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GEOMORPHOLOGICAL MAP AND RAISED-RELIEF MODEL OF THE CARRARA MARBLE BASINS, TUSCANY, ITALY

ABSTRACT: BARONI C., RIBOLINI A., BRUSCHI G. & MANNUCCI P.,
Geomorphological map and raised-relief model of the Carrara Marble Basins, Tuscany, Italy. (IT ISSN 0391-9838, 2010).

Marble extraction in the Carrara basins has occurred since the 1st millennium BC, with relevant exploitation periods during the Roman period and the Renaissance, when Michelangelo visited the Carrara quarries to personally select the marble blocks he used for sculpting his legendary works of art. As a consequence of this long-lasting activity, the landscape is almost completely notched by extensive quarry fronts and covered by huge quarry dump deposits, locally named *ravaneti*.

Through a detailed field survey and the interpretation of aerial photographs, we compiled a geomorphological map at a scale of 1:10,000 of the Carrara marble basins. Additionally, a raised-relief model at a scale of 1:10,000 was derived from the geomorphological map. To our knowledge, this model is the first product of this kind.

A geomorphologic survey, historical documents, and stratigraphic and grain-size analyses allowed us to reconstruct the evolution of the anthropogenic landscape and allowed for the characterization of past and current geomorphic processes. Four main stratigraphic units are recognizable in the *ravaneti*. The different textures and structures of these units reflect the evolution of marble quarrying techniques. The oldest and deepest debris layer dates back to pre-Roman and Roman periods and is made up of flat pebbles with an open-work structure. In several localities, this manually produced debris is associated with very distinctive excavation cutting traces (*caesurae* in Latin), covering paleosols predating the Roman excavation activity. Medieval and Renaissance *ravaneti* are locally documented on top of this unit, burying post-Roman soil. Coarse multi-decimeter-sized cobbles («head man» size cobbles) with a scarce fine matrix constitute the typical *ravaneto* of the end of 19th century. The uppermost layer, with boulders and an abundant fine matrix (ranging from sand to silt), is the consequence of the new diamond wire cutting methods that were introduced in the 1970s.

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The fine matrix produced by the recent techniques of block cutting and grinding destabilizes the dump deposits, making them very prone to hazardous remobilization of debris flows and shallow landslides. These are the most significant geomorphologic processes acting in this anthropogenic landscape.

In general, the geomorphological map of this extractive environment offered the opportunity i) to verify that anthropogenic landforms archived the principal steps of technological development of such industrial context strictly linked to important cultural events, and ii) to evaluate what are the technological developments in excavation activities that could generate situations of geomorphological risk.

KEY WORDS: Anthropogenic geomorphology, Quarry dump deposit, Debris flow, Human-induced hazard, Carrara marble, Apuane Alps.

RIASSUNTO: BARONI C., RIBOLINI A., BRUSCHI G. & MANNUCCI P.,
Carta geomorfologica e plastico geomorfologico dei bacini marmiferi di Carrara (Toscana, Italia). (IT ISSN 0391-9838, 2010).

L'estrazione del marmo nei bacini di Carrara risale a I millennio A.C. ed ha attraversato momenti di particolare intensità e rilevanza in età romana e durante il Rinascimento, epoca alla quale risale la leggendaria frequentazione dei bacini marmiferi da parte di Michelangelo per la selezione e l'estrazione dei blocchi utilizzati per realizzare le sue insuperabili opere d'arte. Come conseguenza del protrarsi nel tempo dell'attività estrattiva, il paesaggio è quasi completamente caratterizzato da ampi fronti di cava e da depositi derivanti dagli scarti dell'attività estrattiva, localmente denominati *ravaneti*.

Attraverso rilevamenti geomorfologici di dettaglio e l'analisi delle fotografie aeree, abbiamo elaborato una carta geomorfologica alla scala di 1:10.000 dei bacini marmiferi di Carrara. Dalla carta geomorfologica è stato realizzato un plastico tridimensionale, sempre alla scala di 1:10.000, che rappresenta un unicum nel panorama degli elaborati geomorfologici finora realizzati.

Grazie a rilevamenti geomorfologici di dettaglio, ad analisi di documenti storici e ad analisi stratigrafiche e sedimentologiche, abbiamo ricostruito le principali tappe dell'evoluzione del paesaggio antropico e caratterizzato sia i processi geomorfologici in atto sia i processi che hanno agito nel passato. I *ravaneti* sono costituiti da quattro principali unità stratigrafiche. Le caratteristiche tessiturali e la struttura dei *ravaneti* sono espressione delle diverse tecniche di estrazione del marmo che si sono succedute nel tempo. Gli scarti di lavorazione più antichi e più profondi sono costituiti da scaglie di marmo appiattite, delle dimensioni dei ciottoli, di età pre-romana e romana. In molte località questi detriti sono asso-

ciati a tracce di escavazione eseguite manualmente, molto caratteristiche (note come *caesurae*) e coprono paleosuoli di età pre-romana. *Ravaneti* di età medievale e rinascimentale si sovrappongono a quelli di età romana, localmente coprendo paleosuoli di età post-romana. I tipici *ravaneti* del XIX Secolo sono costituiti da blocchi delle dimensioni medie inferiori ai 30 cm («a testa d'uomo»). I *ravaneti* più recenti, costituiti da massi con abbondante matrice fine (dalla sabbia al limo) derivano dagli scarti derivanti da nuovi metodi di escavazione, quali il filo diamantato, introdotto negli anni '70 del XX Secolo e le tagliatrici a catena.

La matrice fine prodotta dalle moderne tecniche di taglio e di lavorazione dei blocchi di marmo, che è stata, nel passato, direttamente immessa nei *ravaneti* ha creato condizioni di potenziale instabilità, esponendo i *ravaneti* ad elevata pericolosità indotta da fenomeni di debris flow e di frane superficiali. Tali processi geomorfologici sono attualmente i più attivi nel contesto del paesaggio fortemente antropizzato dei bacini marmiferi di Carrara.

In generale, la carta geomorfologica di quest'area estrattiva ha offerto l'opportunità di verificare che le forme antropiche hanno registrato i principali passaggi dello sviluppo tecnologico di tale contesto industriale strettamente legati ad importanti eventi culturali, ma anche di valutare quali sviluppi tecnologici nelle attività estrattive possano portare a situazioni di rischio geomorfologico.

TERMINI CHIAVE: Geomorfologia antropica, Depositi da attività estrattiva, Debris flow, Rischio indotto, Marmo di Carrara, Alpi Apuane.

INTRODUCTION

Although interaction between humans and the environment is an extremely recent development in terms of geological time, human activities are much more effective in shaping the landscape than are most of natural processes, both with respect to the intensity and the extent of resulting transformations (Nir, 1983; Szabò & alii, 2010). Recently, anthropogenic impacts on the landscape have been the subject of many studies (David & Patrick, 1998; David, 2007; Rivas & alii, 2006), including analyses of variations in landscape morphology and of the direct or indirect consequences of geomorphological risk. However, despite the growing interest in this topic, attempts at cartographic synthesis related to human-sculpted and human-induced landforms and processes are still deficient.

Among the anthropogenic transformations of the landscape, quarry activities are one of the most prominent transformations, and the marble quarries of Carrara, Italy, are a prime example (fig. 1). Indeed, the Carrara marble basins are one of the most excavated areas in the world, with an average density of 7 quarries/km². Moreover, the marble extraction in the Carrara basins has occurred for an exceptionally long time, and quarry activities have been documented since the Roman period (Dolci, 1985; Dolci, 2003; Paribeni, 2003; Bruschi & alii, 2004) and likely occurred even earlier. Periods of particularly intense exploitation were during the Renaissance (the quarries from which Michelangelo personally selected marble for extraction to be used in creating his astonishing works of art are legendary) and the second half of the 19th century, when the widespread use of explosives meant that up to 90% of the material that was quarried was rejected (Zaccagna, 1905). For this reason, the rejected debris dispersed along the slopes below the quarries, locally named *ravaneto* (plural *ravaneti*), became a dominant element in the land-

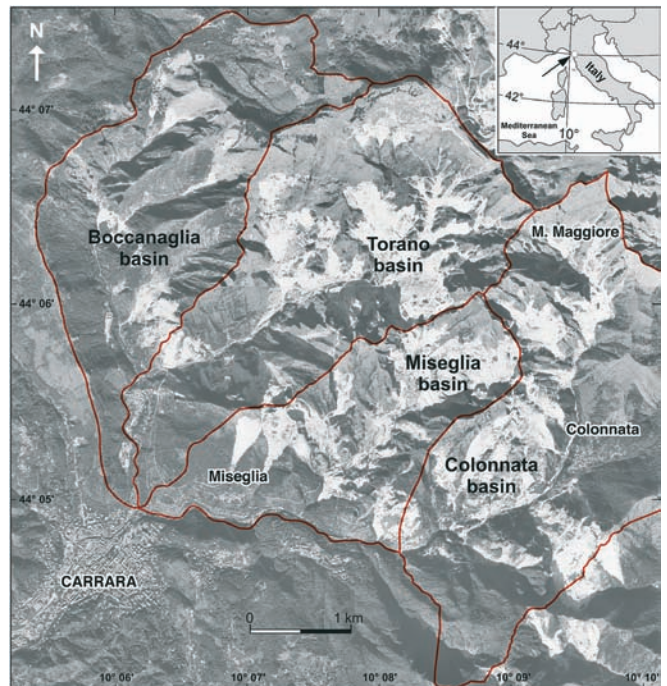


FIG. 1 - Geographic sketch of the Carrara marble basins. The limits of the basins are indicated.

scape of the Carrara quarries (fig. 2 and 3). The invasive extraction techniques were progressively abandoned, beginning in 1900 with the introduction of mechanical systems of marble cutting (e.g., helicoidal iron wire) that limited the impact on the slopes and reduced the volume of rejected material (Bradley, 1991; Pandolfi & Pandolfi, 2003).

Marble production in the second half of the 19th century was less than 100,000 tons per year (Zaccagna, 1905), and marble was extracted from only a few dozen active quarries.

Today, there are 78 active quarries, 68 of which are open-air and 10 of which are underground. In 2009, the 3,930,000 tons of total material extracted yielded only about 930,000 tons of marble for commercial use, with the rejected stones comprising approximately 70% of the total material extracted. The rejected stones were dumped on the slopes for a long time, enlarging the *ravaneti*. Only during the last decade has this practice of spreading the rejected material on the slope of the quarry been prohibited.

The progressive increase in marble production that has occurred in recent decades is the result of modern techniques that have allowed for increased speed in marble cutting. This reduces the volume of material yield, but it also allows for the rapid and massive enlargement of excavation fronts, profoundly changing the relief and landscape of quarries. Moreover, the modern cutting techniques generate abundant silty and sandy sediments that are eventually dispersed in the *ravaneti*. The new profiles of quarry fronts and the changes in the *ravaneti* composition have resulted in slope instability and have increased

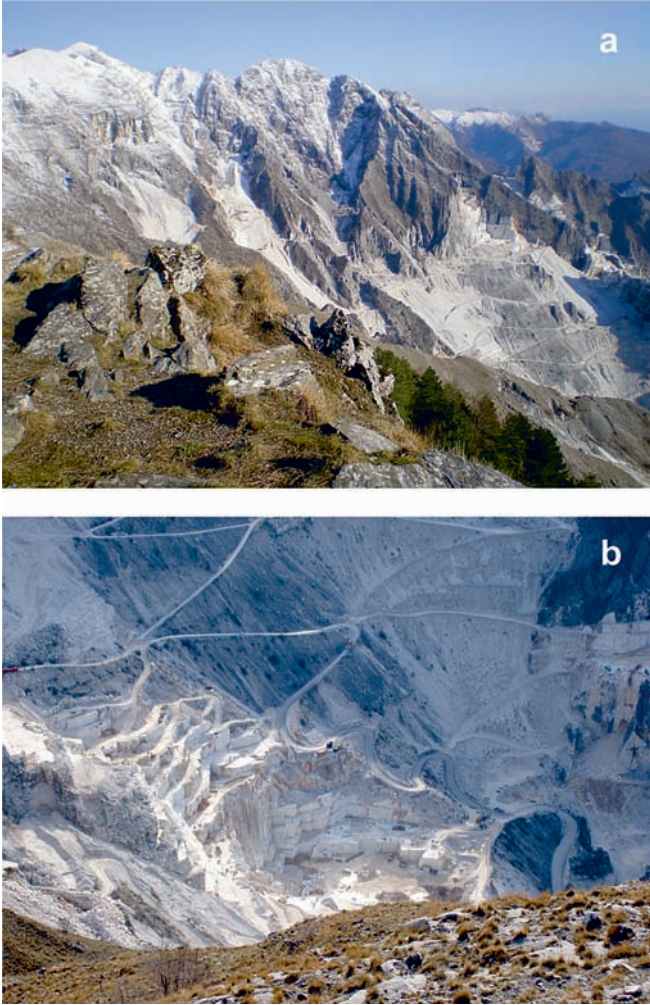


FIG. 2 - Typical landscapes of Carrara marble basins. Old dark coloured and modern white coloured ravaneti (a) (photo by Ponzanelli), quarry fronts and yards (b) (upper Torano basin) (photo by Nicolai).

the occurrence of landslides and debris flows (D'Amato Avanzi & Verani, 1998; Baroni & alii, 2000; Baroni & alii, 2001; Cortopassi & alii, 2008). The instability of the slopes is aggravated by the intense rainfalls that can occur in this area. The marble basins are located on the Tyrrhenian side of the Apuane Alps, and they face the sea (fig. 1). The strong relief (approximately 2000 m of elevation over less than 10 km) forces the humid air masses of Atlantic or Mediterranean origin to rise and cool rapidly, inducing intense mountain rainfalls of up to 3000 mm or more annually (Rapetti and Vittorini, 1994). The catastrophic effects of these events were recently recorded in areas near the study area of the Carrara basins (Rapetti & Rapetti, 1996; D'Amato Avanzi, 1999; D'Amato Avanzi & alii, 2000).

We believe that the Carrara marble basins provide a good test site for a geomorphological map focused on the landforms generated by human activities and also affected by natural processes. In this work, we illustrate the criteria adopted to create this map at a scale of 1:10,000, and we



FIG. 3 - The aspect of ancient ravaneti (Torano basin at the middle of 19th century). Photo by Bessi, reproduced with the authorization of the Quarry Bureau of Carrara Municipality.

describe the most-relevant landforms and processes represented in the area. Moreover, we show a model derived from this geomorphological map, which is the first example of a three-dimensional geomorphological map.

SETTING

The Carrara marble basins are on the Tyrrhenian side of the Apuane Alps, which is an elliptical mountain massif belonging to the northern Apennines in the northwestern region of Italy. The Carrara marble basins are morphologically divided into quarrying «basins» that correspond to four valleys on the western slopes of Monte Sagro (1389 m a.s.l.). From east to west, these basins are known as the Collonnata, Miseglia, Torano, and Pescina-Boccanaglia basins (fig. 1).

The famous Carrara marble is composed of a limestone dated to the Lower Lias (Hettangiano) that metamorphosed to greenschists facies starting in the Late Oligocene period. The marble is part of a tectonic unit known as the Apuane Metamorphic Complex (Paleozoic to Upper-Oligocene) that outcrops in a tectonic window of the fold-chain of the northern Apennines. The complex is overlain by the sedimentary succession of the Tuscan Nappe (Trias-Oligocene) and by the Ligurian units (Cretaceous-Eocene), which are comprised of an oceanic basement and its associated sedimentary rocks (Carmignani & Kligfield 1990). The geological formations outcropping in the marble basins are listed and described in the map.

MATERIALS AND METHODS

The background for the geomorphological map was the 1997 edition of the technical regional topographic map of Tuscany at the scale of 1:10,000. The rapid and intense changes in surface topography as a result of mining (i.e., variation of quarry fronts and exploitation limits, new access roads, and variations in the shape and size of the *ravaneti*) mean that a traditional topographic map, albeit at a suitably large scale, was not sufficiently updated for positioning landforms identified during the field surveys. It was therefore necessary to have more-detailed topographic tools, such as orthophotomaps, with us in the field. Thus, digital orthophotographs (TerraItaly 1998-1999) were georeferenced and reproduced at a scale of 1:5000 (i.e., the scale at which the surveys were conducted). Contour lines, spot heights, and toponyms derived from the technical regional topographic map were superimposed on the orthophotographs using ESRI ArcGis 9.2 software.

Systematic field surveys were conducted in 2004 and were updated in 2007. Several spot and track measurements were conducted with a GPS (Garmin Etrex), and these data were integrated with the detailed field surveys and aerial photographs.

Finally, the interpretation of aerial photographs at a large scale (1:20,000 to 1:5,000) was employed to control field survey data and to correctly map landforms in inaccessible areas.

The first crucial step for accomplishing the survey was to define the map legend. In addition to the use of colors, which are typically used in geomorphological maps (different colors used for different morphogenesis and different tones of the same color used to represent state of activity), the necessity to distinguish landforms and deposits related to anthropogenic activities led us to enlarge the section devoted to man-made landforms, which was enriched by several symbols that are unusual for classical maps. Moreover, a foreground color was used to report information about weathering and vegetation cover of certain man-made deposits (*ravaneti*). For the other landforms, we used the symbols adopted by the national cartographic group (Gruppo Nazionale Geografia Fisica e Geomorfologia, 1993; Gruppo di Lavoro per la Cartografia Geomorfologica, 1994).

Until a few years ago, cartographic model production (i.e., raised-relief cartography) was an extremely slow and expensive process. Now, the development of specific software and the availability of specialized machines has enabled us to include three-dimensional (3D) scale reproductions of digital terrain models with great accuracy and correspondence to the landscape morphology. In this study, Litografia Artistica Cartografica (LAC) was dedicated to the creation of a geomorphological model (i.e., raised-relief model) of the Carrara marble basins. The process consisted of two main steps: mold shaping and map engraving. Based on the digital terrain model of the area, a plaster cast was created by means of hand-finished decimimetric milling (mold shaping). Eventually, the geomorphological map was printed on a 450 gr/m² PVC

sheet and engraved on the plaster cast, adopting a technique of hot deformation in the oven (engraving).

GEOMORPHOLOGICAL MAP AND MODEL

The field survey was particularly focused on the anthropogenic landforms and deposits directly linked to the excavation activities. Nevertheless, the other natural landforms and processes were included in the map and in the 3D model. Illustrations of some typical anthropogenic landforms of the extraction activities in the Carrara marble basins are also reported in the lower margin of the map.

We distinguished five sets of landforms and deposits, specifically those landforms due to gravity, running water, and crinivation and those that were man-made and structural. The geological formations were also reported, redrawn and modified from Meccheri & *alii* (2004a, b).

Man-made landforms and deposits

As previously stated, man-made morphogenesis was the nucleus of the map, and the relative set of landforms was subdivided into three sub-groups: erosive landforms, constructional landforms and deposits, and roads and working plants.

The first group included the landforms directly generated by marble extraction from slopes (e.g., quarry fronts, exploitation limits, and overhanging cliff quarries and quarry yards). The succession of quarry fronts at different elevations in the same quarry yard is common in the map and reflects the progressive enlarging of the excavated area upslope or the lowering of the exploitation level (fig. 2b, fig. 4). The quarry dump exploitation and the quarry dump exploited symbols refer to the recent practice of *ravaneti* recovery by removing the debris that has a commercial use (mainly in the paper, chemical and pharmaceutical industries).

Ravaneti and retaining walls installed to ameliorate their stability represent the man-made constructional landforms and deposits reported in the map (fig. 5). *Ravaneti* have been studied because of their large size and the processes that occur on their surfaces. Considering all of the Carrara marble basins, *ravaneti* accounted for 265 hectares on the FOSSEN'S maps (Regio Corpo delle Miniere, 1890-1892) (fig. 6). In 2007, *ravaneti* in the same area had greatly expanded to cover 478 hectares. The maximum extension of *ravaneti* was reached in 2003 (it is estimated to have been greater than 500 ha) and was then reduced to the area measured in 2007 as a consequence of the re-exploitation of quarry dump deposits for commercial use.

Ravaneti have been differentiated on the basis of grain size, the presence of surface weathering of composing clasts, and the type of vegetation cover. The grain size of *ravaneti* has been the subject of previous studies, and these data have been obtained for many landforms by means of the intercept method (surface texture; see Baroni & *alii*, 2000), sediment sieving in the lab and image analysis of a vertical section of deposits (Baroni & *alii*, 2003; Nicolai,

FIG. 4 - Quarry front (a, c) and multilevel quarry yard (b) in the upper Miseglia and Colonnata basins. Note the presence of abandoned ravaneti suspended on the active quarry yard, relicts of higher levels of extraction (a).

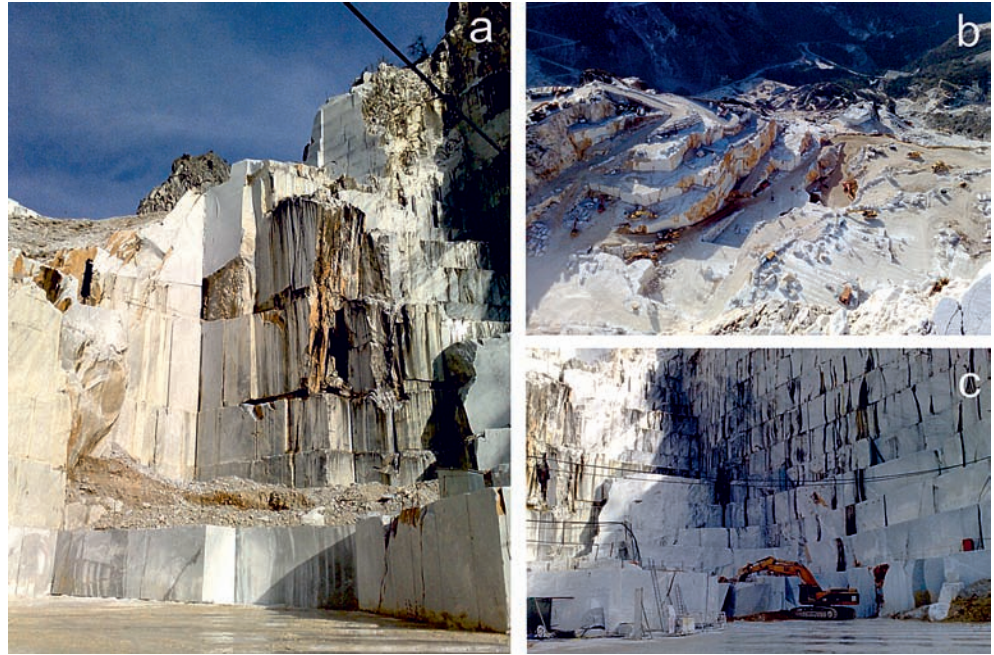


Fig. 5 - Retaining walls of the beginning of 19th century in the Miseglia (a) and Colonnata (b) basins.

2009). On the basis of these data, *ravaneti* were subdivided into four grain size classes (fig. 7):

- 1) fine-grained *ravaneti*: *ravaneti* clast supported or silty sandy matrix supported, with clast maximum diameter < 10 cm (fig. 7b),
- 2) head man *ravaneti* (locally named «testa d'uomo», meaning composted by cobbles «the size of a man's head»): *ravaneti* clast supported or silty sandy matrix supported, with clast maximum diameter between 10 and 30 cm (fig. 7a),
- 3) medium coarse-grained *ravaneti*: *ravaneti* clast supported or silty sandy matrix supported, with clast maximum diameter between 30 and 50 cm (fig. 7c), and
- 4) coarse-grained *ravaneti*: *ravaneti* clast supported or silty sandy matrix supported, with clast maximum diameter > 50 cm (fig. 7d).

These classes may overlap each other (i.e., be visible in the vertical section) and may be juxtaposed along the slopes where the abrupt passage from different surface textures can be easily observed. On the map and the model, different tones of yellow enabled us to indicate the *ravaneti* of any grain size class that presented a surface weathering of clasts. Typically, the oldest inactive *ravaneti* show a dark patina covering the face of the clast exposed to external weathering. In addition to chemical reactions altering these surfaces, biological weathering is mainly responsible for the dark color of ancient *ravaneti* (fig. 7a).

Grass, shrub, or tree covers on *ravaneti* are indicated on the map with different tones of green. Gentili & alii (2010) described the plant species colonizing *ravaneti* and their relation to *ravaneti* stability. The study area is located close to a natural park (Apuane Natural Park) that is rich in endemic species, making it a particularly interesting place

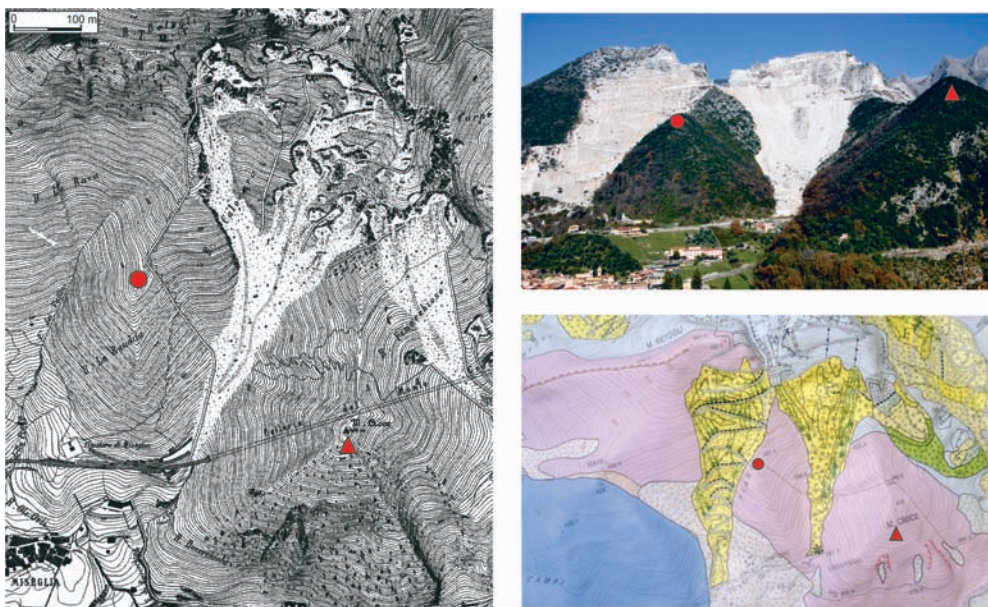


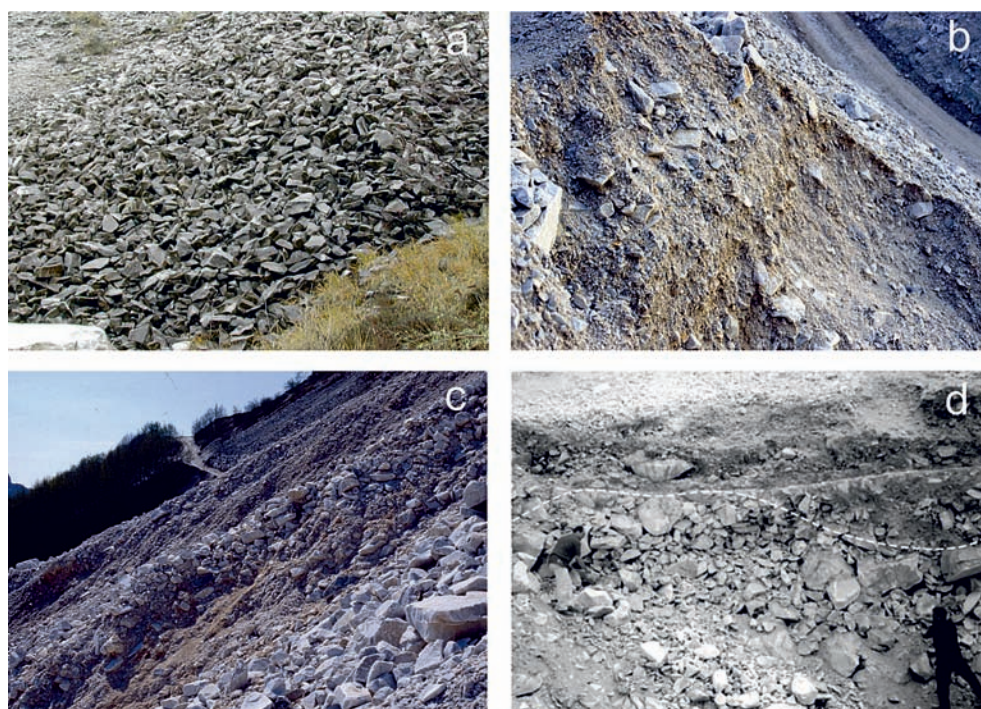
FIG. 6 - Visual comparison between the extensions of the ravaneli in the Calocara area in the 1887-88 (a: Fossen map in Regio Corpo delle Miniere, 1890-92) and today (b: photograph taken in 2009 and c: model updated to 2007).

for studying environmental changes induced by quarrying activities. In disturbed quarry areas, vegetation dynamics have a lower quality (i.e., are less natural) and revegetation patterns are affected by alien, ruderal, and widely-distributed species (Gentili & alii, 2010). In contrast, stability on the ancient deposits has favored vegetation strongly characterized by indigenous and endemic species, such as *Carum apuanum* and *Rubia peregrina* (Gentili & alii, 2010).

Fine-grained *ravaneli* are mainly located on the uppermost portion of composite dump deposits, where clast

weathering is weak or totally absent. «Head man» *ravaneli* are quarry dump deposits typically generated during the last decades of the 19th century, when the rejected stones were sized for transporting in small wagons and were used to build dry stone retaining walls, or eventually dumped along the slopes. Indeed, these *ravaneli* are frequently found at the border of abandoned quarries, and their cobbles show evident surface weathering. Medium coarse-grained *ravaneli* are highly prevalent in the Carrara marble basins, but coarse-grained *ravaneli* represent the more-ex-

FIG. 7 - Different types of ravaneli. a: head man ravanelo (weathered clasts with maximum diameter between 10 and 30 cm, clast supported); b: prevalently fine-grained ravanelo (unweathered clast with maximum diameter < 10 cm, sandymatrix supported); c: medium coarse-grained ravanelo (unweathered clast with maximum diameter between 30 and 50 cm, prevalently clast-supported, locally sandy matrix supported); d: onlap of fine-grained ravanelo (clast with maximum diameter < 10 cm, silty-sandy matrix supported) onto coarse-grained ravanelo (clast with maximum diameter > 50 cm, clast-supported).



tensive quarry dump deposits of the area mantling the lowermost part of the composite *ravaneti* deposits. Clasts around 50 cm in size show irregular shape and are derived from the use of explosives in extraction techniques. Moving up the slope, coarse-grained *ravaneti* frequently pass to «head man» *ravaneti* and finally terminate at the margin of an abandoned quarry. Clasts with >1 m of maximum diameter are mostly due to more recent working activities, showing a lower degree of surface weathering and a more regular shape, with one or more faces generated by a rectilinear cutting.

The grain size of the matrix in all classes of *ravaneti* varies from silt to sand and, to a lesser extent, gravel. A silty matrix is prevalent in the fine-grained *ravaneti*, while gravel-sized matrix material is dominant in the coarse-grained *ravaneti*.

In *ravaneti* that were created by ancient extraction techniques (i.e., «head man» *ravaneti*), a sandy matrix generally corresponds to 30% of the volume of the deposit. In the modern *ravaneti* (i.e., fine-grained *ravaneti*), the matrix content reaches 40%-50% of the deposit volume, and it is equally composed of sand and silt. At several sites, running water tends to wash out the matrix from the superficial layers of *ravaneti* and generates accumulations of fine material at the bottom of the deposits.

In the Pescina-Boccanaglia basin, the *ravaneti* are predominantly fine-grained, locally-weathered, and grass-covered.

In the Torano basin, *ravaneti* are predominantly fine-grained and matrix-supported. They are locally clast supported with a clast maximum diameter between 10 and 30 cm. In the uppermost tract, the basin bottom is completely

invaded by *ravaneti* and small lenses of fluvial deposits outcrops in the lower valley.

In the upper Miseglia basin, *ravaneti* have a prevalent fine grain size clast. «Head man» *ravaneti* are common, whereas coarse-grained deposits are sporadic and concentrated in small areas. Moderate surface weathering and vegetation cover is observed in most of the deposits. In the lower part of the basin, fine-grained and «head man» *ravaneti* were found in equal proportion. The *ravaneti* of Calocara are an example of how the temporal sequence of the excavation techniques can generate a composite deposit of waste materials. Indeed, the western *ravaneto* is made up of fine-grained deposit, neither weathered nor vegetated, with limited accumulations of clasts ranging from 30 to 50 cm in maximum diameter. Conversely, the latter become prevalent in the eastern *ravaneto*, associated with large areas of clast with 10 to 30 cm maximum diameter. In both *ravaneti*, clasts with > 50 cm of maximum diameter are minimally mapped in the apical and peripheral areas.

In the Colonnata basin, the medium, coarse-grained *ravaneti* are prevalent in the upper valley, whereas those that are fine-grained are in the lower sectors. The system of *ravaneti* of Cima Gioia, in the southeast of the Colonnata basin, shows a high grain-size complexity, composed of almost all varieties of the types of deposits described in the marble basins.

In addition to these classes of *ravaneti*, some remnants of archaeological deposits related to ancient extraction activities were found in the Carrara marble basin (fig. 8). These remnants were buried by more recent *ravaneti*. The earliest and deepest debris layers belong to the pre-Roman and Roman ages and are made up of flat pebbles with an



FIG. 8 - Roman quarries with details of festooned carving traces (a) and cutting groove (b) (Fossacava area, Colonnata basin). Buried soils separating a flat-pebbles open work *ravaneto* man-hand produced in Roman period from a 19th century coarse-grained *ravaneto* (c) (Miseglia basin). Finding of semi-manufactured marble block in Roman *ravaneto* (d).

open-work structure. This manually produced debris is associated with very distinctive excavation cutting traces (*caesurae* in Latin) (fig. 8a and b), as witnessed in several archaeological sites, some of which were discovered during this study (e.g., black, broken columns on the map identify the Roman quarries). The location of old dump deposits related to buried soils is identified on the map with asterisks (fig. 8c). At Fossa Carbonera and at Gioia, a paleosoil predating the Roman exploitation covers older, manually-produced debris related to pre-Roman marble exploitation (Bruschi & alii, 2003 and 2004). Several sites have supplied archaeological finds from the Roman period. Semi-manufactured marble blocks, columns, capitals, and iron tools are common findings (fig. 8d), whereas pottery remains are scarce. Semi-processed/unfinished marble products sometimes have carved incisions (*notae lapidicinae* in Latin) (Paribeni & alii, 2003). Medieval-to-Renaissance *ravaneti* are locally documented on top of Roman dump deposits, burying a level of post-Roman soil. Old dump deposits have been discovered in vertical sections during the previous decade, after the onset of the *ravaneti* excavation for debris-recovering purposes. Next in the sequence of the layers, the coarse-grained *ravaneti* with scarce matrix typical of the beginning of the 20th century are a prelude to the recent covering by modern *ravaneti* (fig. 8c and d). The locations of buried soils with a clear stratification of the quarry dump deposits are identified on the map and the model with asterisks.

Landforms and deposits due to superficial running waters

Debris flows are the most important phenomena occurring in the Carrara marble basins because of their fre-

quency and the risk that they pose for the workers and the quarry facilities. Debris flows have developed exclusively on the *ravaneti* and have frequently destroyed the access road to the quarries and blocked the main roads connecting the villages within the basins (fig. 9a). A mechanism for debris flow initiation and development was reported by Baroni & alii (2000 and 2001). The initiation zone for debris flows frequently corresponds to the margin of a horizontal plane, corresponding to a quarry floor or road cuttings. Inspection of vertical sections in the source area of the recent debris flows indicates that the mobilization processes only involve the surface layers of the *ravaneti*, where the fine material is abundant. Moreover, the surface of basal sliding frequently corresponds to the contact between a fine layer and a coarse layer, generally at a depth ranging between 2-5 m. In many cases, the contact between these two layers matches the overlapping of fine-grained and coarse-grained *ravaneti*. These characteristics indicate that the debris flows begin as planar debris-slides and that the moving masses quickly diminish in consistency, becoming debris flows that travel in an erosive channel. A soil contraction mechanism can be invoked to explain why the mass consistency decreases (Ellen & Fleming 1987; Iverson et al 1997). Eventually, the lateral inflows generated by collapses on channel sides progressively increase the volume of the moving mass, enhancing the erosive power of the channel bed. Corresponding with the channel feeding repeated debris flows, the effects of small lateral debris-flow events were observed. In some areas, they draw a debris flow system involving a large sector of the slope.

Finally, in the depositional zone, well-defined levees and lobes were observed, with deposit volumes ranging between 15 and 100 m³ (fig. 9a). The most important (i.e., long-last-

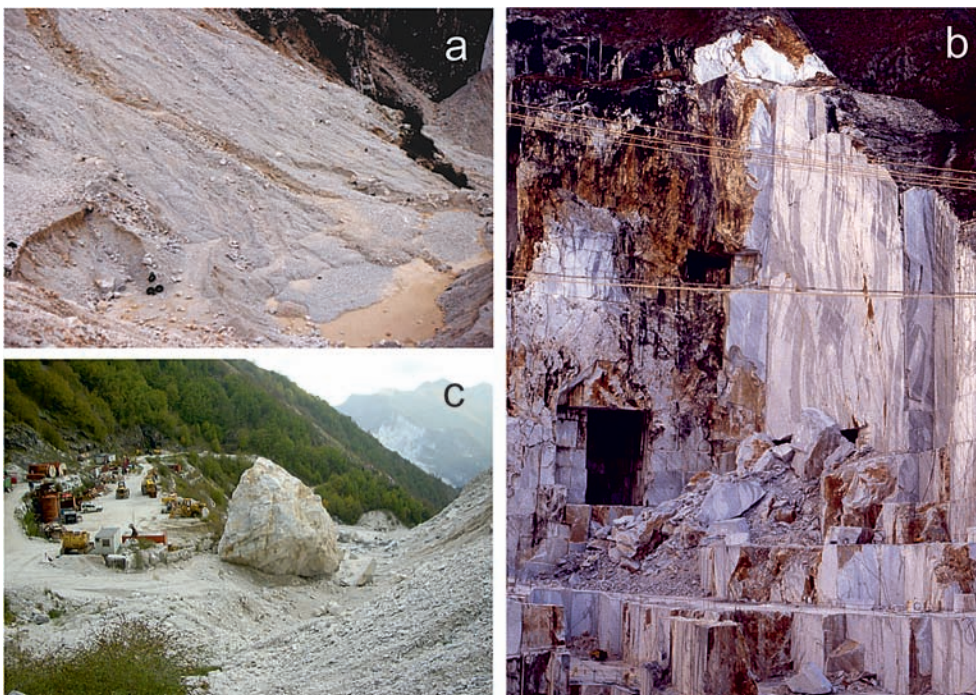


FIG. 9 - Debris flow channel and depositional lobes developed in fine-grained matrix supported *ravaneti* (a) (Fantiscritti area, Mieseglia basin). Complex landslide (slide and rockfall) detached from a vertical quarry front densely fractured (b) (Colonnata basin). Big boulder fallen in a quarry yard (c) (Colonnata basin).

ing and $> 80\text{-}100\text{ m}^3$) debris-flow lobes are reported on the map, whereas levees were too small and ephemeral to be represented. The lobes are primarily matrix-supported, whereas a clast-supported structure is evident only in the largest deposits. When the fabric is well developed, clast orientation in the depositional lobe is consistent with flow-line directions of the final phases of flow (Baroni & alii, 2000).

A prevalent fine-grained debris flow in the *ravaneti* matrix support is evident from the map, even though we must consider that many of the morphological elements of these phenomena are ephemeral and are rapidly removed by surface erosion or by quarry personnel to allow for the continuation of extraction activities.

In the Colonnata basin, the debris flows reach their maximum occurrence, especially in the mid-lower part of the basin, where *ravaneti* are dominantly fine and matrix-supported. Among the other flows, the most evident are those developing along the eastern slopes of M. Serrone and Campanile. In these cases, debris-flow initiation is related to the margins of active or abandoned access roads cross-cutting the *ravaneti*. Locally, the debris flow lobes often bury the main road in the valley bottom, causing temporary interruption of travel.

Analogously, the debris flow occurring in the M. Betogli *ravaneti* started from the slope-cut represented by the access road and involved fine, matrix-supported deposits.

Landforms and deposits due to gravity

Recently, landslides have occurred in the marble basins (fig. 9b), and many have represented a severe risk for the workers and the industrial installations (fig. 9c). There were two victims from recent landslides. The most relevant landslides were noted on the map: the Canalgrande landslide ($30,000\text{ m}^3$, 27.12.97) and the Lorano landslide ($80,000\text{ m}^3$, 7.11.97).

The landslides were all initiated in the topmost part of the vertical front of quarries or near the uppermost limit of the excavated area (fig. 9b). The progressive marble extraction causes a parallel retreat of the vertical quarry front up to the outcropping of a rock whose quality is unsuitable for commercial use, because it is densely fractured. The excavation at the base of the quarry front to exploit a marble outcrop of higher quality increases the base-to-top elevation range up to 50-70 m. The sub-vertical residual slopes are highly prone to trigger landslides. The kinematic analysis of landslides showed additional potential mechanic behavior: i) slide of prisms generated by the intersection of fracture systems, ii) toppling of the uppermost part of the rock face, and iii) structural collapse of a rock mass intensely fractured with sliding vertical and sub-circular surfaces forming a stepped slope (Baroni & alii, 2001).



FIG. 10 - Model of the Carrara marble basins (available on request to Litografia Artistica Cartografica, LAC).

FINAL REMARKS

In this study, we created a geomorphological map and a raised relief model (fig. 10) depicting the anthropogenic landforms and deposits in the marble basins of Carrara, which is one of the most exploited mining areas in the world and has been active since the 1st millennium BC.

The data reported in these cartographic products are relevant for two main reasons: the source of risk, and the geological-cultural archive represented by the anthropogenic landforms and deposits in the quarry basins of Carrara.

The data from the systematic survey confirm that the instability of *ravaneti* is the main source of risk in the area. The geomorphological map shows that debris flows mostly occur in the fine-grained and matrix-supported *ravaneti* and that the initiation areas frequently correspond to the margins of access roads and quarry yards. Debris flows were also mapped in coarse-grained *ravaneti*; however, the presence of fine matrix triggered these phenomena. Hence, we confirmed that debris-flow occurrence is strictly linked to the concentration of the fine fraction matrix in the *ravaneti* that is introduced by the modern techniques of marble cutting, principally by the activities associated with recovery of yield materials by means of sieving. The fine matrix introduced into *ravaneti* deposits is easily saturated during the intense and prolonged rainfalls that are frequent in these areas of the Apuane Alps, triggering debris flows. For these reasons, the fine fractions that are derived from yield material reworking are no longer allowed to be introduced into *ravaneti*, thereby reducing the risk in some areas that are particularly affected by these phenomena.

Furthermore, the parallel retreat of excavation fronts and the progressive lowering of the quarry yards to search for marble of high commercial quality in the past has led to the formation of residual vertical slopes sculptured in rocks of poor geomechanical quality that are highly prone to trigger landslides.

In addition to the remnants of Roman and pre-Roman quarries reported on the map, the deposits generated by the extraction activities are a geological archive that records the time-succession of extraction techniques. Grain size, clast shape, and the nature of the fine matrix can be associated with the techniques of marble cutting. In the vertical section, it is possible to recognize the overlapping of pre-Roman, Roman, Medieval, Renaissance, 19th century, and modern *ravaneti*. The overlap of these stratigraphic units is locally marked by paleosoils that indicate a pause in the activities of the quarry responsible for dump deposit production.

Finally, we believe that geomorphological mapping of anthropogenic landforms in an extractive environment may offer the opportunity to reconstruct the technological development of an industrial context, strictly linked to relevant cultural events, such as the introduction of gun powder and compressed air devices, the advent of new materials (e.g., synthetic diamonds for cutting with helicoidal wire or chain cutter), and new recycling processes of yield materials in favor of modern industrial processes.

Additionally, we believe that this type of cartography, by means of the overlapping of natural and anthropogenic landforms, allows for the evaluation of the technological developments in excavation activities that could generate situations of geomorphological risk. Thereby, the geomorphological map is a fundamental document for producing maps of risk-prone areas in the Carrara marble basins.

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GEOMORPHOLOGICAL MAP OF THE CARRARA MARBLE BASINS (Apuan Alps, Tuscany, Italy)

CARTA GEOMORFOLOGICA DEI BACINI MARMIFERI DI CARRARA (Alpi Apuane, Toscana)

Carlo Baroni¹, Paolo Mannucci¹, Giuseppe Bruschi², Adriano Ribolini¹

Scale 1:10000 - Scala

Digital cartographic representation and printing by: Allestimento cartografico digitale e stampa:

LITOGRAFIA artistica CARTOGRAFICA - FIRENZE - 2010

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Landforms and deposits due to gravity

- Forme e depositi originati alla gravità
Erosional landforms
Forme di erosione
Active/Inactive
Scarp, Nichia di frana, Edge of degradation scarp, etc.

Landforms and deposits

- Forme di accumulo e relativi depositi
Active/Inactive
Rotational landslide, Complex landslide, Slope debris, etc.

Landforms and deposits due to superficial running water

- Forme e depositi originati dallo scorrimento delle acque superficiali
Erosional landforms
Forme di erosione
Active/Inactive
Debris flow track, Gully, etc.

Landforms and deposits

- Forme di accumulo e relativi depositi
Active/Inactive
Debris flow lobe, Alluvial deposits, etc.

Crio-nivation landforms

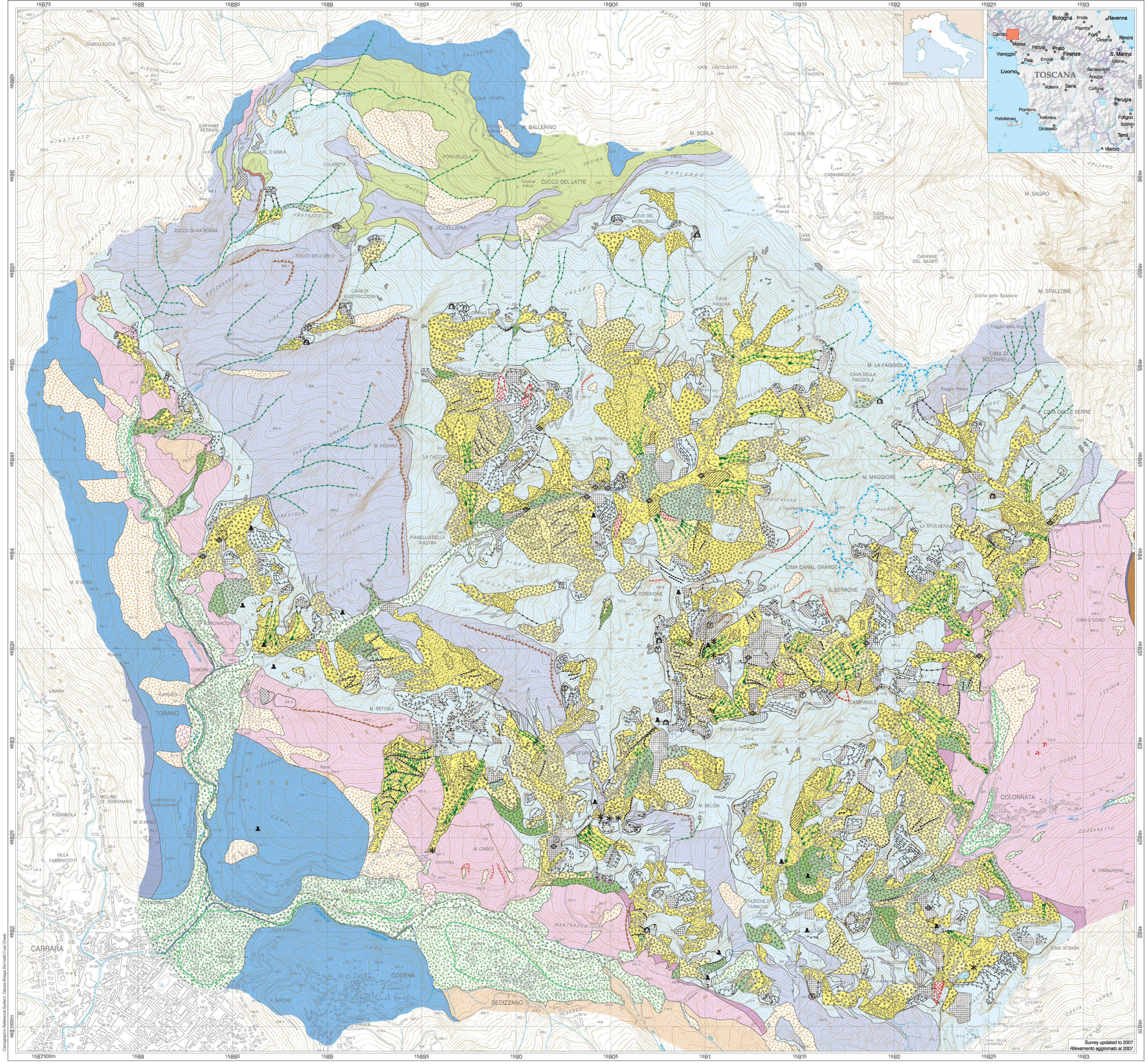
- Forme criovalanti
Active/Inactive
Nivation hollow, etc.

Man made landforms and deposits

- Forme e depositi di origine antropica
Erosional landforms
Forme di erosione
Active/Inactive
Quarry front, Exploitation limit, etc.



Cava Gioia (Colonnata Basin)
The marble extraction spreads over a number of fronts that have affected Cava Gioia. Access roads run on dump deposits and reach several active quarry fronts (May 30, 2003).



Constructional landforms and deposits
Forme di accumulo e di costruzione
Quarry dump deposits
Reveted
Texture:
Classi supporti, Matrix supported, Supporto classico, etc.

Roads and working plants
Visibilità ed impianti di lavorazione
Active/Inactive
Access road, Artificial stoneblock run, etc.

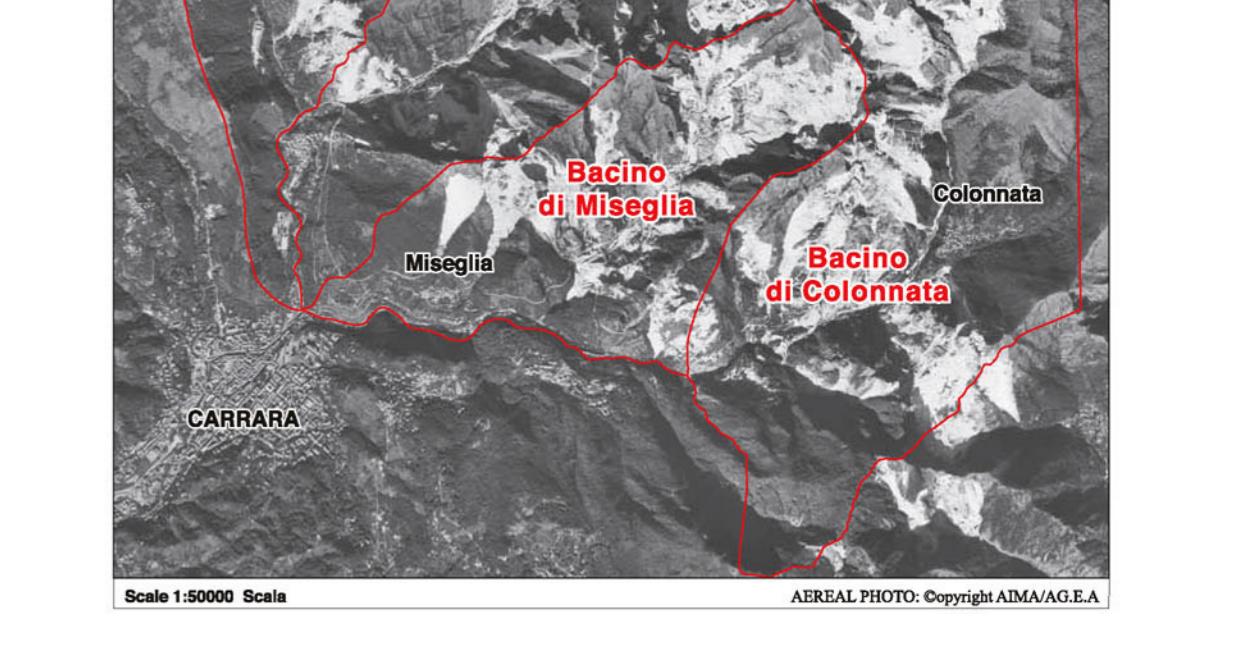
Structural landforms
Forme strutturali
Saddle, Scarp, Monoclinical top edge, etc.

Geological - structural elements
Elementi geologico-strutturali
Anchimetamorphic formations of Tuscan nappes
Formazioni anchimetamorfiche della "Falda Toscana"

Epimetamorphic formations of Massa Unit
Formazioni epimetamorfiche dell' "Unità di Massa"

Epimetamorphic formations of autochthonous
Formazioni epimetamorfiche dell' "Autoctono" Auct.

Palaeozoic bedrock
Basamento paleozoico
Lower Phyllites (Cambrian-Ordovician), etc.



Quarry area near Trugliano (Colonnata Basin)
Two sub-vertical cliffs result from the superposition of inactive quarry fronts; the marble extraction occurs on three active fronts that divide the quarry yard (May 1, 2003).



Steep stoneblock run near Fantocelli
Series of retaining walls on "head man" size cobbles are visible on the top of the stoneblock run. Weathered quarry dumps with visible marble are used for the stoneblock run, from the ancient quarry of the Ravaccone Basin (May 18, 2006).



Overview of the Ravaccone area in the Torano Basin (from Campocecina)
The quarries of Cava Caravignolo (on the left) and weathered quarry dumps (gray in the picture), Active quarry dumps (light gray in the picture), on the right developed from the quarries of Betogli. Micromarble picked out the marble is used for the stoneblock run, from the ancient quarry of the Ravaccone Basin (May 18, 2006).



Quarry dump at "Porti di Vena"
The quarry creates dump deposits with fine texture cut by debris-flow channels. Several debris-flow lobes are deposited at the bottom of the quarry dump deposit (November 11, 2008).



Overview of the quarry area near Lorenzo
Active and inactive quarry fronts, access roads, and dump deposits with different classes of texture and degrees of weathering developed all over the area. Dumping channel tracks arise from the quarry yards. Debris flow channels and lobes are observed in the upper right of the photograph (May 30, 2003).



Panoramic overview of Cava presso Lorenzo
Si notano fronti di lavorazione attivi e inattivi, strade d'accesso e canali di drenaggio con diverse classi di tessitura e grado di alterazione. Canali di drenaggio si sviluppano dal piazzale di cava; canali di sbo di ottone flow si osservano in alto a destra (20 Maggio 2003).