- to decametre-sized D_1 folds at Sponda Quarry north of Torano.

M: The banded marble structure above the "Zebrino" of the abandoned Vallini Quarry.



ries) and is characterised by a well marked grey matrix, thicker and more persistent than in the normal metabreccias, with about isometric whitish clasts.

Though less abundant, the "Arabescato" marble forms several bodies and levels of conspicuous size associated to or interlyered in the ordinary and veined types.

"Marmo Statuario", "Statuario Venato" (statuary marble, veined statuary; Fig. 3H): highly homogeneous and pure marble with crystal size commonly about 0.3–0.5 mm (rarely minor, Crisci et al. 1975) and floor-like microfabric. The main commercial property of the statuary marble is the colour: it spans from milk- and ivory-white to very feeble and light yellow-beige, given by accessory amounts (less than 1 %) of muscovite microcrysts uniformly distributed among the large calcite crystals; most important, this pigmentation may be very regular and persistent over volumes up to several cubic metres.

Such colour uniformity is seldom broken by very soft and well shaded off into light yellowish-grey haloes, or dispersed tiny grey spots due to only local concentration of pyrite microcrysts. Where these pyrite spots (plus quartz and phyllosilicates) form veins and more marked haloes within the same bulk marble, the last is named "veined statuary".

Locally, these types may include more marked grey-greenish veins (enriched with phyllosilicates, fine-grained quartz and larger pyrite crystals) with usual thickness from a few millimetres to some centimetres, seldom up to 5–7 decimetres (in the exploitation work they are named "Madre-Macchia"). These more evident veins may concentrate in sort of dykes with attitudes generally discordant with respect to the dominant S_1 (the "Verso di Macchia"), and in these cases these volumes are basically metabreccias with dm to m in size marble boulders in an abundant calcschist matrix (similar to some aspects of the Calacata Marble, see later).

The statuary and its subtypes are not abundant as the preceding marbles, but are commercially much more requested for decoration purposes and works.

"Marmo Calacata" (Calacata Marble; Fig. 3I): Calacata is the name of a locality close to Torano village, a few kilometres north of Carrara, where probably the first quarries were open for the extraction of this marble. It is a clast-supported metabreccia with heterometric pebbles and boulders of very light white-yellowish marble identical to the statuary type, occasionally with light grey haloes, in a calcite matrix enriched by muscovite, chlorite plus quartz, albite, etc., and a little more greenish to yellow-ochre coloured than the clasts.

Even though less striking than the "Arabescato" marble, the clastic nature of the parent limestone is apparent in most quarries open in this marble type. However, in several places the metabreccia aspect becomes almost unrecognizable, as the matrix accessory minerals are nearly missing, and clasts and matrix are almost amalgamated by metamorphism and deformation(s). Under these conditions two subtypes are distinguished: the "Calacata Macchia Oro" (golden-spotted Calacata Marble) very appreciated and nearly identical to the statuary except for the presence of ochre-golden coloured feeble haloes and short veins; and the more abundant "Calacata Macchia Grigia" (grey-spotted Calacata Marble) in which the bulk rock is crossed by sparse, pale grey to grey-greenish veins, often shaded off toward the marble fragments.

As already seen for the "Arabescato", also the Calacata Marble is obviously characterised by a wide range of decorations and draws depending on the cut orientation in the quarries and on the measures.

"Marmo Bardiglio" ("Bardiglio" marble; Fig. 3J): fine-grained grey, heavy grey and grey-bluish marble crossed by grey veins and strips usually darker than the bulk rock; a subtype named veined "Bardiglio" is defined when the vein network becomes more abundant and persistent. The more or less uniform grey colour is given by microcrystalline pyrite and/or carbonaceous pigment (Crisci et al. 1975) all over the fundamental calcite, with a few major additions of dolomite, quartz, and phyllosilicates; finally, ash-grey dolomitic metasediments form local roughly regular and discontinuous beds or spread chips. Because of these features, the "Bardiglio" and veined "Bardiglio" marbles are often confused with the "Nuvolato" type, the main differences being a more homogeneous grey colour for the fundamental rock and the darker grey veins. In the Carrara basins this type is scarce, minor lenses may be present indifferently in all the other varieties.

"Marmo Paonazzo" (purple-violet marble; Fig. 3K): clast-supported metabreccia with clasts chiefly referable to statuary and/or Calacata types, and a minor, phyllosilicate-rich, grey-blackish to red-violet calcite matrix; in the latter Fe-minerals are abundant, whose alteration causes the often widespread, characteristic purple-violet pigmentation of both clasts and matrix.

Due to its remarkable decoration features, the purple-violet marble is a very valuable variety but, according to the quarrymen, it is almost worked out or in negligible amounts: a few metres thick and long lens crops out along the old railway in the southern slope of the Belgia Hill (Colonnata Basin), and the historical "Paonazzo" quarries (Bacchiotto locality) along the Colonnata stream are now buried under thick quarry debris.

"Marmo Zebrino" (striped marble; Fig. 3L): alternance of marble levels with variable colours spanning from light whitish-yellowish to light greenish and banded grey, occasionally with rosy specklings, usually separated by interlayers of grey-green, grey and dark-green calcschists and carbonate phyllites. The levels are more or less regular and persistent, meanly their thickness varies from a few centimetres to some decimetres for the greenish and grey types, up to 1.5–2 m for the whitish-yellowish ones, whilst the calcschists are some millimetres to 10 cm thick.

Again, the bulk component is calcite with additions of muscovite, chlorite, quartz, pyrite, minor dolomite, etc. These accessory minerals have variable distribution: the phyllosilicates are obviously abundant in the calcschists, the quartz is regularly spread within the impure levels or may concentrate to form strips and nodules of whitish quartzite; the pyrite gives microcrystalline distributions chiefly in the grey rocks, or forms 1 mm to 1 cm cubic single crystals and aggregates up to some cm in size.

Exceptionally, the lighter marbles may form 20–100 m long and up to 15–20 m thick homogeneous lenses of very valuable types named "Biancone", "Cremo", and "Cremo Delicato" (roughly white, cream-like and soft cream-like marbles, respectively), coloured in ivory-white to very light cream-beige and about totally free from veins and impurities. The other, more frequent borderline case is a green-yellow to green-grey impure marble or calcschist with almost regularly spread accessory minerals.

The dominant setting is a variegated marble whose banded structure is likely original bedding, now overprinted by the regional S_1 foliation, or involved in D_1 mesofolds (see later).

The "Zebrino" ensemble is a discontinuous horizon and, when present, it always crops out at the top of the marble s.s. formation. This fact and the lithological constitution induced to consider this horizon as the metamorphic counterpart of the ammonite-bearing reddish limestone formation of the Tuscan Nappe sequence, a hypothesis also supported by the presence of rose to rose-grey metalimestone lenses (the "Calcare Rosato" by Coli et al. 1992) at the same level of the "Zebrino".

At present this variety is scarcely exploited close to Ponti di Vara, however, it is cut and well exposed in several abandoned or active quarries of other marble types, particularly statuary, Calacata, and "Arabescato" marbles.

The above description order only takes into account the outcrop extension of the single marble types (starting from the most abundant, the ordinary, the veined and the "Nuvolato"), and is no way related to a possible original sedimentary sequence: in fact, in the Early Liassic carbonate platform the primary vertical–lateral relationships among the different parts should have been very complex, and such a complication was certainly increased by the Tertiary polyphase deformations. As to the marble stratigraphy of the Carrara area, the present knowledge allows only the following remarks:

- The "Zebrino" has the unique established stratigraphic position, at the top of the formation and irrespective of the marble type resting below it;
- the formation base is always in the ordinary and/or veined marbles;
- the statuary, Calacata, and purple-violet marbles seem to be mostly placed at rather high positions, whilst the lower and central levels are mainly occupied by the ordinary and veined types;
- the "Nuvolato" variety is more present in the higher locations, but crops out in the central–low horizons as well;
- the "Arabescato" and other brecciated types exhibit a more irregular (somewhat "transversal") distribution, in origin being mainly associated to a large scale network of synsedimentary brittle structures.

A recent field revision has shown that in some places along the northeastern edge of the wide marble, right flank of the Carrara Syncline, the lithological constitution of the marble s.s. consists of a nearly regular alternance of 1–3 m thick whitish and thinner grey beds, a well banded setting unusual for the Carrara exploitation basin. This setting is clearly exposed at (1) Morlungo-M. Borla area close to the West of Foce di Pianza, (2) M. Faggiola-Vallini Quarry along the M. Sagro southern ridge (Fig. 3M), (3) Ortensia Quarry at the base of the M. Maggiore eastern slopes north of Colonnata.

Meccheri et al. (2007) described the same setting as the unique structure of the marble s.s. involved in the Orto di Donna-M. Altissimo Syncline (northern–central Alpi Apuane; see Fig. 1). The authors related this structure to primary bedding and considered the banded marble as the metamorphic counterpart of the formation named Angulata-bearing marly limestones, which in the Tuscan Nappe sequence follows atop and partly is lateral to the Early Liassic "Calcare massiccio". We propose the same attribution also for the quoted banded marbles of the Carrara Basin.

3. The Carrara Marbles: tectonic setting

In the Carrara inland the marble s.s. forms two major outcrops (Fig.1 and Plate 1). The southwestern outcrop is a narrow, NW–SE lengthened belt close to Carrara, the northeastern one is much larger and thicker and extends up to the M. Sagro southwestern slopes. The two outcrops respectively lie in the overturned and right flanks of the Carrara Syncline (Carmignani 1985; see Fig. 1 and Plate 1), the westernmost of the regional scale isoclinal folds formed in the Apuane Unit by the compression tectonics (D_1 phase) of the Tertiary orogenesis.

The vergence of the syncline is toward the NE and its axis (A_1) trends NW–SE with low plunge northwestwards. Near Carrara the syncline core is represented by the Calcare Selcifero Auct. (Mid–Late Liassic; Fig. 2), but in the highest areas (Campocecina-M. Borla) it comprises the greenish phyllites of the Scisti sericitici Auct. (Early Cretaceous–Oligocene).

In the same areas the axial plane of the structure shows different attitudes: at Campocecina it is weakly inclined west–northwestwards, whilst near Carrara it dips up to 60–70° toward the SW. This is due to presence of a large and open D_2 antiform verging toward the Ligurian Sea with a NW–SE trending axis (Fig. 1 and cross sections in Plate 1).

In general, the marble s.s. formation lacks persistent layers suitable to highlight the geometric features of the D_1 folds. Nevertheless, in spite of the internal complications due to both the primary interfingering of the different marbles and the Tertiary polyphase deformation, in several quarries and some natural outcrops it is possible to recognize some still preserved lengths of the original bedding, represented by laterally persistent alternating beds of different composition. This is the case for the "Zebrino" and the banded marbles, whose layering is affected by metric to pluridecametric D_1 folds (close to the Ponti di Vara and at the Sponda Quarries near the Torano village), or simply crosscut by the S_1 foliation (at Ortensia Quarry).

Some hundred metres far from the Ponti di Vara, in the northwestern slope of the Belgia Hill an active quarry is open close to the contact between the "Zebrino" marble and the "Calcare Selcifero Auct." that forms the core of a hectometric parasitic fold in the Carrara Syncline overturned flank. The "Zebrino" layering is well marked and consists of decimetre-thick levels of whitish-yellowish marble alternating with less thick layers of green to grey-green phyllitic marble and grey calcschist, all the bands being almost regularly separated by phyllosilicate films. Along the SW–NE cuts at the quarry bottom, this layering is clearly involved in metric to decametric tight similar anticlines and synclines (Figs. 3L, 4A), with stretched acute hinges and the regional S_1 as axial planar foliation.

At the Ortensia Quarry north of Colonnata the local light banded ordinary/veined marbles offer another example of D_1 structural setting. In this case the layering and the main S_1 foliation dip westwards and the S_1 is the most inclined (40–50°), a typical example of S_0/S_1 relationships in the right flank of a D_1 ENE verging anticline. But, over about 0.5 km toward northeast the same Ortensia marbles pass to marbles forming the overturned limb of a "Calcare Selcifero" cored D_1 syncline, thus the opposite S_0/S_1 angular relationships are required, and this imposes that geometrically above the syncline a D_1 marble cored anticline must exist, whose axial plane trace passes just below the Ortensia Marbles.

These examples testify that all the Carrara Marbles were affected by quite a lot of D_1 folds, ranging from metric (or less) to kilometric size, and such a structural setting implies several repetitions of stratigraphic horizons leading to huge overthickening of the marble s.s. This is particularly evident for the marbles of the Colonnata sub-basin (from M. Maggiore to the north up to the Cima di Gioia-La Rocchetta sector to the south) where several levels of "Calcare selcifero Autc." occupy the cores of so many hectometric to kilometric synclines (see cross sections in plate1).

It must be pointed out that the marble layering involved in these structures is the relic of pristine bedding, with more or less restricted extension within the calcareous deposits. Moreover, all of these surfaces are overprinted by a greenschist facies metamorphic foliation, with a rarely visible mineralogical stretching lineation, which is involved in the D_1 deformations together with the bedding. Hence, the D_1 tectonic setting, recognised and mapped in the marbles and other metamorphic rocks, must be considered as a composite structure resulting from at least two subsequent deformation episodes in the development of the same D_1 compression regime. Some features of this composite pattern were recently described by Molli & Meccheri (2000), Molli et al. (2000a, b), Molli & Vaselli (2006) and Meccheri et al. (2007), and the reader is referred to these papers for further details.

The D_1 structures deforming the Carrara Marbles comprise frequent shear belts or localized shear surfaces causing apparent laminations of marble varieties. Due to the outcrop similarity and parallelism between these discontinuities and the S_1 foliation, it is not easy to distinguish them in the field, usually this is possible only through microscopic analysis.

In contrast with the D_1 tectonic setting, the D_2 structure inside the Carrara Marbles is quite simpler. Apart from localised feeble undulations at the metre–decimetre scale, large D_2 folds are almost absent, and in general the S_1 foliation is arranged in a monoclinal attitude: it strikes about N120–150°E and dips westwards with inclinations ranging from few degrees at Campocecina-M. Borla to mid–high inclinations along the Torano-Miseglia belt, with rare cases of vertical and overturned attitudes: this variability is determined by the abovementioned, plurikilometric, knee-shaped D_2 antiform verging toward the SW and affecting the entire Carrara Syncline and all the above tectonic units (see in Carmignani et al. 1991).

On the contrary, metric to pluridecametric D_2 folds are widespread along the contact marble s.s./ "Calcare selcifero Auct." (M. Uccelliera-M. Borla; Fig. 4B; Vallini-Seccagna,). At places, shear surfaces are associated to the D_2 folds: they are ductile low angle normal faults, developed at retrogressive greenschist metamorphism and whose kinematics is compatible with the vergence of the coeval D_2 folding in the area. These localised shear structures resulted in an often severe, further reworking of the marble microfabric (see later).

This polydeformed ductile structure is then crosscut by fracture sets associated to the latest stages of the Apuane exhumation. Three major sets can be envisaged:

- The first is parallel to the S_1 foliation and developed preferably inside the marbles containing abundant phyllosilicate-rich veins;

- the second is characterised by a wide azimuth range (from N20–30°E to N80–90°E) and mid to high dips toward both NW and SE around the vertical attitude;
- the third set has about the same strike as the first one, but is vertical or dips toward both NE and SW with high inclinations.

In general these fractures are metre to decametre spaced, but often they become so close that they form locally huge cataclastic fault zones (Fig. 4C).

Very likely several fractures were characterized by relative motion of the blocks: true faults, though with small offsets, are associated to each of the three fracture sets and exhibit complicated kinematics with variable motions. A detailed analysis of the brittle structures in the Carrara Marbles is in Ottria & Molli (2000), who suggest that they are associated to the development of the Versilia-Vara, Lunigiana-Magra, and Garfagnana-Serchio tectonic depressions bounding the Apuane Alps window to the southwest, northwest, and northeast to east, respectively.

4. Carrara Marbles: microfabric variability

Three main microfabric types can be distinguished in the Carrara Marble Basin, they represent end-members of a wide range of transitional types. The three main microfabric types are shown in figure 5 and hereafter described.

4.1. Type A microfabric

This type of microfabric is characterized by equant polygonal grains (granoblastic or "foam" microstructure; Fig. 5A), with straight to slightly curved grain boundaries that meet in triple points at angles of nearly 120°.

A unimodal grain size distribution with an average grain size variable between 0,20–0,35 mm characterizes this microfabric (Molli and Heilbronner 1999, Molli et al. 2000b). The preferred orientation of grain boundary surfaces (SURFOR; Panozzo 1984) reveals a slightly bimodal surface distribution which can be observed in the rose diagram of figure 5A.

The analysis of the preferred orientation of particle axes (PAROR; Panozzo 1983) also shows a slightly bimodal distribution of long axis orientation, with maxima being inclined at approximately 20–30° clockwise and anticlockwise with respect to the foliation plane (Fig. 5A). The asymmetry of the orientation of grain boundary surfaces (SURFOR) and the preferred orientations of the particle axes (PAROR) of the sample coincide rather well. The average aspect ratios (short/long axis) of the individual grains are in the order of 0.65–0.80. Whereas the PARIS factor (Panozzo & Hurlimann 1983) for this microstructures is very low (1.8–3), implying straight grain boundaries. The c-axis pole figure reveals a weak great circle distribution at the periphery of the pole figure. Crystallographic preferred orientation (CPO) of samples collected in the Carrara Basin and showing similar microstructural features referable to type A can be found in Leiss & Weiss (2000), Pieri et al. (2001a, b), Siegesmund et al. (2007) and references therein.

Type A microfabric is interpreted as developed during static recrystallisation after deformation representing a classical example of annealed geological material, e.g. Schmid et al. (1987), Molli & Heilbronner (1999), Molli et al. (2000b). The statically recrystallized microfabric, observable in samples showing large finite strain (e.g. Fig. 3) and folding from kilometre- to micro-scale (Fig. 1, Plate 1, and Fig. 6) clearly indicates that grain growth and recovery occurred after the main folding phase D_1.

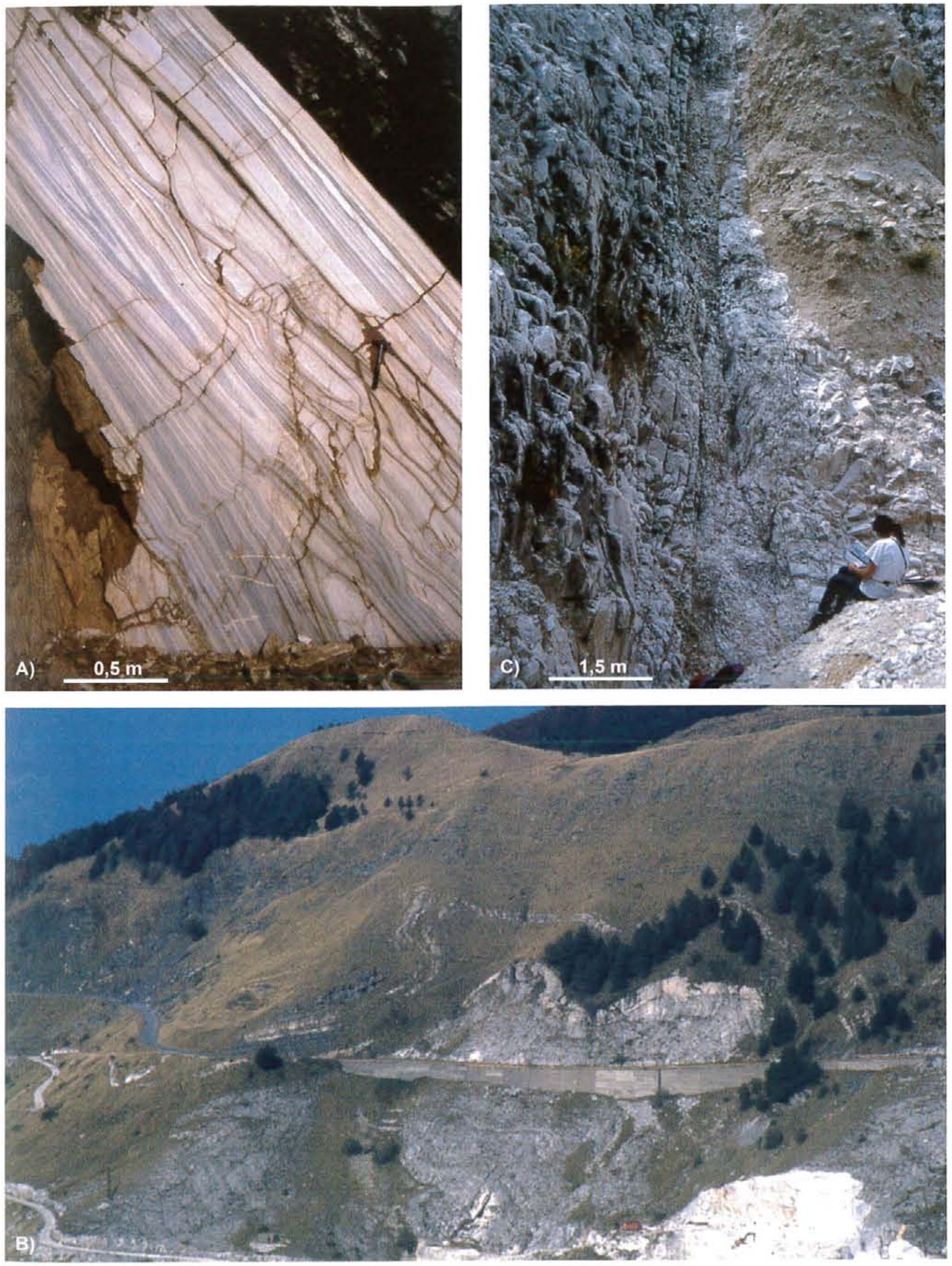
4.2. Type B microfabric

This microfabric type comprises marbles with different microstructures associated with a dynamic reworking of the previously developed type A microfabric (Fig. 5B).

It includes marbles with variable grain size showing evidence of intracrystalline deformation (mainly undulatory extinction and deformation twins), sutured grain boundaries and dynamically recrystallized calcite grains with smaller grain size (0,02–0,05 mm) with respect to the protolith (0,15–0,20 mm).

The type B microfabric is associated with millimetre to centimetre-scale D_2 shear zones; approaching these shear zones, a gradual change in marble microfabric can be observed and was firstly described by Molli & Heilbronner (1999), Molli et al. (2000b). In the low strain domains, the granoblastic protolith (mean grain diameter approximately 0,150 mm) shows type A microfabric, even if low-temperature deformation features can be observed. Towards the high strain zone, the grain boundary corrugation of the relict calcite, i.e. the PARIS factor, increases

Fig. 4: A) metric–decametric D_1 folds in the "Zebrino" marble close to Ponti di Vara. Apart from the two folds, other structures are evident such as boudinage (D_1), and undulations (D_2) deforming both flanks of the D_1 folds. B) Hectometric knee-shaped D_2 folds affecting the right flank of the Carrara Syncline in the southeastern slope of Zucco del Latte (northern part of plate 1), the fold vergence is towards the SW. C) A cataclastic fault zone in the ordinary marble of the M. Maggiore southeastern slope.



from about 10 to 23. Recrystallisation occurs preferentially at the grain boundaries and a progressive localization of recrystallized grains in layers, subparallel to the shear zone boundaries, is observed. The recrystallized layers show a bimodal grain size distribution. Coarse, twinned relict grains (modal grain diameter about 0,200 mm) are embedded in a matrix of recrystallized grains with a diameter of approximately 0,04 mm (Fig. 5B).

Crystallographic preferred orientation of this microfabric type is variable depending from the stage of dynamic overprint; figure 5B shows an example of strong texture with asymmetric distribution of c-axis at high angle to the foliation plane.

Tab. 1: Partial and total production in the Carrara Marble District (year 2004).

Area	ton	%
Carrara	915 000	75
Massa	90 000	7
Lunigiana	89 000	7
Garfagnana	83 000	7
Versilia	51 000	4
Total	**1 228 000**	**100**

4.3. Type C microfabric

This microfabric type can be observed in impure marbles and calcschists of "Zebrino" and some "Nuvolato" and "Bardiglio" levels. It is characterized by a strong shape preferred orientation parallel to the main mesoscopic foliation (Fig. 5C), grain boundaries from straight to lobate and a variable grain size (from 0,10–0,250 mm).

In mica-rich layers, pinning and window microstructures (Jessel 1987) are visible (Fig. 6B) as result of a grain boundary migration process. Quantitative microstructural analysis (sample of "Nuvolato" from the high Colonnata Valley) shows an average grain size of 0,15–0,20 mm and a unimodal nearly symmetrical surface orientation with an orientation subparallel to the foliation trace. The analysis of the preferred orientation of particle axes (PAROR) shows a unimodal distribution of long axis orientation, with a maximum inclined at low angle approximately 10° with respect to the foliation plane. Individual grains are characterized by an average aspect ratio in the order of 0.50. A c-axis preferred orientation with maxima distributed on a great circle normal to the foliation plane can be observed in this sample (Fig. 5C).

Texture referable to this kind of microfabric is generally weak, e.g. figure 5C, and can be found in Leiss & Weiss (2000) and Leiss & Molli (2003).

Type C microfabrics can be observed in late-D_1 high strain zones such as the limbs of folds and shear zones (Molli & Meccheri 2000, Molli et al. 2000b, Leiss & Molli 2003) as well as in D_2 shear zones (Molli et al. 2001).

The three types of microfabric can be observed as variably affected by low-strain and low-temperature crystal plastic deformation mechanisms, characterized by thin straight e-twins (Figs. 5A, 5C), they occur with different intensities in all the marble outcrops of the Carrara Basin. Twinning is well developed where large calcite grains are present (Rowe & Rutter 1990) and from tectonic point of view can be related with late-orogenic deformations such as kink and fault structures.

Since it is well established by the works of different authors (Franzini et al. 1984, Logan et al. 1993, Bouineau & Perrier 1995, Franzini 1995, Barsotelli et al. 1998, Leiss & Weiss 2000, Siegesmund et al. 2000, Cantisani et al. 2000, Logan 2004, Scheffzuk et al. 2004, Cantisani et al. 2005) that microfabric features such as grain size and grain size distribution, grain shape and grain shape distribution, crystallographic preferred orientation and grain boundary morphologies altogether with internal residual stress are the dominant factors controlling marble degradation and alteration processes (e.g. Scheffzuk et al. 2007), present ongoing researches are focused on the mapping of the microstructural variability at the scale of the whole Carrara Marble Basin.

5. Carrara Marbles: economic data

Marble quarrying activities throughout the entire Apuane region are carried out in five different areas: Carrara, Massa, Lunigiana (Fivizzano), Garfagnana (Vagli, Minucciano, Villa Collemandina) and Versilia (Stazzema, Seravezza).

All these areas take the name of Carrara Marble District, an overview of the whole Apuane ornamental stones can be found in Carmignani et al. (2005). It is noteworthy that from the geological point of view the Carrara Basin

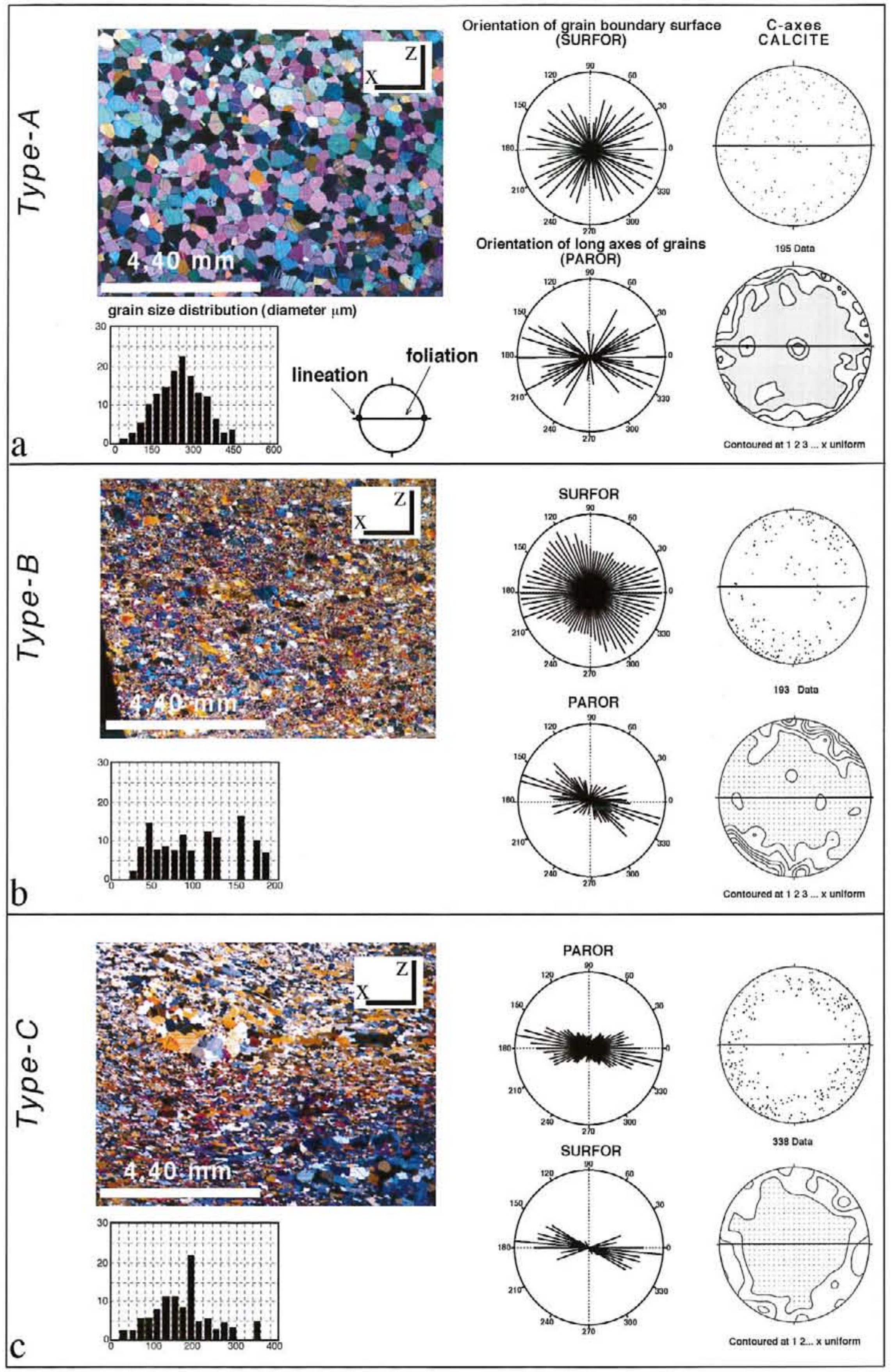


Fig. 5: Microfabric features of the three main types of Carrara Marbles. Typical microstructural features, SURFOR and PAROR analysis and c-axis orientation of type A (a), type B (b), and type C (c). Number of grains analyzed with PAROR and SURFOR routines is more than 200.

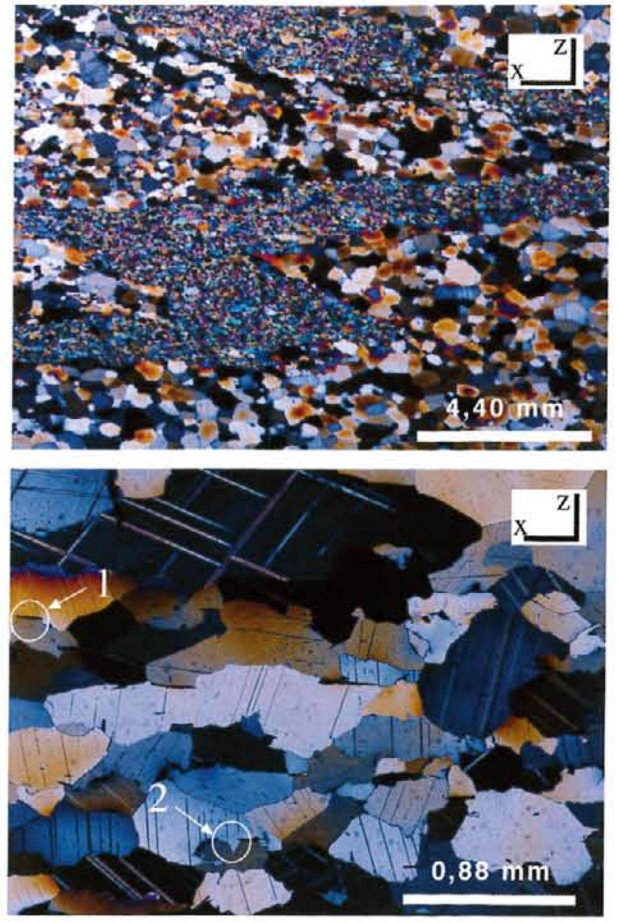


Fig. 6: (a) Annealed microstructure (type A) in marble affected by D_1 isoclinal folding. The folded level is made up of fine-grained calcite and dolomite; phyllosilicates represent former stratigraphic layer. Ordinary sample from Belgia, Colonnata Basin. (b) marble with type B microfabric showing pinning (1) and window (2) microstructure evidence of grain boundary migration process. "Zebrino" sample from Artana, Colonnata Basin.

marbles are considered as a unique ensemble, while considering the commercial-economical aspects, the same marbles are subdivided in the three sub-basins Torano, Miseglia, and Colonnata, corresponding to three main valleys inland of Carrara.

Types of marble and production

The total number of open quarries is of about 140, of which 90 are concentrated in the Carrara basins (Bradley 1997, Bradley 1999).

The annual production, in terms of squared and shapeless blocks, is around 1 200 000 tons (years 2003–2006), against the 1 400 000 tons in the years 2000–2002 (IMM 2006). As regards quantity, the Carrara quarries dominate the scene with 75 % of the production, followed by Massa, Lunigiana and Garfagnana with 7 % and Versilia with 4 %.

The ratio between the two types of blocks (squared and shapeless) varies substantially according to the type of marble considered, but for the most important varieties it is calculated that, on average, squared blocks (including semi-squared blocks and squared blocks with defects that give a loss less than 40 %) account for 60 % of the total production in the Carrara Marble District (year 2004; Tab. 1).

The Apuane marbles include a certain range of materials which follow a well-defined geographical distribution. In order of quantity, "Bianco" and "Bianco Venato-Venatino" dominate production. The former is mainly extracted in the Carrara District, where it is the most abundant, and in the Massa District. In other quarrying areas, the white marble extracted with similar characteristics to "Bianco", is generally named after the place where it is quarried, and is produced in small quantities.

"Bianco Venato-Venatino" is more widespread since, in addition to the two districts mentioned above, it is also quarried in fairly substantial quantities in Garfagnana. "Bianco" and "Bianco Venato" are further classed as C, C/D, D, and "Edilizia". The C type is characterised by a very clear and regular groundmass, while the "Edilizia" type has a dark and spotted groundmass. The other types show intermediate characteristics.

Another marble variety, "Arabescato" is extracted in large quantities especially in Versilia, but is also present in the Garfagnana and Massa areas. There are a number of varieties available in small quantities, which include, however, materials of great economic importance. Among these, "Statuario" and "Cremo" partly located in the Carrara basins, "Bianco P" present in Massa and partly in Garfagnana, and "Calacata" which is typical of a few quarries in Carrara and Massa. Other materials unevenly distributed in various Apuan basins are "Bardiglio", "Nuvolato", and "Zebrino". The latter two are only extracted in Carrara and Massa. Small quantities of coloured marbles (Rossi/Red and Breccias) are quarried in Garfagnana and Versilia.

According to a product classification (Tab. 2), it is possible to determine 6 classes of marbles on the basis of their commercial value and lithological characteristics:

Class 1: "Statuario", "Bianco P", "Calacata", "Cremo", "Arabescato";
Class 2: "Bianco C", "Bianco Venato-Venatino", "Bardiglio", Class 1 of second rate;
Class 3: "Bianco C/D", "Bianco Venato C/D";
Class 4: "Bianco D", "Bianco Venato D", "Nuvolato";
Class 5: the "darkest" "Bianco" and "Bianco Venato", "Bardiglio" and "Nuvolato" of second rate;
Class 6: coloured marbles ("Rosso Collemandina", "Rosso Rubino", "Breccia di Seravezza", etc).

Tab. 2: Product classification of the marbles on the basis of their value and lithological characteristics.

Areas	Class 1		Class 2		Class 3		Class 4		Class 5		Class 6		Total
	ton	%	ton	%	ton	%	ton	%	ton	%	ton	%	ton
Carrara	10 869	2	70719	17	176423	42	154853	37	9282	2	0	0	422146
Massa	2700	8	12010	36	13000	38	5100	15	200	1	698	2	33708
Lunigiana	0	0	12600	47	3200	12	10800	41	0	0	0	0	26600
Garfagnana	3100	9	14500	44	4200	13	7500	23	0	0	3550	11	32850
Versilia	16775	45	17517	47	0	0	0	0	1316	4	1283	4	36891
Total	**33444**	**6**	**127346**	**23**	**196823**	**36**	**178253**	**32**	**10798**	**2**	**5531**	**1**	**552195**

A recent study on the Carrara Marble District has taken into consideration a sample of 31 quarries (equal to the 45 % of the total quarry output) and has shown that the production is mainly concentrated on the central classes 2, 3 and 4.

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Bausandsteine Südwestdeutschlands: Vorkommen, Beschaffenheit, Verwendung und Prospektion

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Werner, W. & Hoffmann, B. (2007): Bausandsteine Südwestdeutschlands: Vorkommen, Beschaffenheit, Verwendung und Prospektion. [Dimension sandstones of Southwest Germany: occurrence, composition, use and exploration.] – Z. dt. Ges. Geowiss., 158: 737–750, Stuttgart.

Kurzfassung: Die geologische Entwicklung in Südwestdeutschland – vor allem die rasche tektonische Hebung und Erosion seit dem höchsten Oberjura – führte dazu, dass im weiteren Umfeld der variszischen Grundgebirgsaufbrüche von Schwarzwald und Odenwald alle in den letzten rund 300 Mio. Jahren gebildeten sedimentären Formationen angeschnitten wurden. Bausandsteinführende Schichten sind im Schichtstufenland besonders in der Trias (Buntsandstein und Sandsteinkeuper), untergeordnet auch im Braunjura zu finden. Tertiäre Kalksandsteine treten im Voralpenland und im südlichen Oberrheingraben auf. Die industrielle Nutzung der Bausandsteinvorkommen begann schon zu römischer Zeit. Über 1000 Sandsteinbrüche sind heute nachweisbar, von denen derzeit aber nur noch 27 in Betrieb sind. In 25 weiteren Steinbrüchen werden andere werksteinfähige Gesteine wie Granit, Muschelkalk, Weißjurakalkstein, Süßwasserkalkstein oder Travertin gewonnen. In Baden-Württemberg wurden z. B. im Jahr 2005 insgesamt rund 150 000 t bearbeitungstaugliche Gesteine gebrochen, wovon rund 80 000 t Sandsteine waren.

Die Gründe für die Auflassung von Werksteinbrüchen sind vielfältig – sie reichen von der Erschöpfung der Lagerstätte, der Ausdehnung von Siedlungsflächen sowie von Natur- und Wasserschutzgebieten bis hin zum Wandel in den architektonischen Vorstellungen.

Zudem sind wegen der für humide Klimabereiche typischen raschen Verwitterung und Bodenbildung die meisten alten Abbauwände nicht oder nur noch in kleinen Teilen zugänglich. Die Prospektion auf verbliebene Sandsteinlagerstätten und die Wiederinbetriebnahme alter Brüche gestalten sich daher schwierig. Sanierungsmaßnahmen am immensen denkmalgeschützten Baubestand des Landes treffen somit auf eklatante Beschaffungsprobleme. Hinzu kommt, dass einheimisches Material im Vergleich zu importierten Werksteinen teuer geworden ist. Ein Ausweichen auf Sandsteine aus anderen Ländern ist aber nicht nur vom Standpunkt des Denkmalschützers problematisch, auch das Verwitterungsverhalten der Gesteine ist unter den humiden mitteleuropäischen Klimabedingungen oft ungünstig.

Die Prospektion auf einheimische Sandsteinvorkommen erhielt in den letzten Jahren durch neue Techniken und die Erkundungsarbeiten zum Rohstoffsicherungskonzept der Landesregierung Baden-Württembergs neue Impulse. Interessenten an einer Wiedereröffnung alter Brüche können auf zahlreiche, meist auch digital verfügbare Informationen zur Landesgeologie, Topographie, Landnutzung und zur Abgrenzung von Schutzgebieten zurückgreifen. Laufende Erkundungsprogramme und Prüfaufträge der Denkmalverwaltung bringen neue Erkenntnisse hinsichtlich der gesteinsphysikalischen Parameter. Erste erfolgreiche, obgleich zeitintensive Arbeiten zur Gewinnung von Austauschmaterial für wichtige Bauwerke aus historisch betriebenen Steinbrüchen haben stattgefunden, weitere sind in Vorbereitung (Lepper 1997, Singewald 1992, Weber et al. 2001).

Abstract: Numerous dimension stone occurrences exist in Southwest Germany. In particular, sandstones of diverse stratigraphic units (Permian–Tertiary) were frequently used for the construction of houses, walls, castles, churches, monasteries etc. The most important sandstone beds are those of the Bunter and the so-called Sandstone Keuper (Lower and Upper Triassic). Dimension sandstones can also be found in the Middle Jurassic and in the Tertiary Molasse Basin in the foreland of the Alpine belt. The use of sandstone in an industrial scale started already in Roman times. More than 1000 sandstone quarries are known in SW-Germany, but only 26 of them are still in operation. About 80 000 tons of workable sandstone were exploited in 2005.

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