Boll.Soc.Geol.It. (*Ital.J.Geosci.*), Vol. 126, No. 1 (2007), pp. 25-35, 8 figs., 1 pl. f.t.

The Mt. Altissimo marbles (Apuane Alps, Tuscany): commercial types and structural setting

MARCO MECCHERI (*), ELENA BELLAGOTTI (*), GLORIA BERRETTI (*), PAOLO CONTI (**), FIORENZO DUMAS (***), SERGIO MANCINI (****) & GIANCARLO MOLLI (*****)

ABSTRACT

The Marbles *sensu stricto* of the Mt. Altissimo region form an important district in the central Apuane Alps and were exploited in many quarries active up to some decades ago. The marble varieties are characterized by high quality physical-mechanical properties often joined with very appreciated ornamental features (Tacca Bianca Statuary, Absolute white Porracci, Arabesque-like types, ecc.).

At present only two large quarries are active. The most important is the Cervaiole quarry, SE of the Mt. Altissimo, from which decorative Arabesque marbles are extracted; the La Buca quarry, Mt. Altissimo eastern slopes, has been reactivated a few years ago and shows high potentiality of development principally toward the underground production.

The marbles here concerned crop out at the core of the Altissimo Syncline, one of the major megastructures of the Apuane Unit that formed during the D_1 compressional tectonics of the Tertiary orogenesis, and were severely affected by the D_2 tectonic phase. In the southern sector of the Altissimo Syncline, the closure of the megafold shows several kilometric-hectometric parasitic folds characterized by diffuse sheath style that controlled orientation and geometry of the following D_2 structures.

KEY WORDS: *Apuane Alps, Mt. Altissimo, Marbles s.s., commercial types, polydeformed structures, interference patterns.*

RIASSUNTO

I marmi di M. Altissimo (Alpi Apuane, Toscana): varietà merceologiche e caratteristiche strutturali.

I Marmi *sensu stricto* del M. Altissimo formano un importante bacino estrattivo nelle Alpi Apuane centrali e sono stati oggetto di intensa coltivazione in numerose cave, tutte attive fino ad alcuni decenni fa con produzione di varietà ad elevate proprietà fisico-meccaniche, spesso associate a qualità ornamentali di grande pregio (Statuario Tacca Bianca, Bianco assoluto Porracci, Arabescati, ecc.). Attualmente sono attivi solo due impianti di grandi dimensioni, quello di località Cervaiole a SE della cima dell'Altissimo, da cui vengono estratti Arabescati molto apprezzati sul mercato, e quello di cava La Buca nel versante orientale dell'Altissimo, che mostra notevoli potenzialità di sviluppo soprattutto in rapporto al possibile sfruttamento in galleria.

I marmi qui considerati affiorano al nucleo della Sinclinale di M. Altissimo, una delle maggiori strutture plicative dell'Unità delle Apuane, nata durante la fase compressiva D_1 dell'orogenesi terziaria e intensamente deformata dalla seconda fase D_2. Nella zona di chiusura meridionale della grande sinclinale l'assetto strutturale di prima fase è caratterizzato da pieghe parassite da chilometriche a ettometriche, con geometria tridimensionale a guaina (*sheath folds*). Questa strutturazione ha in parte controllato l'orientazione delle successive pieghe D_2 e il complesso *pattern* d'interferenza risultante.

TERMINI CHIAVE: *Alpi Apuane, M. Altissimo, Marmi s.s., varietà merceologiche, strutture polideformate, strutture d'interferenza.*

INTRODUCTION

In the central Apuane Alps Metamorphic Complex (AMC) the marble-cored Mt. Altissimo Syncline (hereafter AS) belongs to the Apuane Unit and is the southern part of the major Orto di Donna-Mt. Altissimo Syncline (A in the tectonic sketch on the geological map table). This is a N-S trending, first order isoclinal-subisoclinal megastructure that extends for 15 km from the AMC-Tuscan Nappe contact in the North, to inland of Seravezza in the South.

According to the tectonic evolution proposed by CARMIGNANI & KLIGFIELD (1990), the AS and other megafolds of comparable size (the Carrara Syncline and Vinca-Forno Anticline to the West; the Mt. Tambura Anticline and several minor anticlines and synclines in the Arni-Vagli area to the East, see the tectonic sketch on the map) resulted from the compression tectonics of the Tertiary orogenesis (D_1 phase, Late Oligocene-very Early Miocene), during the development of the northern Apennine fold-and-thrust belt.

Since the Early Miocene, a subsequent deformation (D_2 phase) overprinted the earlier structures, generating new ductile to brittle-ductile (and later only brittle) structures linked to post-compression tectonic uplift and internal extension of the piled-up tectonic units.

These polydeformed structures developed under greenschist facies metamorphic conditions (0.4-0.6 GPa, 350-450°C: MOLLI *et alii*, 2000, with bibl.), with mineral assemblages generally showing progressive syn-D_1, and retrogressive syn-D_2 features.

The most recent and low-T stages of the D_2 tectonics resulted in a widespread network of fractures and joints crosscutting the whole rockmass. In the area considered here, the main set strikes SW-NE to W-E with almost verti-

(*) Dipartimento di Scienze della Terra, Via Laterina 8, I - 53100 Siena. Corresponding author: M. Meccheri: tel. 0577 233833 - fax 0577 233938 - e-mail meccheri@unisi.it

(**) Centro di Geotecnologie Univ. Siena, Via Vetri Vecchi 34, I - 52027 S. Giovanni Valdarno (AR).

(***) Studio di Geologia Tecnica, Via Codena 2, I - 54033 Carrara.

(****) Man. Ser., Via Palestro 48, I - 55042 Forte dei Marmi (LU).

(*****) Dipartimento di Scienze della Terra, Via S. Maria 53, I - 56126 Pisa.

cal attitudes, and several fractures are revealed to be true faults with a major strike-slip component of motion, though the related throws are almost always negligible, and only in a few cases were offsets of some ten metres observed.

The AS geology was described in a few publications, among which the ZACCAGNA (1932) and GIGLIA (1967) papers are the most important. In the last twenty years, the updating of knowledge on both lithostratigraphy and tectonics was achieved through unpublished degree theses by LORENZONI (1984), CONTI (1987), VIETTI (1987), BELLAGOTTI (2002), GALMACCI (2002) and BERRETTI (2005), preliminarly divulged at recent scientific meetings (MECCHERI *et alii*, 2004; 2005a,b).

LITHOSTRATIGRAPHIC OUTLINE

The rocks involved in the AS (see the geological map) belong to the Apuane Unit, in particular to the oldest terms of its sequence overlying some units of the pre-Alpine basement. The latter is represented by (1) quartzitic metasandstones, phyllitic quartzites and phyllites (the Lower Phyllites: BARBERI & GIGLIA, 1966); (2) Porphyroids and Porphyritic Schists (respectively derived from original, rhyolitic-dacitic subaerial volcanites and from the products of their primary reworking: BARBERI & GIGLIA, 1966); (3) thinly-layered dark grey dolostones (the Late Silurian Orthoceras-bearing Dolostones: VAI, 1970; BAGNOLI & TONGIORGI, 1980) and associated blackish graphitic phyllites, forming only an unmappable lens along the road to the Cervaiole Quarry. The age of these rocks spans from the Upper Cambrian? to the Upper Silurian.

The Alpine sedimentary sequence begins with the «Verrucano» quartzitic metarudites («anageniti»), quartzarenites, metasiltstones and phyllites (Carnian?-Early Norian?). These lithotypes form a thin and discontinuous layer at the base of the Grezzoni Formation (Norian-Lower Rhaetian) that consists of coarsely- to well-bedded dolostones, with local massive structure and with bodies of monogenetic sedimentary breccias. The Grezzoni formation is followed by whitish to very light pale cream, often well foliated metalimestones, with frequent muscovite ± chlorite films or veins and discontinuous intercalations of calcschist and yellowish-ochreous dolostones. Due to the association with the Seravezza Breccias and rare lenses of Chloritoid-bearing Phyllites, these metalimestones are correlated with the Megalodon-bearing Marbles (Rhaetian) defined further North in the Orto di Donna Syncline (NOTINI, 1982; CARMIGNANI, 1985). The Dolomitic Marbles (very Early Liassic), mainly present along the AS overturned limb, form a discontinuous layer at the base of the Marbles *sensu stricto* formation, reaching a maximum thickness of some ten metres west of the Mt. Altissimo peak. The Marbles *sensu stricto* (Early-Middle? Liassic) are the youngest term in the wide core of the main megastructure, and are constituted by different, more or less commercially important varieties that will be briefly described in the next paragraph.

ORNAMENTAL STONES FROM THE ALTISSIMO SYNCLINE

Large amounts of ornamental stones were exploited from several quarries working the metacalcareous lithotypes, most of which are now inactive. An insert in the table of the geological map shows the location and the known names of these quarries all over the region, and of the several trial quarries as well.

Apart from the Marbles *s.s.*, rocks useful for decoration and building were extracted from the Megalodon-bearing Marbles, in particular from the Seravezza Breccias. These are grain-supported metarudites with calcareous and very rare dolomitic clasts, a few cm to some dm in size, variably coloured from whitish and light grey to pink, purple and violet, in a purple-brownish to violet-grey and grey-greenish metasiltitic-phyllitic matrix, usually rich in chloritoid (single crystals or aggregates up to several mm). Almost always the matrix forms a network of anastomosing films and veins, that occasionally may become dm-thick discontinuous horizons or pockets, ranging up to very rare lenses of mappable dimensions (at least a few metres thick and 10-15 m or more in length: the Chloritoid-bearing Phyllites).

Fig. 1 - Some aspects of the main commercial types of the MT. Altissimo ornamental stones: (A) the «brecce fior di pesco» from a level of Seravezza Breccias in the Mt. Corchia area (the height of the cut is about 2 m); (B) the banded structure of the oA Marbles at the Mossa Quarry (the vertical face is about 15 m high); (C) the bA Marbles at the abandoned upper quarry of the Giacceto area, with white and grey layers respectively thicker and thinner than those in the oA (the lower vertical bench is 7-8 m high); (D) the abandoned lowest quarry of the Cave dei Pennacci area, the upper part of which is open in the bA Marbles with some levels of the Absolute White Porracci (in the centre the total height of the artificial wall is about 35 m); (E) whitish to very light grey Veined Marbles separated by narrow Nuvolato-like bands at the Cervaiole Quarry (the exposed vertical cut is about 5-6 m high); (F) in the oA Marbles of the Cervaiole Quarry, a local amalgamation of some grey bands forms a 8-10 m thick body of more or less veined Nuvolato Marble; (G) whitish pebbles and boulders ranging from decimetre-sized to several metres in the Arabesque-like Marbles of the Cervaiole Quarry (the central height of the lower vertical cut is about 12 m); (H) at the Mossa Quarry, the Arabesque-like Marbles form a neptunian dyke crosscutting the oA beds along a synsedimentary fracture. The vertical face in the foreground is about 5 m high and strikes N60°E, while the local oA bands (forming the vertical strips crosscut by the dyke) strike N74°E and dip about 80° southwards.

– Alcuni aspetti delle principali varietà commerciali delle pietre ornamentali di Mt. Altissimo: (A) le «brecce fior di pesco» da un livello di Brecce di Seravezza nell'area di M. Corchia (l'altezza del taglio è circa 2 m); (B) la struttura bandata del Marmo Ordinario Altissimo di Cava Mossa (il taglio verticale è alto circa 15 m); (C) il Marmo Bianco Altissimo della cava abbandonata superiore della zona Giacceto, con letti bianchi e grigi rispettivamente più potenti e più sottili di quelli dell'Ordinario Altissimo (la bancata verticale inferiore è alta 7-8 m); (D) la cava abbandonata inferiore del gruppo Cave dei Pennacci, la parte alta della quale taglia il Bianco Altissimo con alcuni banchi di Marmo Bianco Assoluto Porracci (al centro la parete artificiale è alta circa 35 m); (E) Marmi Venati da biancastri a grigi molto chiari, separati da letti tipo Marmo Nuvolato, a Cava Cervaiole (il taglio verticale è alto 5-6 m); (F) nell'Ordinario Altissimo di Cava Cervaiole, la locale amalgamazione di alcuni banchi grigi forma una lente spessa 8-10 m di Marmo Nuvolato più o meno venato; (G) clasti e blocchi biancastri da decimetrici a plurimetrici nei Marmi Arabescati di Cava Cervaiole (l'altezza centrale del taglio verticale inferiore è intorno a 12 m); (H) alla Cava Mossa, i Marmi Arabescati formano un filone che attraversa la bancatura dell'Ordinario Altissimo lungo una frattura sinsedimentaria. La parete verticale in primo piano è alta circa 5 m ed è orientata intorno a N60°E, mentre i livelli dell'Ordinario Altissimo (che formano le striscie verticali tagliate dal filone) hanno direzione di N74°E e inclinazione di circa 80° verso sud.

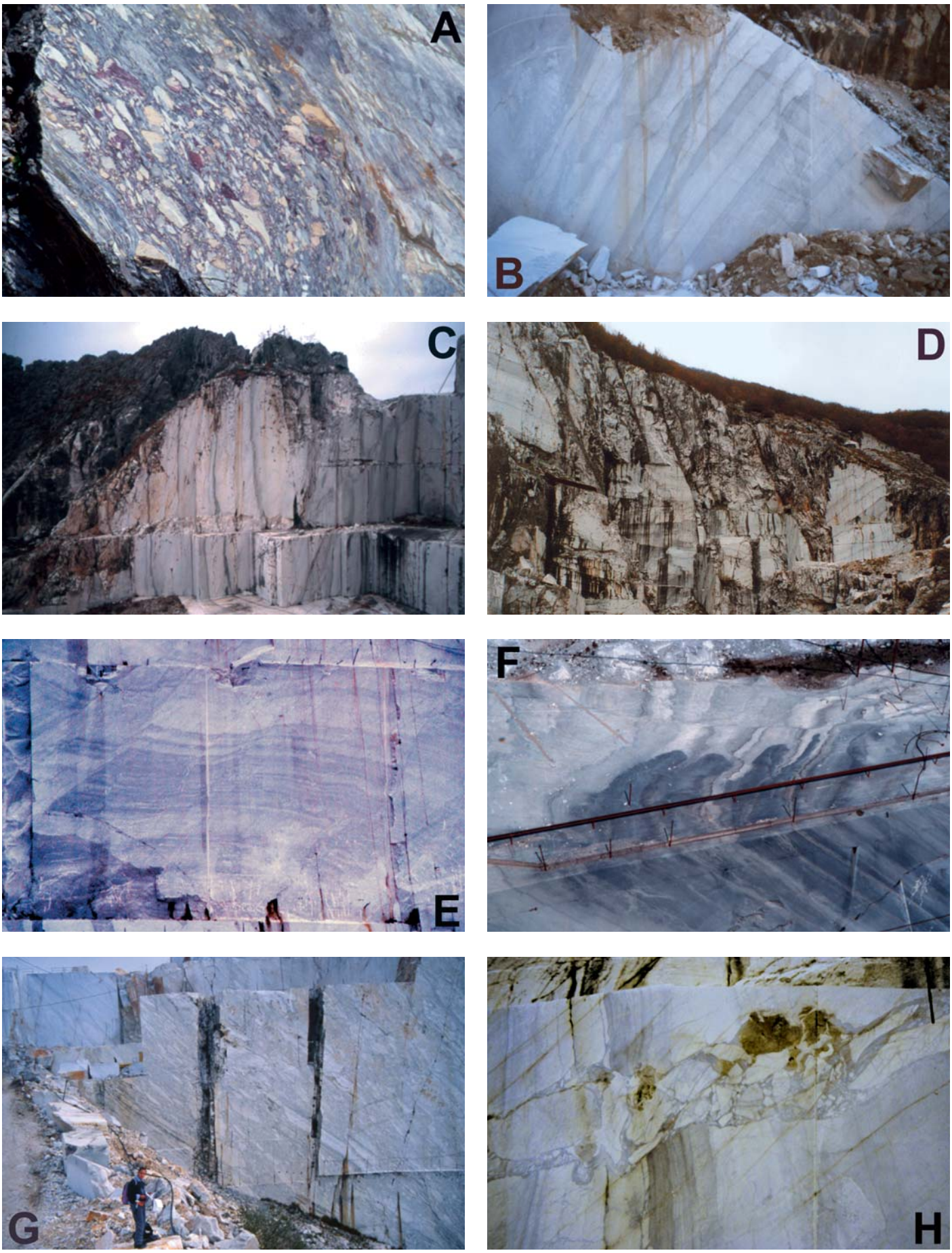

Fig. 1.

In the region described here, the Seravezza Breccias were widely quarried as «brecce fior di pesco» (peach-flower breccias, fig. 1a) about up to the 1940s-1950s. The main quarries were in the Valsora area and the high Giardino Valley (north-west corner and southern edge of the geological map, respectively), and in the Canale del Fondone (the Rana Quarry, Mt. Altissimo eastern slopes); the exploitation was totally abandoned due to the exhaustion of the horizons suitable for dimension stones.

Obviously, the most abundant and commercially important stones are from the Mt. Altissimo Marbles *s.s.* On the whole, this formation provides two main commercial varieties that, according to the quarrymen and industry operators, are usually named Altissimo ordinary Marble and Altissimo white Marble (hereafter oA and bA, respectively). The oA represents the lower portion of the Marbles *s.s.* formation and consists of an almost regular, persistent sequence of beds, dominantly of white and less abundantly of pale whitish-grey marbles, averaging 2-4 m thick, separated by minor, grey to pale grey banded beds rarely thicker than 1-2 m (fig. 1b). The oA grades upwards into the bA type, characterized by major persistence and thickness of the white levels and thinner, light grey interbeds (fig. 1c). Due to the gradational passage, distinction between the two types is very difficult in the virgin outcrops, and the contact was placed with adequate certainty only in some quarry faces (fig. 1d).

Both types contain minor amounts of diverse, even more important marbles:

– in the oA, numerous whitish layers are ornamented with almost regular to anastomosed arrays of several, thin and grey veins, giving rise to bodies and lenses of the Veined Marbles variety (fig. 1e);

– where the grey interbeds become thicker and more regularly coloured, some levels of Nuvolato Marbles (that is, cloudy-like grey marbles) may be distinguished (fig. 1f);

– in the bA, horizons of Veined and Nuvolato marbles are present as well, but the most important varieties are linked to frequent modifications of the white layers;

– the latter may become very pure and free from grey spots or tiny veins, thus forming an homogeneous pearl-white type, the so-called Absolute White Porracci, mainly cropping out in the NE slopes of Mt. Altissimo (Porracci Quarry, in the Cave dei Pennacci area). Some levels of this valuable variety are likely present in the bA now exploited at the Buca Quarry, in the high Canale del Fondone, but other layers crop out in the Giacceto area;

– where the pure, homogeneous white marble contains accessory amounts of microcrystalline muscovite, regularly spread within the dominant (98,5-99%) calcite, the statuary variety is present forming 1,5-2 m-thick, fairly persistent layers both in the SW and NE Mt. Altissimo slopes. This marble was named the Statuary Tacca Bianca, from the main locality of its past exploitation, but it is reported also from other sites more or less in association with the White Porracci beds.

Other appreciated varieties come from the Arabesque-like Marbles intercalated within the oA to the West (Mossa Quarry) and the South (Cervaiole Quarry) of Monte delle Tavole. These marbles are whitish, clast-supported metabreccias with marble clasts ranging in size from centimetric-sized pebbles to boulders several metres across, in a minor grey to greenish grey calcitic matrix with variable amounts of phyllosilicates (muscovite and chlorite), dolomite, quartz and pyrite ± Fe-oxides (fig. 1g). Very often the quarry faces intersect the contacts between the oA and the Arabesque-like Marbles (fig. 1h), showing that the latter mainly derived from the original brecciation of the oA along syn-depositional sets of fractures and/or faults that dissected the Early Liassic carbonate sediments.

Another kind of metabreccia is the so-called Rio Serra Breccia, a clast-supported metarudite with dominant marble and rare dolomite clasts in a light grey carbonate matrix, once exploited from a restricted lens at the base of the Marbles *s.s.* formation in the Mossa Quarry (West of Monte delle Tavole).

In the geological map, the Veined, Nuvolati, Arabesque-like and Rio Serra marbles are represented as more or less long and thick lenses, generally parallel to the main foliation S_1 in the field. Only the White Porracci and the Statuary Tacca Bianca are marked with unbounded very narrow strips, as their beds very rarely exceed two metres of real thickness.

As a whole, the Mt. Altissimo Marbles *s.s.* are characterized by a distinct banded character, represented by the persistent alternation of major white and minor grey layers described above. There is no evidence that such a structure can be associated with either repeated isoclinal folding during the D_1 deformation, or a metamorphic differentiation (inconceivable under the greenschist facies conditions of the Apuane Alps metamorphism). More realistically, the banded framework can be confidently attributed to the primary bedding of the Early Liassic calcareous protoliths.

It is to be noted that (1) with few exceptions, this is the most common aspect in all the discontinuous Marbles *s.s.* along the limbs of the Orto di Donna-Mt. Altissimo Syncline, for a total length of about 30 km; and (2) this aspect is quite different with respect to the massive bulk structure of the marble districts in the westerly and easterly Apuane Alps (Carrara, Massa and Seravezza; Gorfigliano-Vagli, Arni-Mt. Sumbra and Panie group, respectively), where volumes with clearly banded structure are almost totally absent.

In the Tuscan Nappe (the unmetamorphosed counterpart of the Apuane Unit) cropping out northwest (Carrara area), north (southern Lunigiana) and northeast-east (upper Garfagnana) of the AMC, the Early-Middle Liassic carbonate sediments comprise a thin and irregular level of whitish to light grey massive limestones, passing upward, and in part laterally into the well bedded Angulata-bearing marly limestones. We consider that the two formations might have been the protoliths of the Carrara-type massive marbles and the Altissimo-type banded marbles, respectively, but such a correlation, never suggested before, deserves further studies to be confirmed.

TECTONIC FEATURES OF THE MT. ALTISSIMO REGION

The D1 structural setting

As already said, the Mt. Altissimo marbles were deeply involved in the polyphase deformation structures of the Tertiary orogenesis.

The contractional tectonics (D_1 phase) generated kilometre-scale to microscopic, isoclinal-subisoclinal synmetamorphic folds associated with a penetrative axial planar S_1 foliation and an evident L_1 stretching lineation, both widely present in all the lithotypes (except the Grezzoni Fm.). In more detail, the D_1 structural setting reveals a composite origin, resulting from the local superposition of (at least) two generations of structures related to successive deformation stages. The best exposures along the quarry faces show that:

– the primary lithologic layering S_0 is overprinted by a greenschist facies metamorphic foliation;
– the latter is older than the regional S_1 because it is deformed, together with the S_0, by the D_1 folds having the same S_1 as the axial planar foliation.

Thus, the whole D_1 phase is shown to be a polystage tectonic event, and this leads to its structural elements being renamed as follows: the originally defined regional S_1 and L_1, and the A_1 axes as well, become S_{1b}, L_{1b}, and A_{1b}, while S_{1a} is the older foliation, D_{1a} and D_{1b} being the related Tertiary deformation episodes.

It is worth noting that the two sets of structures refer to the same D_1 compression regime, having common top-to-ENE kinematics and being overprinted by the same younger structures pertaining to the D_2 tectonics.

We must recall that the polygenetic nature of the AMC compression tectonics was already known through the studies chiefly performed by the Firenze researchers.

Boccaletti & Gosso (1980) were the first to highlight that the tectonic setting of the Tertiary compression (the D_1 phase *sensu* Carmignani *et alii*, 1978, and references therein) resulted from at least two deformation episodes.

During the eighties and the early nineties, several publications were devoted to the Carrara-Vagli transect in the northern Apuane Alps, by which the Firenze geological school arrived at the above statement through analysis of particular regions (Capitani & Sani, 1983; Coli *et alii*, 1987, 1988, 1992; Moratti *et alii*, 1989; Coli, 1989a) and through synthesis papers (Boccaletti *et alii*, 1982, 1983; Boccaletti & Coli, 1983; Coli, 1989b; Coli & Pandeli, 1992). The main points of this work are briefly reported:

– the AMC tectonic setting resulted from three, synmetamorphic, successive fold generations, the B_1 and B_2 with a clear compression character, and the B_3 associated to the later tectonics of uplift and extension (corresponding to the D_2 phase by Carmignani and coworkers);
– the B_1 folds are isoclinal with thinned or sheared limbs and thickened hinges, usually they have cm to dm size and asymmetric profile, but their field distribution appears to be random due to severe transposition along the coeval S_1 foliation;
– the B_2 folds are close to very close in shape, they have «S» and «Z» asymmetry congruent to their location along the flanks of the largest regional folds (Carrara Syncline, Vinca-Forno Anticline and Orto di Donna-Mt. Altissimo Syncline);
– in contrast to what is widely accepted by many authors, these megafolds are B_2 antiforms and synforms affecting the B_1 setting, whose geometric features suffered further dispersion and complication;
– the B_2 structures face northeast, with mean axial trend NW-SE, plunging gently NW, whilst the B_1 fold axes are dispersed with SW-ward plunges and moderate to high inclination;
– many cases of interference patterns between the B_1 and B_2 structures are reported from the Carrara-Gorfigliano region from the micro- to mesoscopic scale (especially in the phyllitic lithotypes) up to hectometre to kilometre-sized structures affecting the basement-Grezzoni contact (Canale Fondone, Pizzo d'Uccello-Foce Giovo, Mt. Focoletta) or the Jurassic-Cretaceous formations (northern and eastern slopes of Mt. Cavallo);
– the third deformation episode B_3 is responsible for the development of open to very open folds with curved regular hinges, but often with a chevron style as well, characterized by axes plunging gently northwards and axial planes about vertical or with high dips.

The indications on the vergence of the B_1 structures are unclear and partly contradictory:

– in some papers the authors affirm that the B_1 vergence cannot be defined due to scarcity of data, or the high dispersion of the B1 hinges, or even the severe transposition along the subsequent B_2 foliation;
– from the cross-sections by Capitani & Sani (1983) and Moratti *et alii* (1989), however, it seems that NE-verging B_2 folds caused some B_1 structures to be overturned, hence an original westerly to southwesterly vergence might be deduced for the B_1 folds;
– on the contrary, Coli & Pandeli (1992) write that «…..the enveloping surfaces of the D_1 folds point to a NNE-ward vergence …..».

As to the pre-B_1 setting Boccaletti *et alii* (1983) reported that the lithons between the S_1 planes frequently contain relics of a pristine foliation of unknown attribution, underlined by quartz, white mica and chlorite (metamorphic?) overprinted by the S_1 foliation. In the same year Capitani & Sani as well affirmed that the S_1 crenulates a pre-existing anisotropy, whose nature (sedimentary or tectonic) is not definable. A clear pronouncement on the existence of a pre-S_1 foliation is in Moratti *et alii* (1989), who write that «….. in some lithotypes (Scisti sericitici varicolori and Cipollini) a well marked foliation (S_x) is highlighted by alternating mm-thick laminae that, being rotated or crenulated, predate the S_1 and are different from the lithologic layering …., no evidence allows it to be established whether the S_x is sedimentary or tectonic …..».

Though more accuracy is needed to discuss properly the relationships between the deformation phases (and related structures) recognized by the Firenze researchers and those proposed here for the M. Altissimo region, we want to affirm the following:

– we consider our S_{1a} foliation coincident to the S_x as defined by Moratti *et alii* (1989) and the other few reports quoted above;
– hence, all our D_{1b} structures correspond to the whole B_1 setting (maybe plus part of the B_2 setting).

Where recognized, the S_{1a} is bedding-parallel and only in very few cases we were able to detect very low angular relationships between the two surfaces, whose intersections provide the few axial attitudes of the D_{1a} structures, otherwise unrecognizable due to the severe

transposition on the S_{1b} planes. On the contrary, clear hinge zones of D_{1b} folds were observed in some quarries, offering the best evidence of the S_{1a}-S_{1b} intersection: most of these structures are metre (fig. 2) to decimetre (fig. 3a,b) in size, but a D_{1b} fold, several hundred metres across, cored with oA Marbles**,** is exposed in the southern slopes of Mt. Pelato (see the geological-structural map and the B-B' cross-section).

The mesoscopic evidence of the D_{1b} folds is confirmed by the thin section observations on selected oriented samples: the S_1 is the axial planar foliation of frequent, more or less open microfolds that deform single crystals and/or aggregates of blastic muscovite ± chlorite (fig. 4a,b), or alternating, millimetre-thick calcitic layers with coarser and finer crystalline structure of metamorphic nature (fig. 4c).

The measured A_{1b}, and in general all the A_1, are almost parallel to the coeval stretching lineations (see the statistical stereograms in the map table), and this reveals that all the D_1 folds have a sheath-like style diffuse at every scale. Such a geometry bears strongly on the geometry of the AS southern termination, whose essential features will be described below.

The scarcity and small extent of significant outcrops prevent the recognition of the D_{1a} and D_{1b} structures all over the region: in most cases only one composite foliation with a clear stretching lineation is systematically present, thus in the geological map we reported only the S_0, S_1, L_1 and A_1 structural elements. For the same reason, in the statistical stereograms the few measures of S_{1a}, S_{1b}, A_{1b} and L_{1b} were processed together with the S_0, S_1, A_1 and L_1 data, respectively.

At the cartographic scale, the most important, kilometre to decametre-scale D_1 folds not visible in the landscape were mapped through detailed surveys north and south of the Mt. Altissimo, and fig. 5 illustrates the axial plane traces of these structures and their probable mutual connections:

– in the Valsora area the road to the Galleria del Vestito crosses some anticlines and synclines several tens

Fig. 2 - D_{1b} metre-scale fold deforming a minor lens of metasiltitic-phyllitic matrix in the Arabesque-like Marbles of the Cervaiole Quarry. Note that the axial plane foliation S_{1b} of the fold is the surface along which the metabreccia clasts are flattened and stretched.
– Una piega metrica D_{1b} deforma una piccola lente di metasiltiti e filladi appartenente alla matrice dei Marmi Arabescati di Cava Cervaiole. Si noti che la foliazione di piano assiale S_{1b} della piega è parallela alle superfici di appiattimento e allungamento dei clasti della metabreccia.

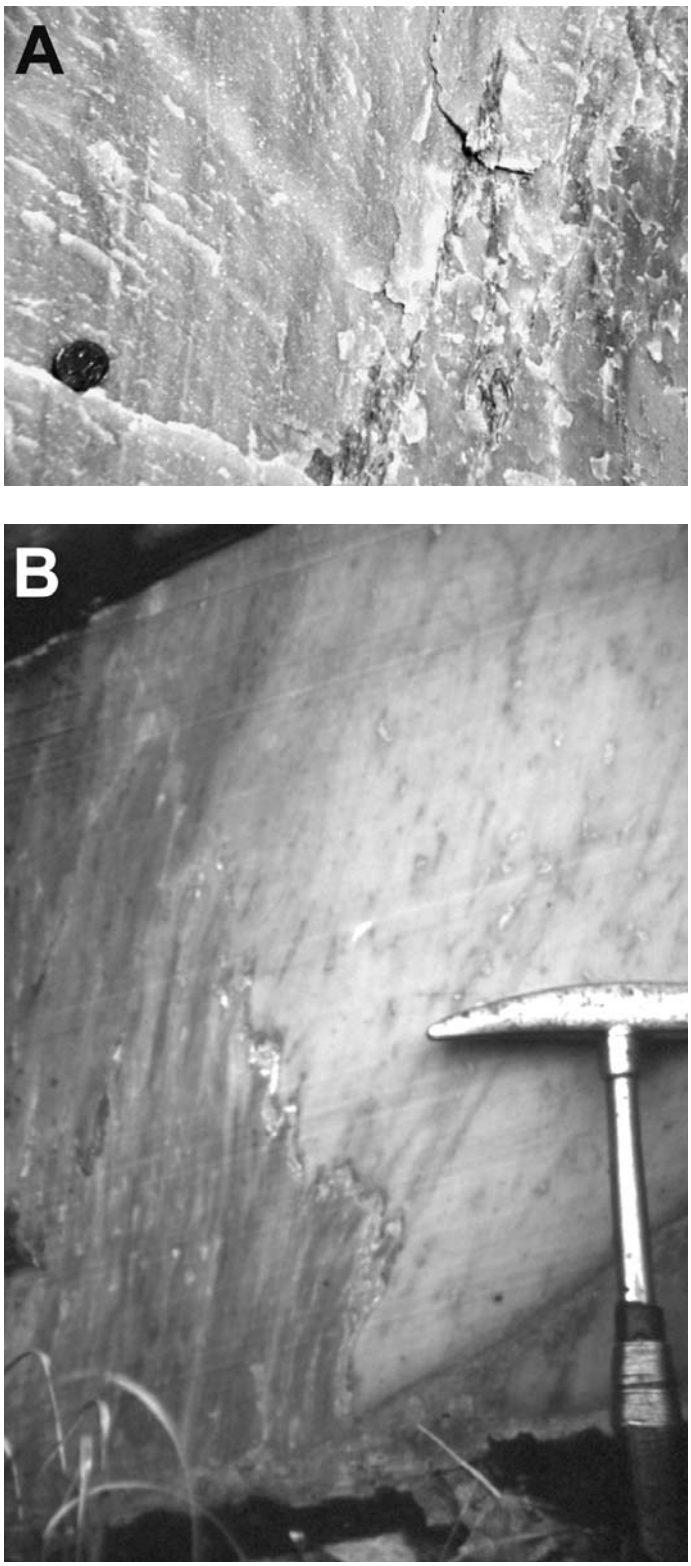

Fig. 3 - D_{1b} decimetre-scale isoclinal-subisoclinal folds deform: (A) a thin vein with abundant metamorphic phyllosilicates marking the local S_{1a} foliation in the bA Marbles close to the abandoned Porracci quarries, Mt. Altissimo eastern ridge; (B) the contact between the Nuvolato and Veined Marbles at an abandoned quarry in the Valsora area.
– Pieghe decimetriche D_{1b}, a geometria isoclinale-subisoclinale, deformano: (A) una sottile vena ad abbondanti fillosilicati che rappresenta la foliazione S_{1a} nei Marmi bA in prossimità delle cave abbandonate Porracci, dorsale orientale di M. Altissimo; (B) il contatto tra Marmi Nuvolati e Venati esposto in una cava abbandonata nella zona di Valsora.

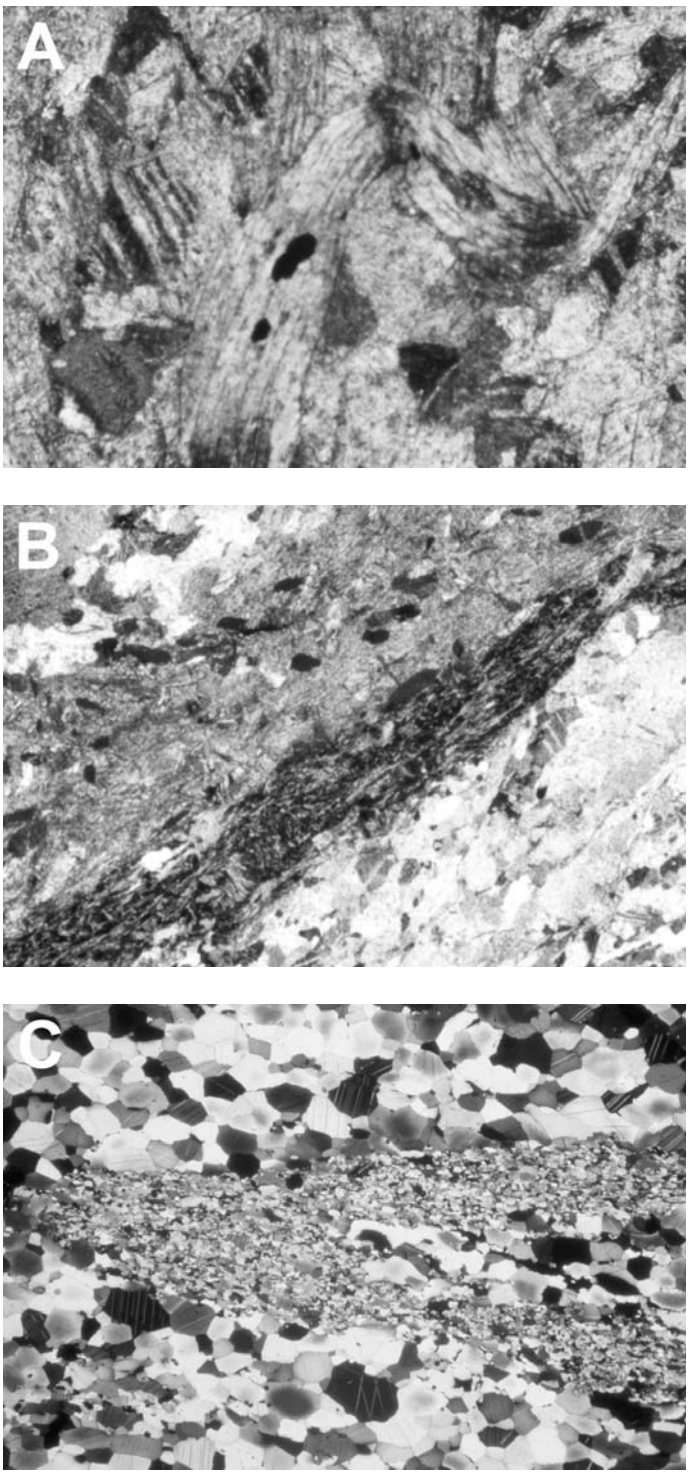

Fig. 4 - D_{1B} microfolds deforming: (A) a very thin continuous film of few phyllosilicate crystals, bA Marbles from the Buca Quarry; (B) polycrystalline aggregation of subparallel phyllosilicate lamellae, bent within an S_1-parallel vein, Seravezza Breccias from Valsora abandoned quarry; (C) fine-grained calcite-dolomite-muscovite layer in the oA Marbles from Fosso delle Gobbie. Horizontal sides of the micrographs (crossed nicols) are 2,1 mm (A) and 4,2 mm (B and C) long.
– Micropieghe di generazione D_{1b} deformano: (A) una sottile ma continua pellicola costituita da alcuni cristalli di fillosilicati nei Marmi bA di Cava Buca; (B) un aggregato policristallino di fillosilicati in lamelle subparallele, piegate all'interno di una vena parallela alla locale S_1, cava abbandonata di Brecce di Seravezza in zona Valsora; (C) livelletto a grana fine di calcite, dolomite e muscovite nei Marmi oA di Fosso delle Gobbie. Le microfoto sono a nicols incrociati ed hanno i lati orizzontali lunghi 2,1 mm (A) e 4,2 mm (B e C).

of metres in size that appear partly laminated a few hundred metres to the southeast;

– along the Canale delle Gobbie an anticline in the Grezzoni formation crops out, having a large hinge zone with a mullion-like closure, and its right limb appears to be laminated along two syn-D_1 shear zones that cut and truncate two minor Marble *s.s.* synclines;

– to the south of Mt. Altissimo, the marble-cored Mossa Syncline seems to be the southward extension of the above marble synclines;

– about 1 km to the east of the Mossa Quarry, another Marble *s.s.* cored structure is present, the Betigna Syncline, whose overturned (western) flank is laminated along the contact with some slices of pre-Alpine rocks belonging to a severely sheared anticline. A length of the hinge zone of the last anticline might be represented by the adjacent mullion structures along the contact Grezzoni-Marbles *s.s.* south of Monte delle Tavole;

– in the northeastern slopes of Monte delle Tavole, decametre-scale parasitic folds were mapped along the normal flank of the Betigna Syncline, and more northwards, a few hundred metres south of Campo delle Gobbie, the Grezzoni to Marbles *s.s.* sequence is involved in partially sheared hectometre-scale anticlines and synclines;

– finally, the Cervaiole, Giardino and Freddane structures of the southern sector are three large-scale D_1 synclines with complicated 3-D geometries due to the overprint of interfering post-D_1 folds (see below).

D_1 shear structures are very common as well, forming the already mentioned laminations of D_1 fold flanks and several, unmappable S_1-parallel shear zones in the marbles and phyllites with mylonitic fabric. It is very likely that at least part of these structures were reactivated during the post-D_1 tectonics: this seems to be the case for the tectonic contacts along which the Mossa and Betigna synclines are partially sheared.

The D2-related structures

In the northern and central parts of the AS all these structures trend about NNW-SSE, but they turn anticlockwise to a mean WSW-ENE direction in the southern closure of the megastructure. The two structural domains, Mt. Altissimo North and Mt. Altissimo South, are reported on the table of the quarry locations and names (see the enclosed geological map) and the related stereograms underline the diverse 3-D settings in charge of the D_1 features:

– in the southern domain the S_0 and S_1-A_1-L_1 data show scattered distributions in high contrast with respect to the same diagrams of the northern domain;

– among the latter the A_1 data dispersion is due to the sheath geometry of the folds, which conversely are characterized by tight clusters of the S_1 and L_1 elements.

This deviation results in the eastward bending of the minor folds that form the bulk «M»-like closure of the major syncline (fig. 5). The clearest example of such a setting is the laminated termination of the Betigna Syncline, crossed by the road from the Cipollaio tunnel to the Cervaiole Quarry, but similar features have been mapped also ENE of Monte delle Tavole (basement-Grezzoni contact) and ESE of Cervaiole Quarry (basement-Grezzoni-

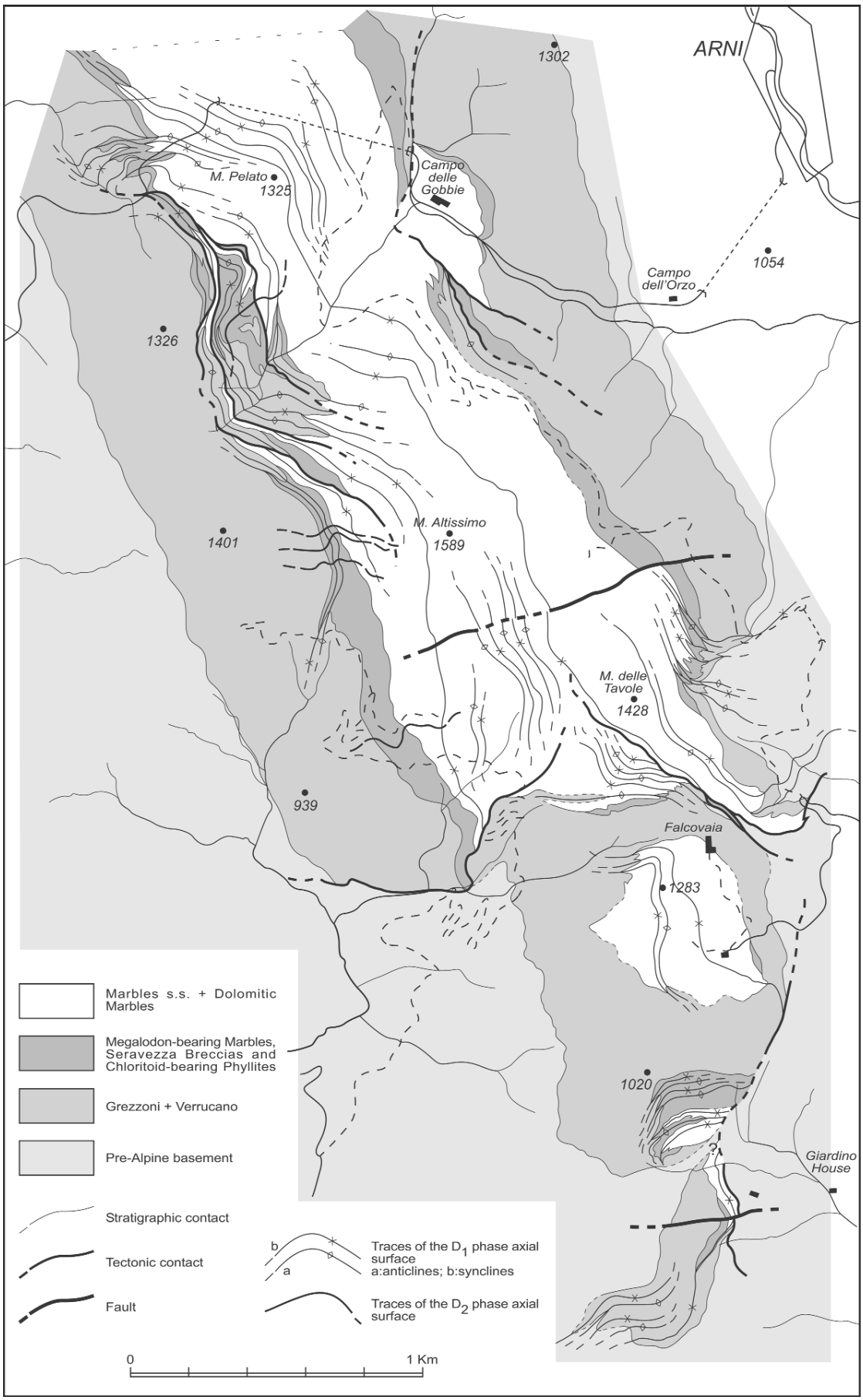

Fig. 5 - Simplified structural map showing the traces of the axial surfaces of the D_1 and D_2 fold settings.
– Carta strutturale semplificata per illustrare le tracce dei piani assiali delle pieghe di fase D_1 e D_2.

Marble contacts). Peculiar aspects of these bent geometries are as follows:

– everywhere they affect the S_1 and, of course, all the earlier compression structures, thus revealing their pertinence to the D_2 deformation phase;

– they range from ten metres to several hundred metres in size and have average 60-110° open, curviplanar profiles;

– in general, in their westerly and southerly parts the S_1 dips toward the W-SW and S-SE (respectively) with high-medium inclinations to upright attitudes (less frequent);

– as a consequence, their «possible» axes have steep to moderate plunges SW-wards, or are vertical (sometimes).

No axial planar cleavage and no true hinge zones of mesofolds were surveyed in association to these cartographic bends. In spite of this, let us label them as D_{2a} open «folds».

In all the parts of D_{2a} structures the S_1 is affected by a further generation of late crenulations and less frequent folds, the latter being distinguishable from D_{2a} «folds» due to diverse 3-D features and average attitudes of axes and axial planes:

– the crenulation is intense in every lithotype with a component of, or dominated by phyllosilicates, and affects the S_{1a} and S_{1b} foliations or the regional S_1;

– crenulations and fold hinges strike NNW-SSE and WSW-ENE (respectively along the westerly and southerly D_{2a} flanks) with mean gentle plunges (0-20°);

– the axial planes of these folds are almost always represented by a crenulation to spaced cleavage with gen-

Fig. 6 - D_2 metre-scale fold from the Megalodon-bearing Marbles cropping out east of the Mossa Quarry.
– Piega metrica D_2 nei Marmi a Megalodonti affioranti a oriente di Cava Mossa.

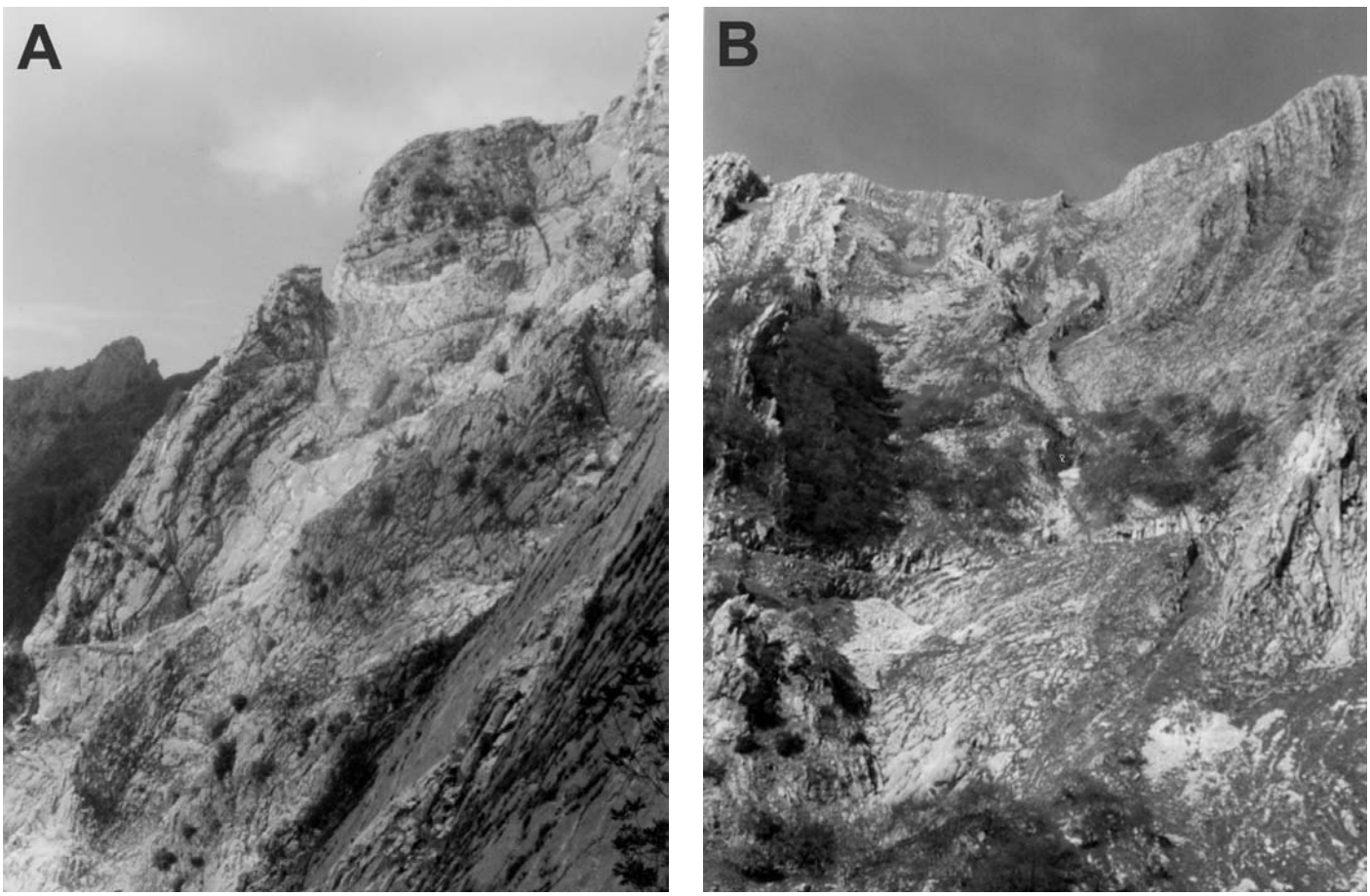

Fig. 7 - D_2 very open undulations in the Megalodon-bearing Marbles southwest of Tacca Bianca locality (A, the wall height is about 150 m), and in the southern slope of the Mt. Altissimo west ridge (B, total height of about 350 m).
– Ondulazioni molto aperte di fase D_2 nei Marmi a Megalodonti a sudovest di Tacca Bianca (A, l'altezza della parete fotografata è di circa 150 m), e nel versante meridionale della cresta ovest di M. Altissimo (B, l'altezza totale è intorno a 350 m).

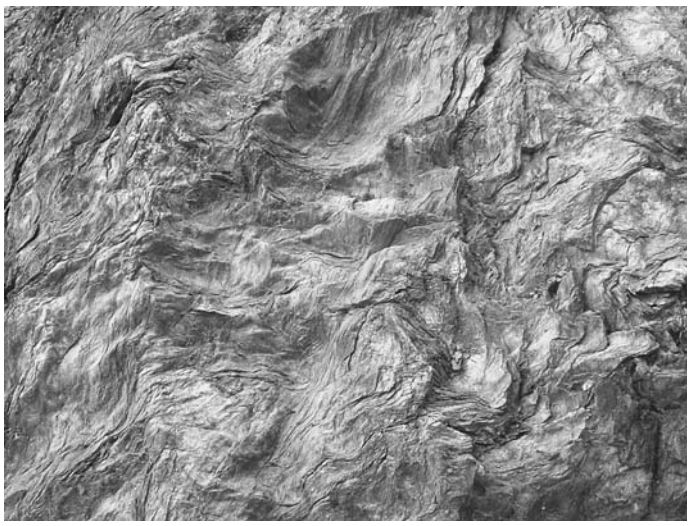

Fig. 8 - Dome-basin D_2 interference structure in the pre-Alpine Lower Phyllites to the east of Monte delle Tavole. Central width is about 2 metres.
– Struttura d'interferenza a duomi e bacini di fase D_2 nelle Filladi Inferiori pre-alpine a est di Monte delle Tavole. Al centro l'immagine è larga circa 2 metri.

tle dips toward different orientations (depending on the local axis attitude);

– the folds range from metre-scale (fig. 6) to tens of metres or more in size, open to very open, seldom asymmetric structures or simple undulations (fig. 7a,b);

– at a wider scale, they extend (with the same orientation, style and vergence) from the Mt. Altissimo South domain to the D_2 fold systems outcropping northward in the Mt. Altissimo North domain up to the Frigido valley (inland of Massa), and eastward in the Cipollaio gallery-Mt. Freddone region.

On the basis of such features, these structures are referable to the extensional D_2 tectonics *sensu* CARMIGNANI & KLIGFIELD (1990, and references therein), that is, to the «….. large-scale reverse drag folds having S and Z sense of asymmetry on the southwestern and northeastern flanks, respectively, …..» of the entire AMC (CARMIGNANI & GIGLIA, 1979); this setting is labelled as D_{2b}.

It must be noted that interference patterns between the two D_2 deformation settings may result in local dome-basin structures within suitable lithotypes (fig. 8).

DISCUSSION AND CONCLUSIONS

As recently underlined by MECCHERI *et alii* (2005a), the problem is to establish whether the D_{2a} and D_{2b} structures are genetically or kinematically linked to each other (that is, they form parts of a single, progressive deformation), or whether they resulted from different, superimposed deformation episodes.

A first interpretation envisages that, during the early stages of the post-compression uplift that triggered the D_2 deformations, the doming of the Vagli-Mt. Sumbra area (about 5-6 km NNE of the region here considered) caused differential motions toward W, SW and SSW in the large southwestern slope of the exhuming structure. These kinematics resulted in a syn-metamorphic sinistral extrusion of the huge Mt. Altissimo carbonate structure. Taking into account that at the southern edge of the AS the local sheath-shaped synclines are separated by anticlines cored with the pre-Alpine phyllosilicate-rich rocks, these cores might have worked as the weak lineaments along which left-hand strike-slip shears developed to accommodate the required extrusion.

As an example, the tectonic contacts of T. Serra-Mossa Quarry and of Monte delle Tavole-Betigna areas cut D_1 folds and are clearly affected by D_{2b} crenulations, a fact that indicates that al least part of the D_{2b} folding postdates the D_{2a} anticlockwise deviations.

Problems arise in relating the proposed D_2 progressive deformation also to the areas between the Cervaiole Quarry and the Giardino Quarries and between the latter and the Freddane Syncline, the only D_{2a} shear being at the base of the last structure. However, a fact is that all of these D_1 carbonate synclines are torqued to the E-ENE and more or less tilted.

The second scenario, firstly underlined by MOLLI (2004) and MOLLI & VASELLI (2006), starts from former suggestions of CARMIGNANI & GIGLIA (1983) and emphasizes the role of large-scale sheath fold geometry of the D_1 structural setting. In this frame, the Turrite Secca valley (east of Mt. Altissimo) would correspond to a prominent, kilometre-scale ENE-ward undulation of the AS hinge zone, so that a thick sheath-like body, cored by pre-Alpine schists and now almost totally eroded, would lie above the D_1 Mt. Tambura Anticline and the Mt. Freddone structures (see the tectonic sketch in the geological map). This sharp, sheath-like D_1 bulge represents the large-scale apex linking the AS (that «opens» N-wards) to its eastern continuation, the Mt. Corchia Syncline (that «opens» SE-wards). The same structure would have caused the mechanical discontinuity between Mesozoic metacarbonates and pre-Alpine schists to extend from the Valle del Giardino ENE-wards for about 3.5 km, and this could have passively controlled both the general anti-Apennine trend of D_2 deformations, and the resulting D_1/D_2 interference patterns. The diverse attitudes and geometries of D_2 structures may be local, or even wide complications imposed by competence contrasts and strain partitioning during the D_2 progressive deformation.

Although we are still working in detail to the two alternative solutions, very recent field revisions of some crucial outcrops seem to support (1) the model of a large, mainly phyllitic anticlinal body separating the lateral closures of two, inversely open, carbonate sheath megasynclines, as the heritage of the D_1 compression tectonics; and (2) that such a setting played an important role in controlling the D_2 structures and interference patterns developed in a frame of progressive deformation history.

ACKNOWLEDGEMENTS

Publication supported by MIUR (ex-COFIN 2002047219). Prof. M. Coli and an anonymous referee are thanked for stimulating revision and suggestions.

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Received 8 March 2006; revised version accepted 27 November 2006.