Ilaria Isola Istituto Nazionale di Geofisica e Vulcanologia
Giancarlo Molli Università di Pisa
Patrizia Landi Istituto Nazionale di Geofisica e Vulcanologia
Francesco Mazzarini Istituto Nazionale di Geofisica e Vulcanologia

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1. Geographical and geomorphological setting

I. Isola

Landscape and environment variety characterises the mountain areas of the Alpi Apuane. The name derives from their harsh morphology, very similar to an “alpine” landscape with deep valleys and very steep slopes, and from the name of an ancient semi-nomad population, the *Liguri Apuani*, who lived in this area few hundreds years B.C.

Alpi Apuane are a mainly calcareous rocky-massif about 50 km long, 20 km wide and up to 1947 m high (the highest peak is Mt. Pisanino) located in the northwest of Tuscany. They extend in NW-SE direction between the coastline of north Tyrrhenian See to the west and the inner basin of the Serchio River to the east (Fig. 1).

The alpine-like landscape of this peculiar region is due to several factors. Particularly, differential erosion processes are highly enhanced by the Alpi Apuane complex structural setting with very steep foliations and tectonic repetition of rocks with different mechanical properties (mainly limestone and shale).

The present topography is presumed to be the result of a rapid tectonic uplift, accompanied by heavy fluvial erosion working up till now, while glacial and periglacial processes reshaped the landscape mainly during the last glacial stage, emphasising the “alpine-like” features of this mountain range (Braschi et al., 1987).

The peculiar climate in this area is influenced by elements like elevation, high relief energy, aspect, closeness to the coastal plain (only few kilometres from Versilia) and the lengthened direction of the main watershed.

The chain actually represents, an orographic barrier which traps eastward-moving moist air masses from the Atlantic Ocean thus being one of the rainiest area in Europe. Mean annual rainfall exceeds 2500 mm over a large part of the chain and on the central ridges it is more than 3000 mm/yr (Rapetti and Vittorini, 1994).

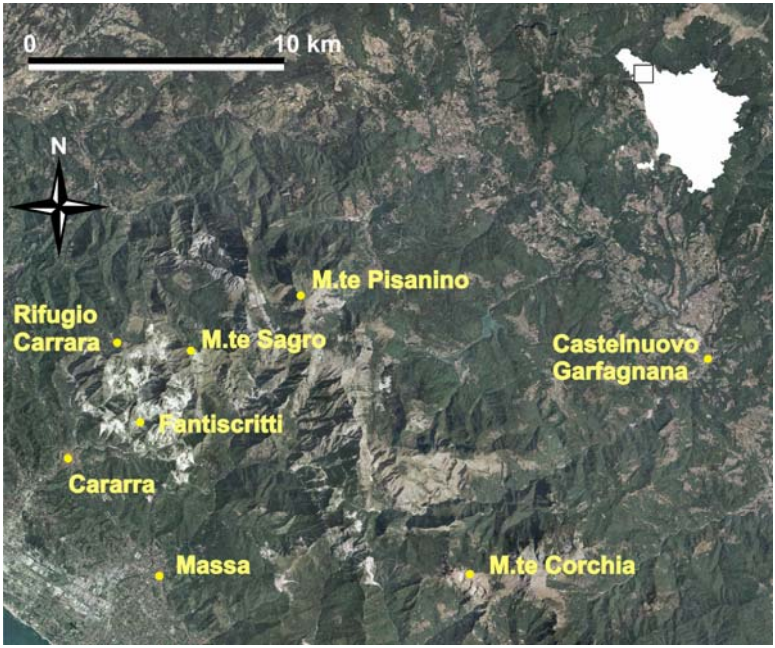

Figure 1 – Map location

1.1 Geomorphological features

From a geomorphological point of view the most interesting features are glacial and karst landforms.

Glacial activity takes place in Alpi Apuane during the final part of Pleistocene. There has been large debate on the magnitude and the age of the *Apuan glaciation*. The first description of traces of glaciation is by Stoppani, (1872), De Stefani (1874) and others at the end of nineteen century. According to these authors the Alpi Apuane were covered by a huge ice cap, while recent works sketch a rather modest phenomenon (if compared with Alpine glaciers).

It is undoubted that several glaciers formed on the eastern side of Alpi Apuane and slid down into the tributary valleys of the Serchio River. Their estimated fronts located in an extraordinarily low position (down to 600 m a.s.l.), the lowest deposits in the whole Apennines. Minor glaciers formed on the seeward side, mostly circle glaciers or little tongues (Federici, 1981)

The equilibrium line altitude (ELA), that is the location where winter accumulation of snow is equal to the summer loss, in Alpi Apuane is calculated between 1250 m in the south and 1100 m in the north sides, respectively (Braschi et al 1987). In the north side of Alpi Apuane traces of glaciers are better preserved, being the lowest ELA recorded in the Apennines chain. Because of the exposition and the high slopes gradient the seaward side is mainly characterised by erosional forms rather than depositional ones. In this area the little circle glaciers of Mt Spallone is evident, while little tongues slid down from Mt. Sagro through Campocecina ondulation to the head of Carrione and Lucido valleys (Federici, 1981).

Large part of the chain consisting of carbonatic rocks (marble and dolomite) has been widely reshaped by karst process forming essentially medium and small-scale landforms (Fig. 2).
In fact, the actual high relief along the higher ridges favours physical degradation by running waters and cryogenic processes thus limiting the effects of karst processes on the landscape.

Photo by I. Isola

Figure 2 – Karst landscape in Carcaraia (Mt . Tambura)

On the contrary, in the past a subdued relief has permitted the development of a very advanced exokarst and of large cave systems. Therefore, most of the major karst landforms and caves in Alpi Apuane are relict forms (Piccini, 1998).
More than 1300 caves comprising four of the five deepest caves in Italy are in this area. For example, the famous *Complesso Carsico del Monte Corchia* that is 1.190 m deep and more than 60 km long is the longest cave in Italy (Fig. 3).

Photo by I. Isola

Figure 3 – The "Galleria delle Stalattiti" is the sector of Corchia Cave where paleoclimatic speleothem-based studies have been presently focused.

The *Antro del Corchia* Cave, a portion of the *Complesso Carsico del Monte Corchia*, has in recent times been the subject of investigation on its speleothems as paleoclimate archives. Speleothems provide in fact, precise and independent radiometric ages estimates of paleoclimatic events (Drysdale et al. 2004, 2009, Zanchetta et al., 2007)
This cave is an exceptional archive of past climate, it can provide a record of North Atlantic climatic evolution long 1Ma at least.

A third and shocking character of Alpi Apuane is the quarry activity that represents not only an economic resource but also cultural and historical goods. Oldest remains of quarries are ascribed to Etruscan and Roman populations.
Combining safeguard of this area and development of very profitable but destroying activity is very difficult or even impossible. In 1985 a regional act founded the "Parco Regionale delle Alpi Apuane" (http://www.parcapuane.toscana.it/) to get around this difficulty, but until now economic business prevail over the preservation.
Almost 300 quarries are situated on Alpi Apuane, more than 1.5 million of tons of stone and 2 millions of tons of crushed stone are extracted every year, seriously compromising the integrity of natural landscape.

2. The history of Carrara marble quarries

P. Landi

The first records of quarrying activity in the Carrara area date back to the 1st century B.C.

Apuan marble was certainly widely used during the Roman Imperial period, up until the 4th century AD (Fig. 4). Thereafter there are no more records of its extraction until the end of the 13th century, when Apuan marble began to be used for ecclesiastical buildings, from cathedrals to small churches, and for the most prestigious palaces. From the 13th century to this day, quarrying activity has continued without interruption. The marble was more intensely quarried in certain periods, for example in the first half of the 20th century, when it was widely used in public works and monuments (e.g. the EUR buildings in Roma).

When discussing the history of Carrara marble we cannot but mention Michelangelo Buonarroti (1475-1564), a great painter and sculptor who used to personally select blocks of *statuario* marble from the Carrara quarries to create his famous works (e.g. the "David" housed at the Galleria dell'Accademia in Firenze and the "Pietà" in Basilica di S. Pietro in Roma).

Photo by R. Vecci

Figure 4 – Traces of Roman "cuttings"

2.1 *Extracting blocks from the mountain*

Extraction techniques did not change significantly in two millennia of Apuan marble quarrying history until the introduction, in the 1700s, of explosive powders and subsequently, in the early 1900s, of helical wire.

Prior to the 18th century extraction was essentially a manual, labour-intensive procedure involving the use of tools such as chisels and wooden and iron wedges. To detach a block from the rock face the most was made of natural fissures through the use of wooden wedges and iron levers. In particular, the wooden wedges were inserted into the fractures, which were then filled with water: as the wood expanded, it broke the rock loose. To obtain blocks of specific dimensions, the Romans used the "*formella*" technique. A small groove or *formella*, 15-20 cm deep, was cut into the selected portion of stone. Iron wedges inserted along the cut were hammered repeatedly to break away blocks 2 m in thickness. The pickaxe was apparently little used in the Roman period, whereas it was used systematically, along with the chisel, in the medieval and pre-industrial periods.

In the 18th century, with the advent of explosives, the *varata* technique was adopted. It continued to be used until the early decades of the 20th century. Deep holes were sunk by hand and subsequently deepened and widened through the use of hydrochloric acid to create a space large enough to contain the required amount of explosive.

The greatest innovation in extraction techniques was the introduction of helical wire in the late 1800s. This could be used to cut blocks of marble directly from the mountain. Just six years after its presentation at the 1889 Paris World Fair, this new extraction technique was adopted in the Carrara quarries. The "helical wire" method was based on the slow erosive action of a metal rope which carried an abrasive mixture of water and silica sand. The system consisted of a steel wire 4-6 mm in diameter (obtained by twisting together three threads) laid out over the entire area of the quarry area through a series of return pulleys mounted on iron tubes. Through a clutch connected to a series of pulleys, an electric motor set the wire in motion.

Helical wire was subsequently replaced by diamond wire, a steel rope covered with segments containing industrial diamonds of appropriate grain size. In order to limit economic loss and the production of debris, charge blasting is now rarely used, and only during the preparatory phases. In the present days quarries the most popular type of sawing machine is the diamond wire cutting machines, consisting of an automatic trolley upon which an electric engine is installed and

connected with a large pulley. The wire is set in motion by this machine. Very often, the wire cutting machines are combined with chain saws which are more suitable for the horizontal cut at the base of the bench.
Since antiquity, the essential aspects of excavation have remained linked to the understanding of the geological properties of the marble basin and to the metamorphic characteristics of the stone and its fissures. Based on empirical knowledge, increased and reinforced through millennia of quarrying activity, a terminology developed that is used by quarrymen to describe the properties of a marble mass so as to obtain commercially viable blocks in the least possible time and with the least possible effort. For example, «*pelo del verso*» indicates the direction of marks and veining in marble: along this plane the marble is detached with relative ease. «*Pelo del contro*», the plane perpendicular to the «pelo del verso», lies in the direction of the bench; «*pelo del secondo*» is a fracture plane intersecting the other two planes and along which the block is detached.

2.2 Changes in transporting marble over the years

Once a bench is separated from the rock mass, quarrymen overturn it onto the quarry floor. To break the fall and limit damage to the bench, it is generally made to fall on a "bed" of fine marble detritus mixed with the sludge produced through previous working.
Once transported to the quarry floor, the masses are shaped into blocks of suitable size to be easily transported to the sawmills after being squared by specific machinery such as wire cutting machines. Lastly, trucks are used to transport the marble blocks to the port of Marina di Carrara or other destinations.
The marble blocks are nowadays transported on trucks which can complete very dangerous manoeuvres in the quarry and climb narrow zigzag roads. Before trucks came into use, the transport of blocks from the quarry to the valley floor was perhaps the most difficult phase of the extraction process.
Of the various methods of transport, the "*lizzatura*", in use up to the early 20th century, has a dominant role throughout the history of marble quarrying in the Alpi Apuane. Certain archaeological findings suggest that the "*lizzatura*" method was already employed at the Carrara quarries in Roman times. The first written records date back to the 1500s. The most famous are the notes by Michelangelo Buonarroti regarding activity in the Altissimo quarries.
During the "*lizzatura*" operation, the block was placed on two thick, sturdy wooden beams (i.e. the "*lizza*" Fig.5) to which it was strapped

with thick hemp ropes whose ends were wound around large wooden stocks (Fig. 5a) planted in the ground or in blocks of marble (Fig. 5b) "*piri*". The sled was gradually guided down the slope by a team of twelve men who paid out the ropes. The "*lizza*" came down the mountain by the force of gravity. For this purpose very steep paths, the so-called "*vie di lizza*", were built on the flanks of the mountain; these started at the quarry floor and ended in an area where wagons could continue the journey. The "*lizzatura*" was one of the most dangerous phases of the entire production cycle: when the load broke loose from the ropes and went careening down the hill, it frequently mowed down one or more men in the team, with grave consequences.

Photo by R. Vecci

Figure 5 – The lizza and two types of "piri" wooden (inset a) and marble (inset b). The lizzatura has been for many centuries the method to transport the marble blocks from the quarry down the foot of the mountain.

Numerous "*vie di lizza*" are still visible to this day throughout the Alpi Apuane, and many of them are now used as trek paths.
Between 1876 and 1890 a railroad was built to connect the main storage areas for blocks from the three Carrara marble basins- Torano, Miseglia and Colonnata – with the sawmills in the valleys, the port of Marina di Carrara, and the national railroad network. The "*Marmifera*" railway line climbed almost 450m (with a 6 percent slope) and extended for a total of 22 km, crossing a large number of bridges (e.g. Ponti di Vara; Fig. 6). It transported marble for almost a century, competing with the more traditional "*lizzatura*" method, convoys of oxcarts and, initially, trucks. Railroad operations ceased in 1964, and the tracks have been for the most part dismantled and replaced by roads.

Photo by P.Landi

Figure 6 – One of the three Vara bridges at the foot of the Miseglia basin.

After the Second World War, most transport was by truck, especially after the introduction of the German-made Magirus-Deutz trucks. All the quarried marble is currently transported in trucks to the port of Marina di Carrara or other transport hubs.

2.3 The Carrara marble basin

Almost all the quarries lie within the large natural amphitheatre comprising from west to east: Monte Uccelliera (m. 1246), Monte Borla (m. 1470), Monte Sagro (m. 1749), Cima di Gioia (m. 810) and Monte Brugiana (m. 960). The marble basin comprises three valleys separated by the slopes of Monte Maggiore (m. 1396): the Torano, Miseglia and Colonnata basins (Fig. 7).

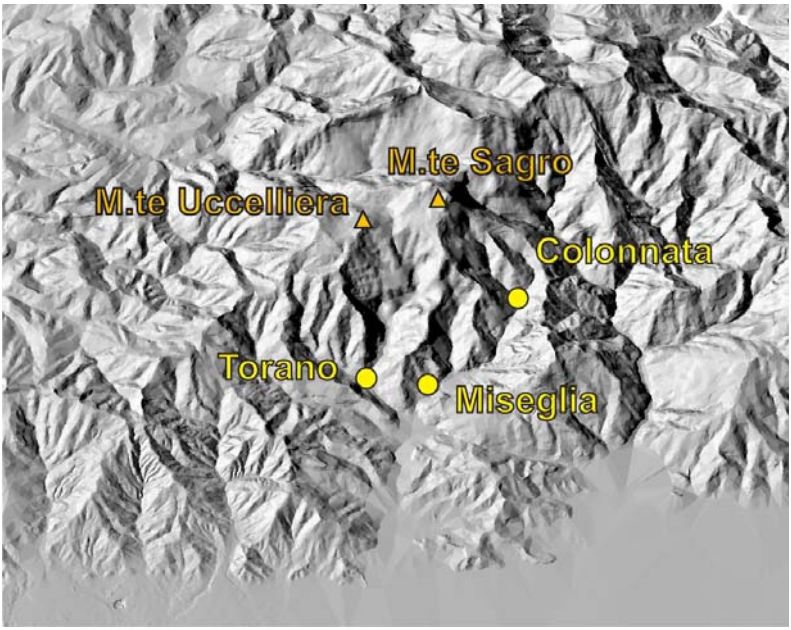

Figure 7 – Topography of the Carrara marble basin. It comprises three valleys: the Torano, Miseglia and Colonnata basins.

The types of quarries present in the Carrara basin may be summarised as follows:

- slope and peak quarries – develop on hillsides or hilltops according to a bench geometry in which each bench can host one or more excavation fronts (Fig. 8);

- pit and shaft quarries - develop vertically, extraction occurs at increasingly deeper levels, so that the quarry front tends to deepen gradually;
- underground quarries – a quarry develops below the surface when there is a need to extract blocks from deeply buried strata, such that the surface quarry is abandoned. In recent times subterranean quarrying has been adopted to safeguard the morphology of the mountain;

Photo by P.Landi

Figure 8 – A peak quarries: each step represents one or more quarry fronts. A chain saw machine is shown (see inset).

3. Geological Setting

G. Molli, F. Mazzarini

3.1 Northern Apennine geology

The Northern Apennine is a fold-thrust belt formed during the Tertiary by eastward thrusting of tectonic units derived from oceanic domains, the Ligurian units, onto the external units of the continental margin, the Tuscan-Umbria units (Molli, 2008 and references therein). The Ligurian units are characterized by the presence of ophiolite covered by deep water sediments, and represent part of the Ligurian-Piemont Ocean (or Alpine Tethys; Ligurian Units in Fig. 9). The Tuscan-Umbria domain (Tuscan Nappe in Fig. 9) represent the continental margin of the Adria (Apulia) plate and is formed by a Palaeozoic basement with its Mesozoic-Tertiary cover.

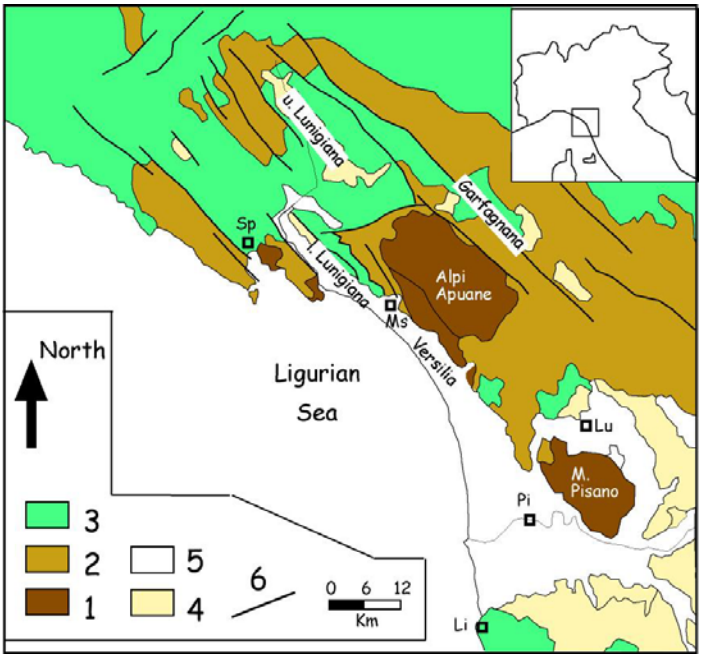

Figure 9 – Tectonic sketch of the northern Apennine close to the Ligurian Sea (see inset). 1=Tuscan metamorphic units; 2=Tuscan Nappe; 3=Ligurian Units; 4=Neogene deposits; 5=Quaternary deposits; 6= main faults.

Transition from the Adria continental crust to the Tethyan oceanic crust is referred to as Subligurian Domain. Northwest-ward motion of Adria lead to closure of oceanic domain and deformation in the Adria continental crust since Late Oligocene with continental crust subduction below Corsica-Sardinia. Later on back-arc rifting due to slab retreat led to oceanic crust formation first in the Liguro-Provençal basin and then in the Tyrrhenian Sea, contemporaneous with eastward migration of subduction, collision zone and deformation. Therefore, in the northern Apennines we find today rocks of the Apulia margin covered by the Ligurian units, first strongly deformed and metamorphosed during the collisional tectonic phases, and then affected by exhumation-related tectonics, normal faulting and uplift (Fig. 9).

3.2 Alpi Apuane geology

In the inner northern Apennines, the Alpi Apuane are well known 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 and Kligfield 1990), in which the regional Apennine structure is best exposed. The deepest part of northern Apennines consists of the so-called Apuane Metamorphic Complex (AMC) that comprises the metamorphic sequences of the Massa Unit and underlying Apuane Unit (see Molli and Vaselli, 2006; Meccheri et al., 2007). Upwards the AMC is followed by un-metamorphosed cover units, which are the Tuscan Nappe, the Canetolo Unit, and some ophiolite-bearing Liguride Units. Referring to the pre-orogenetic Tethyan palaeogeography, the AMC units and the Tuscan Nappe derived from the Tuscan Domain (distal part of Adria), the Canetolo Unit from the Subligurian Domain, and the Liguride Units from the oceanic Ligurian Domain (Fig. 10). As a whole the lithostratigraphic successions of continental units exposed in the Alpi Apuane 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 lithostratigraphic sequence comprises the following main groups of metasediments (Fig. 11):

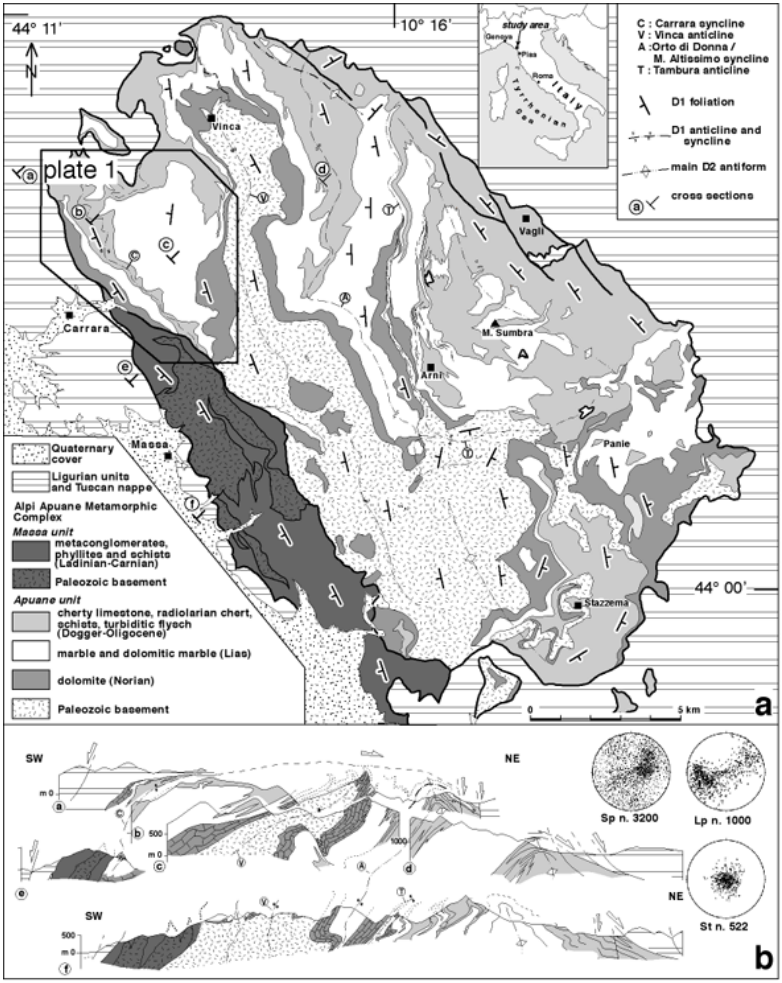

Figure 10 – Geology of the Apuane Metamorphic Complex (AMC). a) Geological sketch map of the Alpi Apuane, the area of the Carrara Basin is indicated as plate 1 (after Molli and Vaselli, 2006). b) Cross sections across the Alpi Apuane and stereonets of major structural elements, Sp=main foliation; Lp=stretching lineation; St=crenulation cleavage (after Molli and Vaselli, 2006).

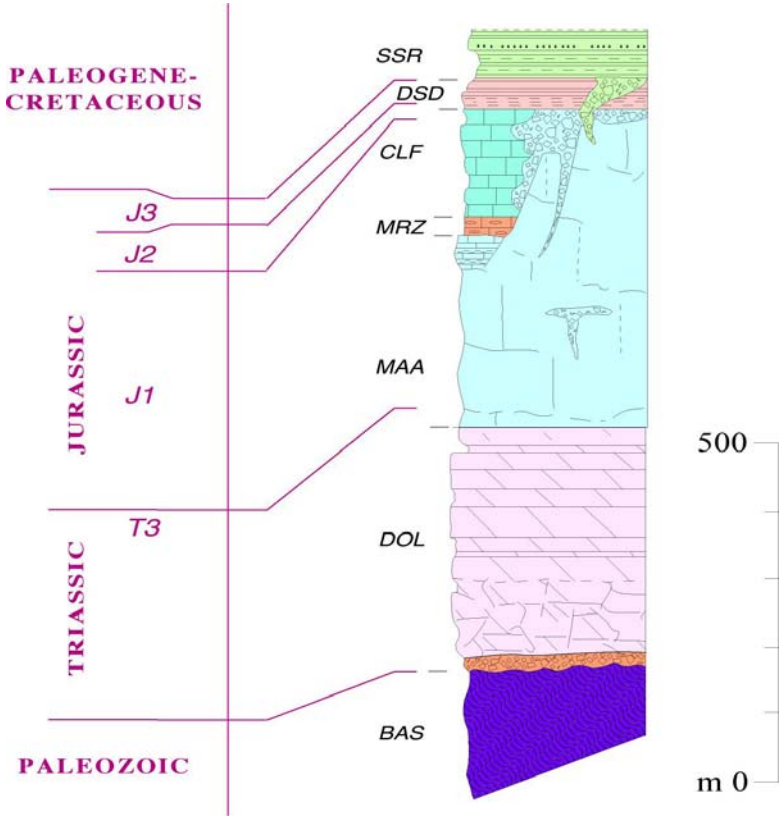

Figure 11 – Schematic stratigraphic column of the metasediments cropping out in the western Alpi Apuane (after Meccheri et al., 2007). BAS = Pre-Alpine basement, DOL = siliciclastic deposits, dolostones and dolomitic marble, MAA = marble "Marmi s.s. Auct.", MRZ = calcschists, CLF = cherty limestone "Calcare Selcifero Auct.", DSD= metacherts "Diaspri Auct.", SSR = phyllites and metasiltites"Scisti Sericitici Auct."

– Middle–Late Triassic to Early Liassic (c.a. 240-180 Ma) metadolostones (Grezzoni, with basal discontinuous and thin siliciclastic deposits), local dolomitic marbles, and pure marbles sensu stricto;
– Early–Middle Liassic to Early Cretaceous (c.a. 180-130 Ma) cherty metalimestones (Calcari selciferi), metacherts (Diaspri) and cherty calcschists (Calcari selciferi a entrochi);

– Early Cretaceous to Early Oligocene (c.a. 130-30 Ma) phyllites and metasiltites (Scisti sericitici) locally containing marble interlayers, calcschists, and lenses of metacalcarenites;
– Late Oligocene to very Early(?) Miocene (c.a. 30-20 Ma) quartz-feldspathic micaceous metasandstone (Pseudomacigno).
This sequence deposited over a portion of the paleo-Adria 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 (D1), active at Oligocene/Miocene boundary, was compression-related and related to nappe stacking. The rocks of the Apuane Unit suffered severe deformation through development of a penetrative foliation (S1) axial planar to NE verging, sub-millimetric to pluri-kilometric isoclinal folds coeval to a green schist facies metamorphism. 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. 10). The following tectonic phase (D2) 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 D2 structures are variously sized folds, with axial planar foliation (S2) accompanied by a green schist facies retrogression of the former syn–late D1 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”. During the final stages of the Alpi 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.

3.3 The Carrara Marbles Basin

In the Carrara inland the marble s.s. forms two major outcrops (Fig. 10). 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 (Fig. 12). The two outcrops respectively lie in the overturned and right flanks of the Carrara Syncline, the westernmost of the regional scale isoclinal folds formed in the Apuane Unit by the compression tectonics (D1 phase) of the Tertiary orogenesis (Meccheri et al., 2007 and referenceres therein) . The vergence of the syncline is toward the NE and its axis trends NW–SE with low plunge northwestwards. Near Carrara the syncline core is represented by the Calcare Selcifero Auct. (Mid–Late Liassic), 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 late antiform (D2 phase) verging toward the Ligurian Sea with a NW–SE trending axis. In general, the marble s.s. formation lacks persistent layers suitable to highlight the geometric features of the D1 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 D1 folds (close to the Ponti di Vara and at the Sponda Quarries near the Torano village), or simply crosscut by the S1 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 greygreen phyllitic marble and grey calcschist, all the bands being almost regularly separated by phyllosilicate films.

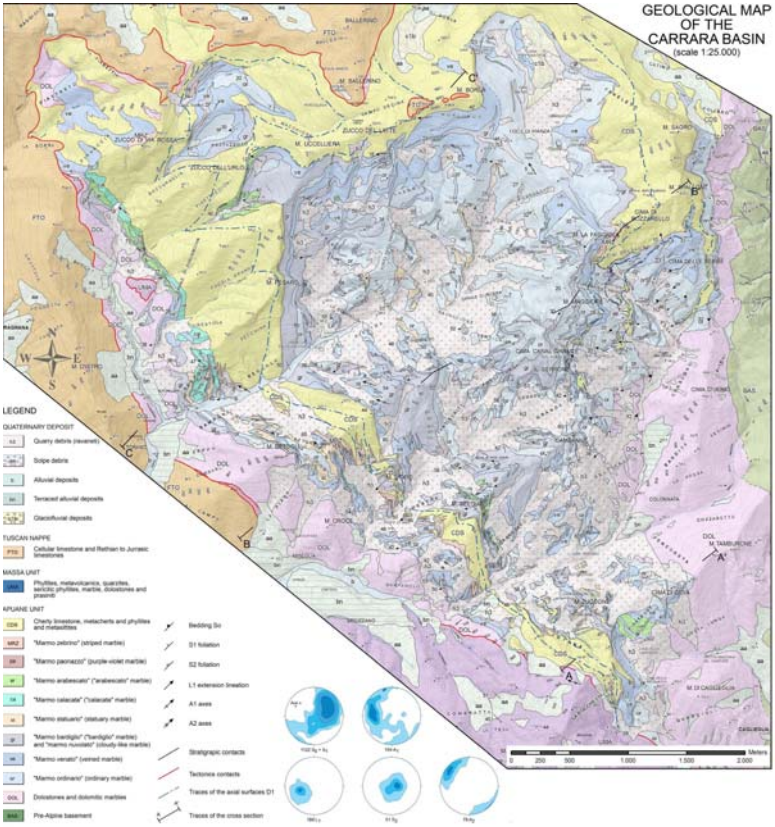

Figure 12 – Geology of the Carrara Basin (after Meccheri et al., 2007).

Along the SW–NE cuts at the quarry bottom, this layering is clearly involved in metric to decametric tight similar anticlines and synclines (Fig. 13), with stretched acute hinges and the regional S1 as axial planar foliation. All the Carrara Marbles were affected by quite a lot of D1 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 Fig. 13).

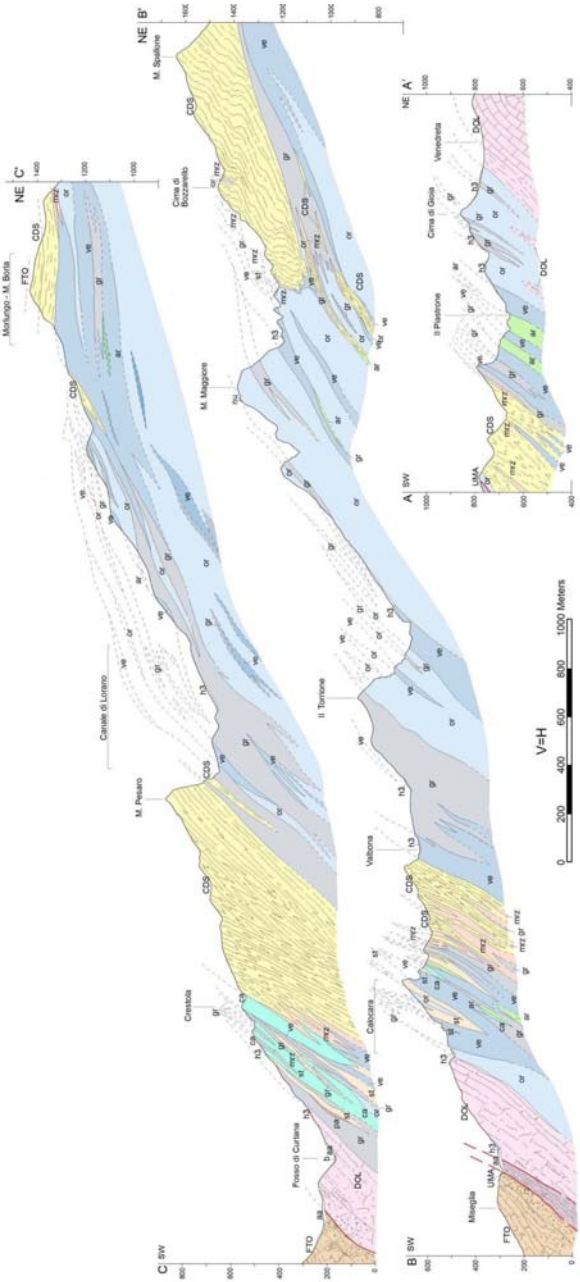

Figure 13 Cross sections across the Carrara Basin (after Meccheri et al., 2007).

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 D1 deformations together with the bedding. Hence, the D1 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 D1 contractional regime (e.g. Molli and Vaselli, 2006 and references therein).

In contrast with the D1 tectonic setting, the D2 structure inside the Carrara Marbles is quite simpler. Apart from localised feeble undulations at the metre–decimetre scale, large D2 folds are almost absent, and in general the S1 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 D2 antiform verging toward the SW and affecting the entire Carrara Syncline and all the above tectonic units (Figs. 12 and 13). On the contrary, metric to pluridecametric D2 folds are widespread along the contact marble s.s./ "Calcare selcifero Auct." (M. Uccelliera-M. Borla; Vallini-Seccagna,). 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 S1 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. 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 and Molli (2000), Molli et al., 2010, 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. The marble of the Alpi Apuane

G. Molli, P. Landi

In general, based on mesoscopic features, it is possible to distinguish three main types of marble in the Alpi Apuane:
1) prevalently solid white and/or banded marble with or without light and/or dark grey veins, lenses or spots. This group comprises commercial varieties such as *statuario*, *bianco* s.l., *venato*;
2) "in situ" monogenic or polygenic matrix-supported or clast-supported breccias (e.g. *arabescato*); 3) grey marble (e.g. *bardiglo* and *nuvolato*).
These three main types of marble comprise the more than fifteen different commercial varieties quarried in the Alpi Apuane.
Of these, the most important are:

Statuario
The most prized marble in absolute: since Roman times it has been used for sculpting thanks to its colour and particular crystalline texture. It has a large grain size and a generally very uniform ivory white or very pale beige-yellow colour. Traces of microcrystalline muscovite homogeneously distributed in the dominant carbonate matrix are responsible for this colouring. The local presence of grey marks is due to low concentrations of pyrite and phyllosilicates in thin anastomosing veins.

Bianco
This is one of the most classic of Carrara marbles. It has a fine or medium grain size, is extremely homogeneous and has a pure white to pearlescent white colour. It is devoid of impurities, and dark marks with a preferred orientation, small veins of calcite (more or less regular and continuous) and ochre yellow levels containing pyrite are present only locally.

Venato
Medium-grained, white to pearlescent white marble with darker regular to anastomosing veins of mm to cm thickness. May contain irregularly-shaped grey marks sometimes showing a preferred orientation. This variety shows a wide range of patterns due to the different orientation, frequency and thickness of the veins and of the dark grey marks.

Nuvolato and *Bardiglio*

Fine- or medium-grained light to dark grey marble cross-cut by dark grey to white veins. The pattern is extremely variable, but always of a certain general type: certain specimens are heterogeneous and variegated, given by the more or less irregular alternation of grey to light grey levels (*Nuvolato*), whereas others appear very homogeneous with a bluish grey to dark grey colour and thin, darker veins (*Bardiglio*). The darker, more or less uniform colour of the marble as a whole is given by microcrystalline pyrite and/or carbonaceous pigments. There are sometimes masses and/or more or less regular and continuous layers of dolomite and ochre-yellow levels containing pyrite.

Arabescato

Clast-supported metabreccia with heterometric elements of marble in a grey to dark green matrix. The clasts, typically light grey to white, determine a wide range of features and patterns according to their their size, relative position and relationship with the surrounding matrix.

Calacatta

Metabreccia with heterometric clasts of white to ivory white marble, sometimes with light green hues, in an ochre yellow to grey-green matrix. In general, the low percentage of matrix does not highlight the clastic nature of the material.

Cipollino

Calcschists of grey-green to green or red to purplish-red colour with levels of carbonate phyllites and muscovite phyllites of dark green to purplish red colour. There are generally numerous variably deformed and folded calcite veins. Colour variations, the different relative percentages of the phyllite and carbonate components, and the different patterns determined by the veins of calcite and quartz are such that its appearance and patterns are extremely variable, as revealed by the quarry cuts.

The major differences in the mesoscopic appearance of these marbles are essentially linked to their different position and depositional environment within the Rhaetian and especially Liassic carbonate platform. These differences and the original variability of the protolith (i.e. of the original rock) determine pre-orogenic (associated with certain types of breccias) and, above all, orogenic deformation with locally variable conditions of finite strain; in inhomogeneous rocks (e.g.

breccias), such conditions produce a great variety of patterns, as revealed by the shape and elongation of clasts in the marble breccia in relation to the shape and type of deformation and finite strain ellipsoids.

5. Thursday 9 Giugno 2010: Geology of Western Alpi Apuane

Field leaders: G.Molli and F.Mazzarini

Itinerary: Pisa-Carrara
Themes: introduction to the Alpi Apuane geology, stratigraphic sequences and deformation history of the western Alpi Apuane, Carrara quarries.

Stop 1.
Locality: Fantiscritti underground (Carrara).
Topics: Underground Quarry, Marbles *Bianco Carrara Venato Nuvolato*

Photo by R. Vecci

Figure 14. Large room in the underground quarry at Fantiscritti.

Stop 2.
Locality: Ponti di Vara (Carrara).
Topics: the hinge zone of Kilometer-Scale Carrara syncline.

In this area, which is named after the junction of three historical bridges (1890) of the former Marble Railway, we can see the hinge zone of the

"Carrara syncline". This structure strikes NW-SE and along this section has a core of Late Liassic Calcare selcifero whereas at M.Uccelliera/Foce di Pianza (Stop 3), that is further north and upward along the its axial plane, it is cored with Cretaceous to Tertiary schists.

Photo by R. Vecci

Figure 15. Calcschist thigh Fold at Ponti di Vara.

Along the road the boundary between marble and cherty metalimestone is marked by impure marbles and calcschist levels, a marble variety called "Zebrino", where tight isoclinal folds can be observed. At map scale and in the panoramic view interfingering of calcschist levels within cherty metalimestones can be observed as marking the hinge zone of kilometer-scale Carrara syncline.

Stop 3.

Locality: M.Uccelliera – Foce di Pianza.

Topics: Panoramic view of the Carrara marble basin, the Carrara syncline, superimposed folds and overprinting foliation patterns, marble types and brittle faults.

The structural map and cross-section of figures 12 and 13 show the geology of the Carrara area in some detail. From the Uccelliera pass

looking southestward, we can observe the outline of the Carrara Syncline, the westernmost large scale structure in the Apuane unit.
Along the raod and in this area the following lithotypes can be observed:
"Carrara marble", varieties *Bianco* and *Venato* with lenses of metabreccias;
"Cherty metalimestones" (Calcare Selcifero), grey metalimestones with quartz levels and lenses associated with carbonatic metapelites. At the base of this formation quartz-rudites levels can be observed and interpretable as debris-flow deposits produced by syn-sedimentary tectonics related with Liassic block-faulting. One level of these breccias called "Bancone del Morlungo" containing quartz clast up to pluridecimeters in size can be followed along all the ridge; Cherts discontinuosly present are formed by greenish to whitesh quartzite and quartzitic phyllites.

Photo by R. Vecci

Figure 16. Folded quartzite level along the road at Stop 3.

"Scisti Sericitici" and "Calcari a nummuliti" fms. greenish-purple slates and schist with marble levels, locally containing micro breccias.
The M.Borla ridge is characterized by the whithish-yellowish rocks of a klippe of the Calcare Cavernoso, the base of Falda Toscana.

Along the road we can observe pluridecametric scale anticline-syncline D1 fold pairs with a core of marble and cherty limestone respectively. In this locality the late deformation (D2) is well expressed in the Calcare selcifero and Scisti sericitici and testified by a sub-horizontal pervasive crenulation cleavage axial plane of SW-verging decametric to decimetric scale folds.

As a whole we can intepreted the structures in the area as a normal limb of megascale D1 NE vergent structures (the Carrara syncline) overprinted by structures related to the early D2 deformation well developed in the the slates and cherty metalimestones.

Along the road toward Foce di Pianza we can furthermore observe some high angle faults which represent the younger exumation-related deformation structures. These are related to the recent (from 5 Ma up to now) history of the Alpi Apuane. These faults show evidence of polyphasic movements testified by oblique and down-dip slickensides (Molli et al., 2010 and references therein) .

References

Braschi S., Del Freo P., Trevisan L., 1987. Ricostruzione degli antichi ghiacciai sulle Alpi Apuane.
Atti Soc. Tosc. Sc. Nat., Mem., Serie A. 93, 203-219, fig. 10, tav.f.t. 1

Carmignani L. and Kligfield R., 1990. The transition from compression to extension in mountain belts: evidence from the Northern Apennines Core Complex. Tectonics, 9, 1275–1303.

De Stefani C., 1874. Gli antichi ghiacciai dell'Alpe di Corfino, ed altri dell'Appennino settentrionale e delle Alpi Apuane. Boll. R. Com. Geol. d'It, 5, 86-95

Drysdale R., Zanchetta G., J. Hellstrom, Fallick A.E., Zhao J., Isola I., Bruschi G., 2004. The palaeoclimatic significance of a Middle to late Pleistocene stalagmite from the Alpi Apuane karst, central-western Italy. Earth Planetary Science Letters, 227, 215-229

Drysdale R.N., Hellstrom, J.C., Zanchetta, G., Fallick, A.E., Sanchez-Goni, M.F., Couchoud, I., McDonald, J., Maas, R., Lohmann, G., Isola, I., 2009. Evidence for obliquity forcing of glacial Termination II. Science DOI: 10.1126/science.1170371

Federici P. R., 1981. The quaternary glaciation on the seawardside of Alpi Apuane. Riv. Geogr. It 88, (2), 183-199.

Meccheri M., Molli G., Conti P., Blasi P. and Vaselli L., 2007. The Carrara Marbles (Alpi Apuane, Italy): a geological and economical updated review. Z. dt. Ges. Geowiss., 158/4, 719–735.

Molli G. and Vaselli L., 2006. Structures, interference patterns, and strain regime during midcrustal deformation in the Alpi Apuane (Northern Apennines, Italy). In: Mazzoli S. and Butler, R.W.H. (eds), Styles of Continental Contraction. Geological Society of America Special Paper 414, 79–93.

Molli G., 2008. Northern Apennine–Corsica orogenic system: an updated overview. In: Siegemund S., Fugenschuh B. and Froitzheim N. (eds), Tectonic aspect of the Alpine-Dinaride-Carpathian System. Geological Society, London, Special Pubblications, 298, 413-442.

Molli G., Cortecci G., Vaselli L., Ottria G., COrtopassi A., Dinelli E., Mussi M. and Barbieri M., 2010. Fault zone structure and fluid–rock interaction of a high angle normal fault in Carrara marble (NW Tuscany, Italy). Journal of Structural Geology, in press, doi:10.1016/j.jsg.2009.04.021.

Ottria G. and Molli G., 2000. Superimposed brittle structures in the late-orogenic extension of the Northern Apennines: results from the Carrara area (Alpi Apuane, NW Tuscany). Terra Nova, 12, 52–59.

Piccini L., 1998. Evolution of karst in the Alpi Apuane (Italy): Relationships with the morphotectonic history. Suppl. Geografia Fisica e Dinamica Quaternaria, 3(4) : 21-31.

Rapetti F. E Vittorini S., 1994. Carta climatica della Toscana centro settentrionale. Pacini Editore, Pisa.

Stoppani A., 1872. Sull'esistenza di un antico ghiacciaio delle Alpi Apuane. Rend R. Ist. Lomb. Di Sc e Lett. 5, 733

Zanchetta G., Drysdale R.N., Hellstrom J.C., Fallick A.E., Isola I., Gagan, M., Pareschi M.T. 2007. Enhanced rainfall in the western Mediterranean during deposition of Sapropel S1: stalagmite evidence from Corchia Cave (Central Italy). Quaternary Science Review, 26: 279-286.

Bibliography sources for "The history of Carrara marble quarries" chapter

Blasi P., Bradley F., Pili M., 1993. Cave Apuane, censimento, analisi e tendenze evolutive / Apuan Quarries- Survey, analysis and trends. Printed by Tipografia Ceccotti, Massa.

Bradley F., Medda E., 1989. Le Strade Dimenticate. Printed by Type Service Editore

Bradley F., Guida alle cave di marmo di Carrara/Guide to the marble quarries in Carrara, 1991. Printed by S. Marco Litotipo, Lucca

Dolci E., 1980. Carrara cave antiche. Printed by Tipo-Lito Mario Pezzini, Viareggio.