

Multidisciplinary approach in the study of marble quarries in the Apuan Alps

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ABSTRACT

The Apuan Alps (Northern Tuscany, Italy) represent the world's most important marble mining area, with historical significance and particular geomechanical rocks properties. A detailed knowledge of existing marble rock volumes is required in proper planning and management of mining activities. The aim of this study is the 3D reconstruction of marble formation, taking into consideration the polyphasic deformation history of the Apuan Alps. This goal is pursued through a multidisciplinary approach: geological mapping is integrated with the most modern photogrammetric, GIS (Geographic Information System) and 3D modeling technologies. The project is carried out in different work-stages: i) aerial photo-interpretation; ii) geological field-survey; iii) revision and integration with new data of the existent geological maps; iv) creation of three-dimensional model of marble ore. The photo-interpretation phase is carried out in 3D by means of ESRI™ ArcGIS Pro 1.4 suite with the support of DTMs (Digital Terrain Models) and orthophotos at high spatial resolution (up to 5 cm ground pixel); then, through detailed geological mapping, critical data collected in the previous phase is verified. The integration of previous activities leads to the updating and correction of the currently available geological maps and leads to the production of serial geological cross-sections necessary for the creation of 3D models related to both surface and underground geology. Models have been built within Rhinoceros 5.0®code. Final aim of present work is the calculation of marble formation volumes in some defined areas, with a view to proper manage the resource, as well as to plan the mining activities.

KEY WORDS: Apuan Alps, GIS, 3D Modeling, marble quarries, structural geology.

INTRODUCTION

Apuan Alps are known as the world largest marble mining basin, both for the number of active quarries, estimated at about 140, and for the historical significance of the stone resource. Marble needs proper management, through extraction plans that valorize the ornamental stone chain and, at the same time, guarantee environmental sustainability. For this purpose, it is necessary to define the potential of extractive basins in the Apuan Marble District through a multidisciplinary approach combining photo-interpretation with modern photogrammetry techniques, geological mapping and three-dimensional modeling. Aims of this project are updating the existing geological

cartography as well as estimating of marbles formations volume that, according to the PIT (*Piano di Indirizzo Territoriale*) of the Tuscany Region, is included inside the perimeter of the ACC (*Area Contigua di Cava*) in the Apuan Alps Regional Park.

GEOLOGICAL SETTING

The northern Apennines are a fold and thrust belt, formed during the Tertiary era, due to the emplacement from W to E (in present-day coordinates) of the Ligurian Units on the Tuscan and Umbrian-Marchigian domains (Carmignani & Kligfield, 1990). Apuan Alps are the most important tectonic window in the internal part of the northern Apennine, in which some of the deeper structural levels of the whole belt crop out. In this area, it is possible to observe both the deeper metamorphic units of the belt ("Massa Units" and "Autoctono" *Auct.*) as well as the uppermost tectonic units, represented, from top to bottom, by Ligurian *s.l.* and Sub-Ligurian Units, and by the Tuscan Nappe (Fig. 1). The litho-stratigraphic sequence comprises a Paleozoic basement overlain unconformably by an upper Triassic-Oligocene meta-sedimentary sequence. The Mesozoic cover rocks consist of thin Triassic continental to shallow water Verrucano-like deposits, followed by Upper Triassic-Liassic carbonate platform meta-sediments that include dolomites, called "Grezzoni", dolomitic marbles and marbles. These are overlain by upper Liassic-Lower Cretaceous cherty meta-lime-stone, cherts and calcschists, with marble interlayers, which are related to deep-water sedimentation during drowning of the former carbonate platform. Oligocene sedimentation of turbiditic sandstone, called "Pseudomacigno", completes the sedimentary history of the domain "Autoctono" *Auct.* Marbles quarried in the Apuan Alps, are not limited to the Jurassic marble worldwide known as "Carrara Marbles", but correspond to different stratigraphic horizons of the metamorphic units, from Triassic and Lower Jurassic formations.

The regional tectonic setting of the Apuan Alps Metamorphic Complex is the result of two main tectono-

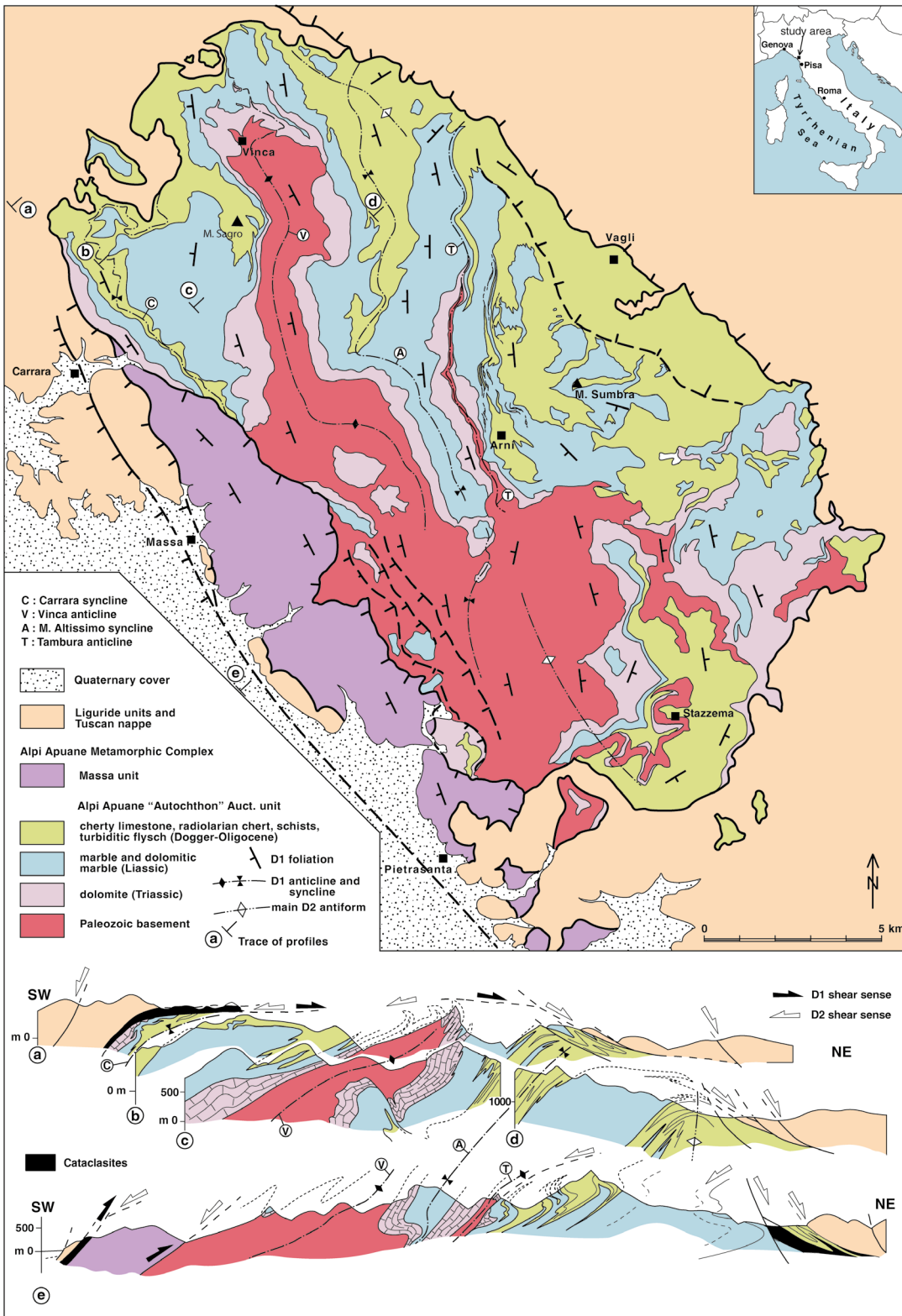


Fig. 1 - Geological sketch map of Apuan Alps Methamorphic Complex with composite cross sections (modified after Conti et al., 2004).

metamorphic events (D1 and D2 phases according to Carmignani & Kligfield, 1990). The ductile compressional D1 event is associated with the thrusting and emplacement of non-metamorphic upper tectonic units, developing isoclinal, strongly non-cylindrical, recumbent folds in the "Autoctono" Auct. Unit; at this stage is the development of an axial plane foliation that transposes the bedding and any

earlier features. This foliation, which characterizes most of the metamorphic rocks of the Apuan Alps, is associated with a stretching lineation SW-NE trending, interpreted as the main transport direction of the inner Northern Apennines (Molli, 2008; Vanneschi et al., 2014). During D2 event, the previous isoclinal structures are transposed with the formation of various non-cylindrical parasitic

folks, with crenulation cleavage and sub-horizontal axial planes. Recently, a third deformative phase, named D3, has been recognized (Conti et al., unpublished) with associated direct shear zone and high and low angle faults.

METHODS

In order to support and encourage a proper scheduling and planning of mining activities for future years, the procedure used in this work can be summarized in two main phases:

- Photo-interpretation and updating of geological cartography (through detailed geological field activities);
- Three-dimensional modelling and estimation of marble volumes.

The first phase of digital photo-interpretation is aimed at the recognition of geological structures that characterize the study areas.

This is possible thanks to ESRI™ ArcGIS Pro software (version 1.4) that allows two-dimensional and three-dimensional viewing of survey areas by using DTMs and high resolution orthophotos; it is noted that DTMs represent the elevation surfaces on which the orthorectified images are overlaid.

This paper considers the study of the “Apuan Marbles” Formation within a specific ACC of the Apuan Alps Regional Park. ACC, as defined in the Tuscany Region regulation, are sites inside the Apuan Alps Regional Park with geodetic borders, where the marble excavation is allowed.

Data used to perform photo-interpretation are:

- DTM, with 1x1 meter spatial resolution, created from available aerial LiDAR (*Light Detection And Ranging*) 3D point clouds made available by Tuscany Region;
- high resolution (50 cm/pixel) and very high resolution (20 cm/pixel) orthophotos in natural colors made available by Tuscany Region;
- orthophotos and DSMs (Digital Surface Models) with a higher spatial resolution (5 cm/pixel and 50 cm/pixel respectively) related to areas not adequately covered by the Tuscany Region orthophotos and properly produced by aero-photogrammetric surveys conducted with an experimental ultralight aircraft called “*Radgyro*”, supplied by the “*Centro di GeoTecnologie*” of Siena University and its Spin-off.

The software Agisoft™ PhotoScan Professional version 1.2.5 (Agisoft, 2016) is used to process the images obtained from the “*Radgyro*” aero-photogrammetric surveys. This software is capable of solving the camera interior and exterior orientation parameters and generating georeferenced spatial data such as 3D point clouds, DSMs and orthophotos. The first processing step has consisted of image alignment, through which the interior and relative orientation parameters have been solved. In order to improve the whole alignment process and to obtain low re-projection error, millions of tie points have been automatically extracted without setting a point limit. Following image alignment, the second processing step has involved georeferencing of the 3D model in such a way as to

solve the exterior orientation parameters by using the GCPs coordinates collected from the available topographic maps at a scale of 1: 2,000. Subsequently, the ‘optimize’ tool has been utilized to adjust the estimated camera positions and to remove possible non-linear deformations, minimizing the errors due to re-projection and misalignment of the photos. Moreover, the optimization has been improved by deleting all the tie points with a re-projection error greater than 1 pixel.

In a subsequent step, the dense 3D point clouds have been generated with medium quality and aggressive depth filtering settings. Automatic classification of clouds, aimed to remove infrastructure and vegetation, has been unnecessary since there is no need for DTM creation. In fact, DSMs in form of polygonal 3D meshes have been created from the point clouds and used to produce the high-resolution orthophotos of the area. The orthophotos have image distortions removed due to camera characteristics (i.e. lens distortions), camera tilt and topographic relief displacement. Unlike an uncorrected aerial photograph with a perspective projection, an orthophoto is geometrically corrected (“orthorectified”) and can be used to measure true distances since it is “scale-corrected”. The corrected orthophotos, with a spatial resolution of 5 cm/pixel, have been then projected in the Italian National Gauss Boaga system and imported together with the DSMs within ESRI™ ArcGIS Pro software for the photo-interpretation.

The combined use of DTMs, DSMs and orthophotos with such a high degree of detail favors the extremely precise recognition of the main brittle and ductile geological structures (Fig. 2).

The geological data collected in ArcGIS Pro project have been integrated with detailed geological survey, in order to verify critical issues identified in the first phase and, secondly, to update the existing geological maps (i.e. *Carta Geologico-Strutturale del Complesso Metamorfico delle Alpi Apuane*, Foglio Nord, Carmignani et al., 1985; *Carta giacimentologica dei marmi delle Alpi Apuane*, A.A.V.V., 2007; *Carta Geologica del Parco delle Alpi Apuane*, Carmignani et al., 2000). The existing geological data is affected by several errors related to past interpretations and the lack of a series of brittle structural data. The field activities have been carried out with support of a rugged tablet in which the original ESRI™ ArcGIS Pro project is upload converted in an ESRI™ ArcMap project. The use of high-resolution orthophotos helps the geological surveys and often allows finding geological structures in the field after their identification in the photo-interpretation step. The geological survey is focused on confirming the elements identified in the photo-interpretation and on the acquisition of new data inside the ACC.

In the second phase the new improved geological maps have become the starting point for the 3D modelling process, which has been done in more detail by using in parallel two different software: ESRI™ ArcGIS Pro (version 1.4) and Rhinoceros 3D™ (version 5.0).

Both procedures follow three main steps:

- Construction of geological cross sections in raster format and visualization in 3D environment;
- Digitalization of the main geological contacts and production of surfaces;
- Reconstruction and estimation of extractable marble volumes.

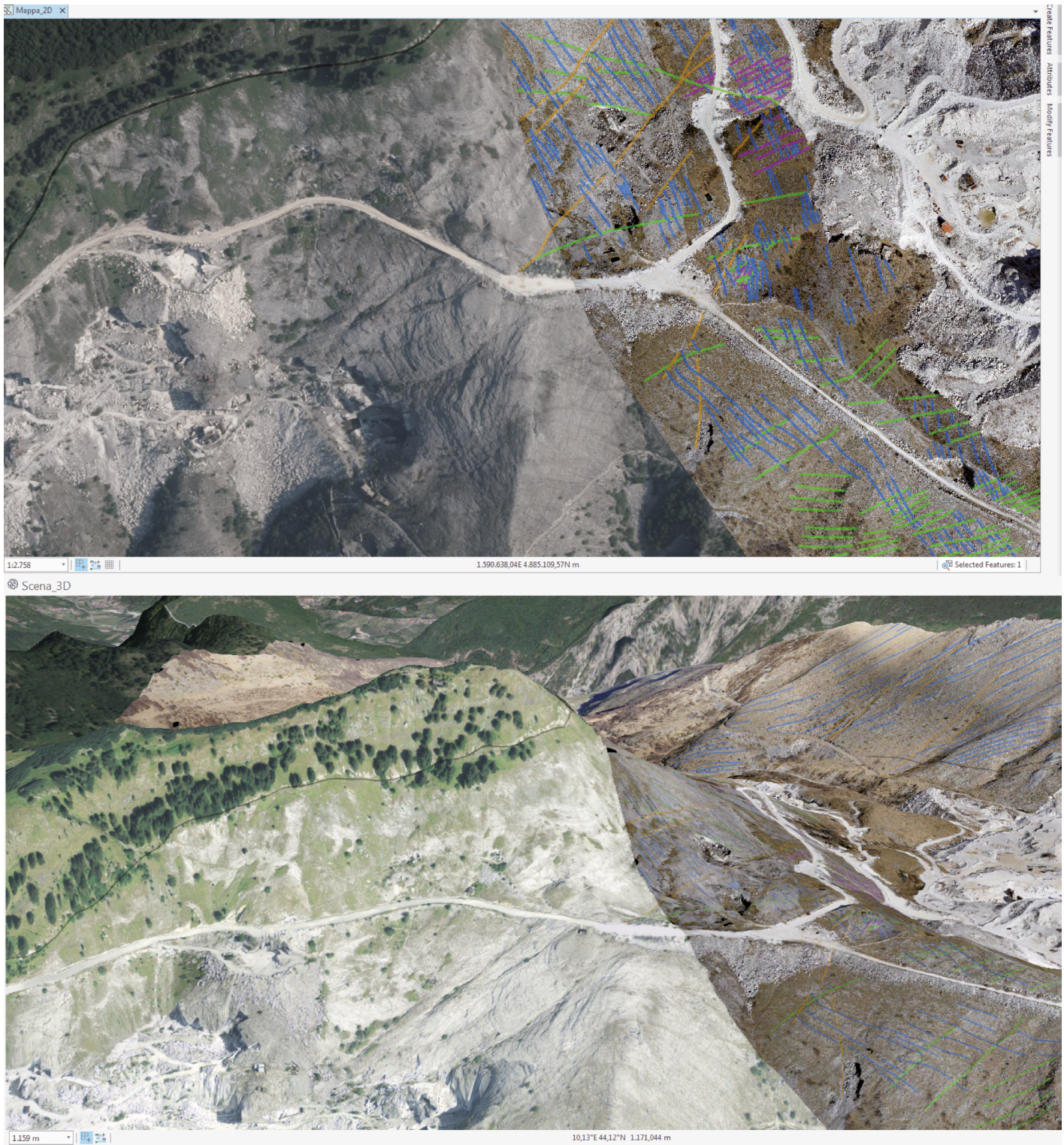


Fig. 2 -Photo-interpretation in ESRI™ ArcGis Pro: 2D view at the top and 3D view at the bottom.

In order to draw the geological cross sections, the geological map of the Tuscany Region at scale of 1:10,000 (*"Continuum geologico della Regione Toscana"*, Regione Toscana - Università di Siena, Centro di Geotecnologie, 2011) has been used as support after the integration with new data collected during field activities and aerial photo-interpretation.

Finally, an additional statistical study on the trend of the main structural elements of the area has been conducted by using Stereo32 software that has allowed choosing the orientation of the cross sections towards the North. The aim of the statistical study is the definition of homogenous area with a defined trend of the main foliation. In order to describe the geometry of the marble resource in a complete

manner, the geological cross sections have been oriented orthogonally to the main foliation strike or the bending axis (Fig. 3a). Geological cross sections have been drawn, at a scale of 1:5,000, by using Adobe™ Illustrator CS5 software, from georeferenced topographic profiles created with ESRI™ ArcMap tools. Every produced geological cross section has been imported in a 3D environment, (Fig. 3 b, c) and used as basis for drawing top and bottom contacts of the “Apuan Marbles” Formation.

The second step of 3D modelling is the construction of the model skeleton, based on the geological cross sections. Starting point of the process is the selection of the topographic surface to be used in model building. Within Rhinoceros 3D™ the process of construction is less articulated than in ESRI™ ArcGIS Pro: the first step is the creation of the cross-section traces, starting from the CTR (*Carta Tecnica Regionale*) and the definition of the C plane (as called in Rhinoceros 3D™) origin of the Cartesian coordinate system. The second step consists in importing, in the project, the cross-sections scaled with the cross-section traces and then drawing the contacts in each section. In ESRI™ ArcGIS Pro vertical plans, in the zones where the geological cross section are attached, are created as multipatches from the imported traces. After that in both methods, with ESRI™ ArcGIS Pro and Rhinoceros 3D™, the geological contacts between the formations of interest are drawn and, subsequently, the surfaces automatically generated. In particular, the format used to represent the surfaces is different: TIN-type (*Triangulated Irregular Network*) in ESRI™ ArcGIS Pro and NURBS type (*Not Uniform Rational Basis-Splines*) in Rhinoceros™. To complete the structure of the model, it has been necessary to produce a base area and an upper surface to delimit the model in space. The base area has been produced, with both software, starting from a horizontal plan re-built to an altitude chosen basing on specific factors in each of the analyzed contexts (e.g. current underground storage limits, accessibility, stability, etc). The top surface has been produced from DTMs: ESRI™ ArcGIS Pro has produced a TIN surface from the LiDAR 3D point

clouds, while Rhinoceros generated a NURBS DTM surface. The 3D model obtained at this point is based on the volume of the drawn geological cross-sections.

The final step has been the calculation of marble volumes from the created 3D surfaces. ESRI™ ArcGIS Pro automatically extrudes the surfaces interposed between the TINs of interest generating a block with a multi-patch geometry; the estimation of volumes, in cubic meters, is automatically performed on the created solid.

In Rhinoceros 3D™, it is possible to perform multiple intersections and trims between NURBS surfaces to fine-tune and close the volume of material with a closed poly-surface (Fig. 4).

The last step, before the estimation of marbles volume, consists in intersecting all the surfaces and volumes created with the vertically-extruded boundary of the ACC border; thus, producing a closed poly-surface, the volume estimation is possible by means of specific calculation tool.

DISCUSSION AND CONCLUSIONS

Results obtained at the end of the described procedures and methodologies, have allowed the comparison with traditional geological survey techniques for the review of existing geological maps as well as the estimation of the extractable marble volumes within the ACC of the Apuan Alps Regional Park. The use of high-resolution spatial data, implemented within Esri™ ArcGIS Pro, has allowed a turning point inside the photo-interpretation activities. This software, in fact, is not the first suite offering such new features (e.g. Esri™ ArcGlobe), but it is resulted extremely stable and flexible for viewing and digitizing, both in two and three dimensions, as well as for realizing reliable geological models and for their volume estimation. The use of this software, in all the phases of this work, has revealed many advantages: the marble volumes analyzed and modeled in GIS environment can be easily

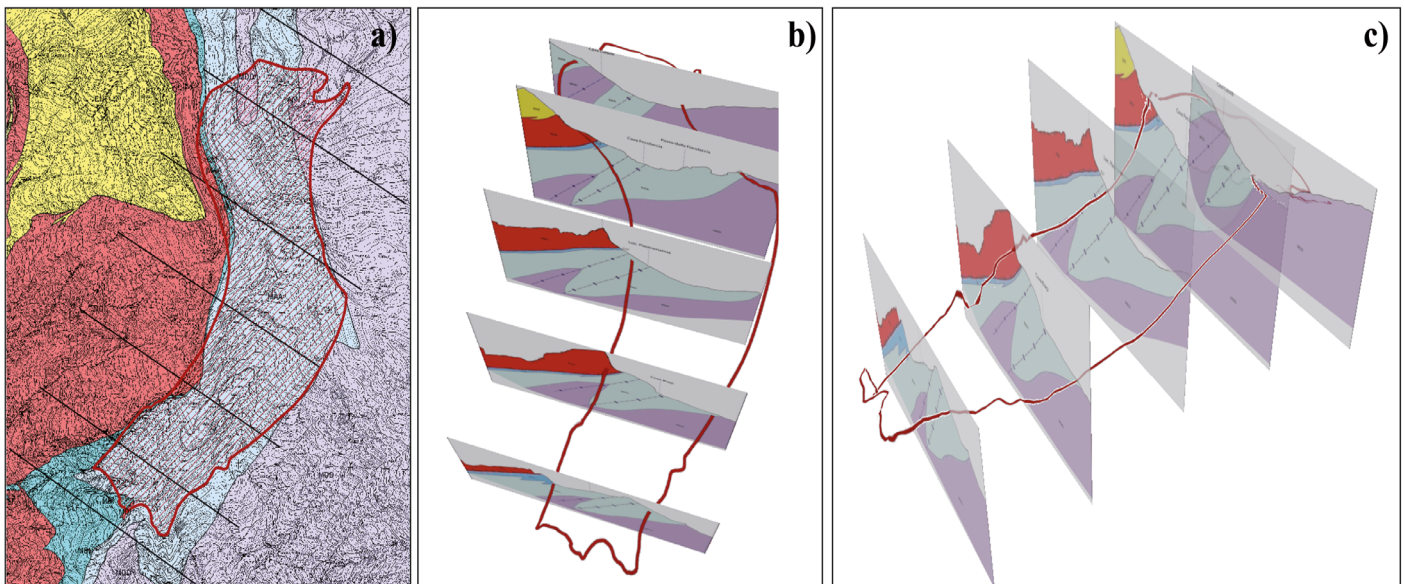
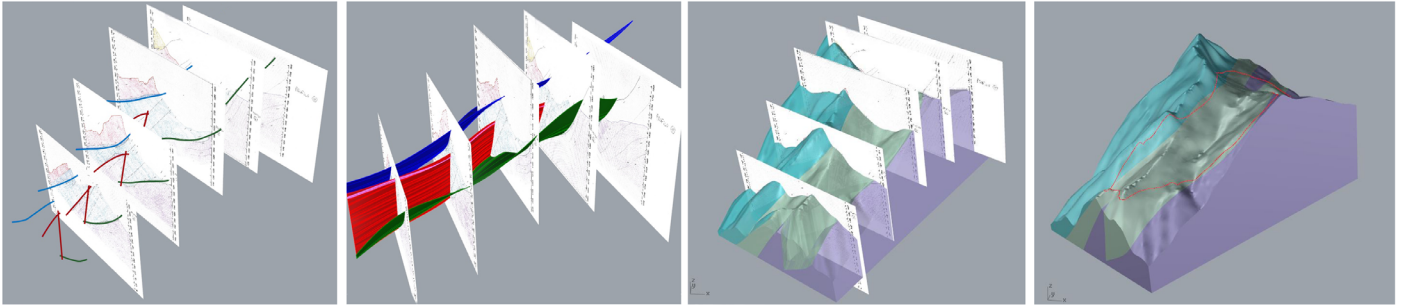


Fig. 3 - Production of geological sections in raster format and visualization in 3D environment.

3D Modeling - Rhinoceros 5.0



3D Modeling - ArcGIS Pro 1.4

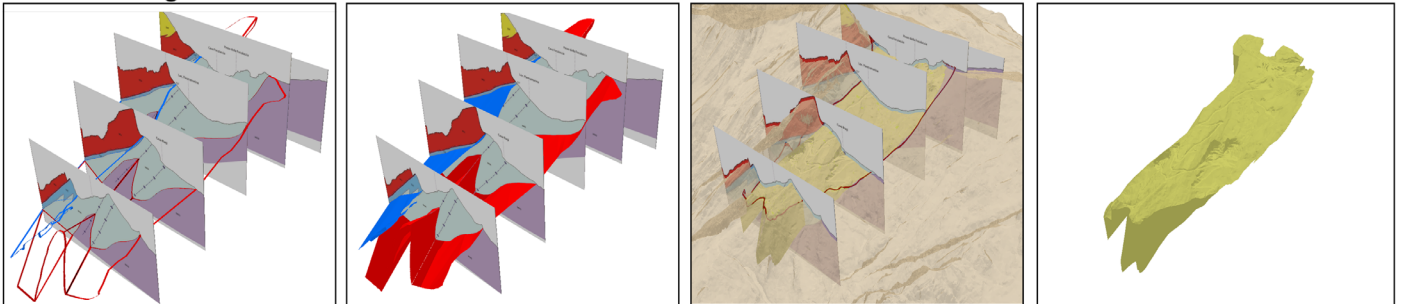


Fig. 4 - Steps of two different 3D modeling based on Rhinoceros and ArcGIS Pro software.

contextualized within the area of interest because they are immediately super-imposed on any spatially georeferenced territorial entity. This has proved to be an efficient decision support tool for mining activities with the least possible environmental impact. For instance, it is possible to overlap the constraint that restricts marble extraction within the ACC and, through critical analysis, to propose variants if such limitations are not adequate. Another advantage of modeling within the GIS environment, if compared with Rhinoceros3D™ software, is the easy management of high-resolution data, such as DTMs, DSMs and orthophotos, and the high detailed obtained by modeling the topographic surface. On the other hand, Esri™ ArcGIS Pro has shown some difficulties and critical issues in the realization of three-dimensional models: for example, TIN surfaces are more difficult to modify in respect of NURBS. To solve this problem, in Esri™ ArcGIS Pro the structure of complex volume has been divided in small part with simple geometry. Moreover Esri™ ArcGIS Pro makes processing difficult even for powerful computers because of the large requirement for memory and high-end video cards.

The three-dimensional modeling tools provided by Rhinoceros 3D™ make the construction of surfaces easier and more suitable in respect to the final volume estimation; NURBS surfaces are better than TIN because they allow the representation of very complex surfaces with important advantages such as greater control, good celerity and easier management of the operations. However, DTMs surface drawn by NURBS involved a loss of detail unlike Esri™ ArcGIS Pro. At the end, the final model of ACC obtained by Rhinoceros™, is considered acceptable for the project aims. The problem that occurs in the use of this second software is the need of working with different suite designs for the final model, which can lead to several errors; for example, even if the imported and exported data within

Rhinoceros 3D™ maintain the absolute coordinates, some troubles in the georeferencing step of geological sections must be considered. Further problems arise for comparing geological 3D models with the original geological maps and additional georeferencing information.

Finally, if comparing the marble volumes achieved by the two described modeling procedures, the obtained values are very similar and, therefore, in respect to accuracy, both methodologies can be considered adequate. Both have strengths and weaknesses that will be evaluated based on the ultimate goal pursued. It is also possible to take into consideration other dataset, such as underground information from excavations, terrestrial laser scanner data, etc. In the present paper these datasets were not involved because of their spotted and spatially limited provenience; the only considered elements are karst and caves. The results are not shown in this paper because they are only preliminary and need for further experimentation.

It should be noted that data here presented has to be considered as preliminary results from a work in progress. A definitive framework of optimum methodologies is postponed, while considering that the proposed procedures can support the planning of activities related to the extraction of ornamental stones.

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