EXTREME GIS APPLICATIONS FOR 3D VISUALIZATION AIMED TO GEOLOGICAL AND MINING MODELING

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EXTENDED ABSTRACT

Gli approfondimenti geologici finalizzati alla prospezione mineraria si basano su carte geologiche, rilievi di superficie e dati di sottosuolo (indagini geofisiche, sondaggi o gallerie minerarie). Nella prospezione mineraria (sia per l'estrazione di minerali, che per l'utilizzo energetico delle fonti rinnovabili o geotermiche), è importante definire il modello geologico e giacimentologico, identificando le geometrie, i volumi, il contenuto mineralogico, in modo da arrivare alla definizione dell'evoluzione in superficie e in sotterraneo della coltivazione, che tenga conto della presenza e della distribuzione superficiale di eventuali infrastrutture esistenti o in sotterraneo di gallerie ed altri vuoti minerari.

Esistono molti software commerciali in grado di rappresentare in un unico ambiente i dati geologici, della topografia e delle altre infrastrutture in 2D, ma solo pochi prodotti, generalmente molto costosi, permettono di mostrare tutte queste informazioni in un ambiente 3D.

In particolare, se si prendono in esame i software Open Source o ricercando codici a costi accettabili, risulta difficile individuare software in grado di rispondere compiutamente a tutte queste esigenze. Il principale problema è che:

i) i modelli geologici 3D si basano solitamente su pochi dati, se confrontati con l'estensione dell'area di studio, i dati geologici disponibili sono sparsi e un importante processo di interpretazione si rende necessario. In questi casi la visualizzazione 3D agevola l'interpretazione del modello geologico anche se i dati sono scarsi;

ii) i progetti di coltivazione mineraria sono spesso prodotti utilizzando tecniche grafiche di tipo CAD, contraddistinte da una elevata precisione e cura dei particolari, ma con scarsa o nulla possibilità di interpretazione.

Pur rappresentando il medesimo oggetto, la modalità di rappresentazione richiesta nella progettazione CAD si trova all'estremo opposto rispetto alla modellazione geologica 3D: nel primo caso l'interpretazione soggettiva dovrebbe essere ridotta al minimo, mentre nel secondo caso l'interpretazione è massimizzata (vicino ad un "pittorica" rappresentazione del sottosuolo).

Il presente studio mostra come sia possibile risolvere questo tipo di problemi ricorrendo a software GIS, con apposite estensioni 3D, ottenendo buoni risultati ed evidenziando grandi potenziali di sviluppo grazie a 3 casi di studio in contesti geologici ed ambientali completamente differenti ma con i medesimi fini minerari.

Nel primo caso è stato ricostruito il più importante complesso minerario storico relativo all'oro nelle Alpi (ai piedi del Monte Rosa) con lo scopo di quantificare (in termini geometrici e di contenuto di minerale) i livelli coltivati in passato al fine di valutare una possibile riapertura della miniera. Lo studio ha interessato circa 4 km² e circa 40 km di gallerie su quasi 30 livelli. I corpi mineralizzati sono composti da livelli quarzosi post-metamorfici spesso discontinui e con complesse strutture geologiche. Tale disposizione ha in passato costituito un grosso impedimento per lo sviluppo industriale della miniera in quanto la coltivazione di questi livelli è sempre stata effettuate semplicemente seguendoli e l'unica prospezione è consistita in cunicoli esplorativi molto spesso infruttuosi.

Il secondo caso illustrato tratta di una grossa cava di gesso, parte all'aperto parte in sotterraneo ubicata sul lato padano dell'Appennino settentrionale (Vezzano sul Crostolo, RE). Si tratta di un complesso estrattivo storico attivo fino agli anni '90 senza alcun intervento di messa in sicurezza sulla coltivazione articolata in circa 15 livelli. La visualizzazione 3D in questo caso è servita per affinare il progetto di recupero ambientale dell'intera area. Il potenziale dei sistemi GIS è stato usato per simulare e valutare le differenti configurazioni morfologiche finali dei versanti in superficie e dei livelli in sotterraneo, sfruttando soprattutto la possibilità di calcolare i volumi di materiale da abbattere nelle operazioni di profilatura e messa in sicurezza.

Il terzo caso tratta di un esempio di analisi dati che richiedono un alta interattività fra differenti specialisti (geofisico, geologo, sondatore e general manager del progetto) e quindi necessitano di facilità di rappresentazione per semplificare le attività di decisione sulla pianificazione delle ulteriori operazioni. Sia i rilievi geologici di superficie che le informazioni da remote sensing sono stati riportati su un DEM di 5 m di risoluzione. Su questa base, i rilievi geofisici sono stati riprodotti in profondità attraverso l'uso di box cubici colorati in base ai valori di resistività o di velocità sismica. Questa tecnica di visualizzazione ha permesso una più semplice correlazione fra complessi geologici in profondità e affioramenti in superficie nonché ha chiarito i contatti fra minerale utile ed incassante, identificando il top ed il bottom dei livelli di interesse minerario.

ABSTRACT

Geological investigations aimed at mining prospecting are based on geological maps, field surveys and on underground data (geophysical survey, boreholes and/or mining tunnels). In mining activity (both raw material and energy supplies), it is important to define geologic features, such as geometries, volumes, mineral contents but also surface and subsurface evolution due to excavation and other mining facilities, such as tunnels, plants and other buildings and roads. There are many commercial software able to represent such features in 2D, but a few very expensive products able to show all these characteristics in 3D. Considering the world of free open source or packages at acceptable costs, it is also impossible to find something fitting these needs. The problem is that: i) usually 3D geological models are based on few data if compared with the extension of the study area so available geological data are scattered and a major interpretation is often necessary and 3D visualization allows to help geological interpretation where data are scarce; ii) mining plan are often produced using cad, with very precise dimension and localization of the object and no need of interpretation. These characteristics are on the opposite side of the 3D modeling: the first is the end-member where interpretation is maximized (close to a "pictorial" – geometrically correct – representation), the other is the end member where "a project must be followed" and subjective interpretation should be minimal. This paper shows how it is possible to use common GIS software to solve these kind of problems, with good results and huge possibility of development.

KEYWORDS: 3D modeling, GIS, engineering geology, mine, quarry

INTRODUCTION

In the framework of mining prospection, 3D modeling has become a crucial phase to get a better insight of the subsurface to plan the following exploration phases. In fact, 3D modeling allows collecting the usually sparse data (e.g. geological observations, maps, cross sections, boreholes logs) to produce an a-priori model, which helps reconstructing the geological features with respect to the collected data and to mathematical and geometrical rules (GUSTAVSSON et alii, 2007). Moreover a realistic 3D geological model can be integrated, calibrated and validated using geophysical observation, to eventually be employed for post-processing computations (CALCAGNO et alii, 2000; GUGLIELMETTI et alii, 2013, MERWADE et alii, 2008).

Mining approach is quite different from geological one in reconstructing rock masses, covers and quality of useful bodies. In many cases, geologist can produce its map without taking care that someone will drill or dug theirs models. When the same geologist needs to answer to a company whose investment depend on his evaluations, the approach must be completely different. He needs to pay more attention to uncertainties and to geometries that an aesthetic representation of his model. In addition, field surveys must be checked with other kind of information: topography, geophysical soundings, drillings and so on.

When a mining company or an oil/gas industry decide to invest ina project, usually, They can afford big expense to buy commercial software able to integrate different information, manipulate them, build geological and technical models, planning further explorations and visualize test and results (i.e Geomodeller by Intrepid Geophysicis or Petrel by Schlumberger) (KAUFMANN & THIERRY, 2007). Most of academic world do not have these possibilities and also small mining companies or geological consultant groups cannot invest such quantity of money. Often these two subjects have to solve minor mining problems or need to deal with visualizations and interpretations of subsurface geological data aimed at building a three dimensional model. In fact, 3D visualization is not only a useful tool to show results, but for geologists and mining engineers is also a way to check the reliability of their conceptual models (TACHER et alii, 2006; ZANCHI et alii, 2007).

In this paper we present some example from our experience in Northern Italy, dealing with different geological conditions and mining problems but solved successfully using low cost software solutions.

EXAMPLES (METHODS AND RESULTS) FROM NORTHERN ITALY
RECONSTRUCTION OF A DISMISSED GOLD MINE AIMED AT RE-OPENING

We need to reconstruct the most important historical gold mine in the Alps aimed at assessment of ore bodies and at a possible re-opening. The study covers an area of 4 km^2 through about 40 km of tunnels on almost 30 levels of different age and dimension (GIULIANI et alii, 2015). The ore bodies are composed of gold-bearing post-metamorphic levels, represented by mineralized cataclasites and veins, often discontinuous and with complex structural geometry. Such a structural complexity makes very difficult to assume a profitable method of exploitation without a whole prospection of the deposit, pursuing the goals of safety and sustainability of the mine.

In order to visualize the geometric relationships between ore bodies and old mine levels, it was necessary to digitalize the unique still existing mining plan, updated at the end of 1960, when the mine was closed. This process led to the creation of a 3D digital map very useful for the understanding of spatial relationships between surface topography and mine elements (ZHOU et alii, 2007). ArcGis package was used and in particular Arcmap. Also Arcscene was very useful for visualization at monitor (KRIVORUCHKO, 2011).

In order to visualize the geometric relationships that bind together different production, a complete digitalization of geo-mining data resulting from the exploitations of this old gold mine was done following such steps:

1. scanning of the huge "paper" mine plans and subsequent post-processing to make it clearly usable;
2. orthorectification and georeferencing (UTM- WGS84 using ArcGIS) of the main base maps;
3. detailed digitalization of major excavation sites, by acquiring more than 30,000 quoted points mainly along subsurface tunnels;
4. assignment of elevation at each point and polygon;
5. plotting all polygons in 3D creating footwall, roof and walls for each tunnel.

The digital map of the mine was therefore implemented with the creation of the 3D geometrical elements for each tunnel (Fig. 1).

After a control of the accessibility of the different tunnels, it was possible to schedule a preliminary prospection campaign, with the help of the new spatial information.

They were focused on the recognition of the exploited and unexploited ore panels, in order to immediately identify the available resources. Thanks to this observations and measurements, it is possible to describe in detail the situation of the underground mine. The visualization of the gold resources in the mine, through the collection of more than 70 samples along the accessible portions allowed the improvement of the 2D and 3D digital modeling of the ore content, where the sampled points were plotted and visually differentiated, by grouping the gold grades into four ranges (Fig. 2, left). The follow step was the digitization of the already mined and exploitable panels, in order to define exactly the borders of each element and transform each group of points in 3D polygons (fig. 2, right).

This step was possible by coupling each point to its elevation: this is obtainable from the Triangulated Irregular Network (TIN) of each mine-floor for points closer to this surface, while for the others is estimated on the height reached by the panel. The digitized points were then duplicated to set the base surface of each panel. Based on the knowledge acquired in the mine, it was assumed an average thickness for a typical ore body, which was set as the distance between the roof and the bed of the same panel. The difference between the two TIN produces a shape file containing area and volume of each panel. This procedure has been carried out in a semi-automatic way for each of the investigated levels, allowing a three-dimensional display of all exploited panels.

Therefore, a possible correlation between volumes of mined panels and the consequent amount of extracted gold was carried out according to some different statistical and mathematical methods that are applied to the obtained volume values of each exploitable panel:
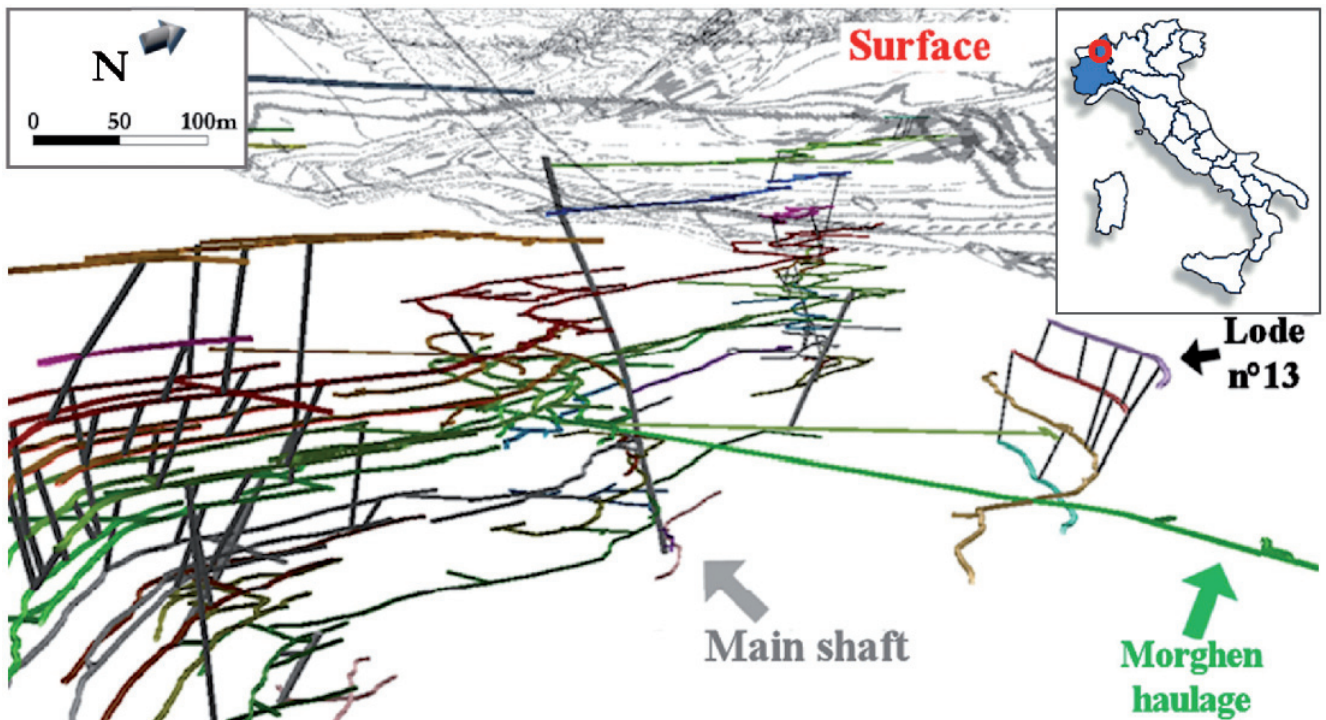

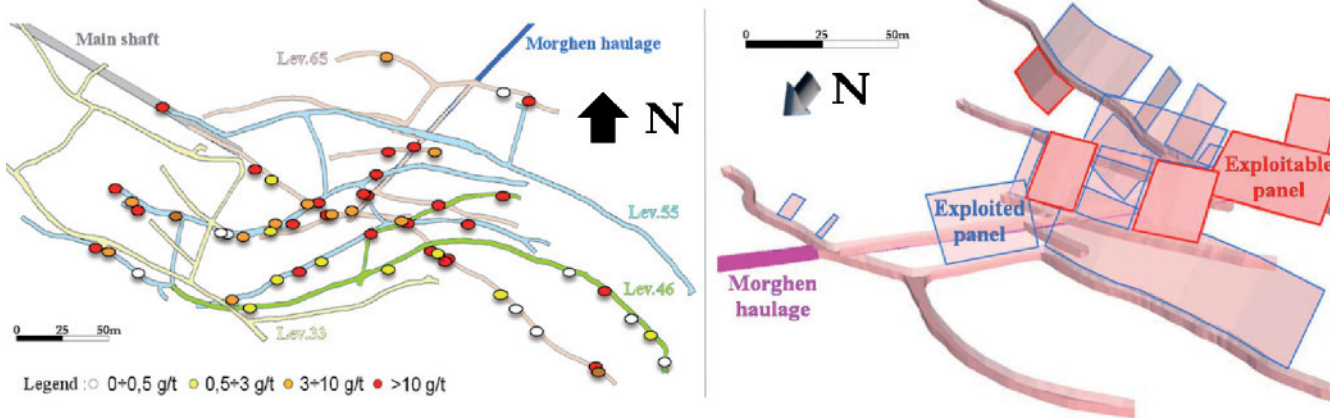Fig. 1 - 3D model reconstruction of the mine

Fig. 2 - On the left, 2D model of explored portions of the mine (dots show georeferenced positioning of analyzed samples and ore content) and, on the right, simplified three-dimensional representation of the exploited panels

- Distributed average method - The definition of percentile allows the determination of the percentage of values below a threshold or the percentage between two thresholds.
- Block method- It needs a preliminary subdivision of the studied levels (65, 55 and 46) in homogeneous blocks of exploitation. Each block was coupled to samples that fall along the same gold-bearing structures, so to calculate a mean value characteristic of each block
- Centerline method- For each panel already mined out was created a barycenter line that crosses the entire element (centerline) and a buffer showing points at distances of 10 and 20 meters from it.

The method allowed planning further field surveys based on new criteria that gave a better geo-mining knowledge of the site. It also demonstrates that there are immediately exploitable gold resources and give interesting highlights on the possible future industrial development of the mine activities.

COMPUTATION OF ENVIRONMENTAL REHABILITATION OF A GYPSUM QUARRY

The three-dimensional visualization of an underground quarry can also be useful in the process of environmental restoration. The potential of the ARC-GIS software may be used for the evaluation of the different possible final configurations of the slopes involved, being able at the same time to accurately calculate the volume of material excavated by the operations of re-profiling.

The case study is focused on a dismissed gypsum underground quarry, which is located in the Apennines (Vezzano sul Crostolo, RE). The exploitation has continued for several tens of years and then it was interrupted in the 1990 without any intervention of safety on the final 15 levels of exploitation. The main purpose of the research was to evaluate the best final morphology of the site that would allow a greater reclamation of unsafe voids and, at the same time, an average degree of steepness of the slope compatible with the neighboring areas.

The beginning of the study consisted in the creation of a DEM of the outer surface of the sector of quarry, based on a detailed laser scanner survey (step 25 cm). In such way, it was possible to have a detailed view the area and to calculate the 2D and 3D areal parameters, otherwise a difficult processing because of the strong morphological existing differences. It was also possible to render graphically the behavior of the slope in relation to the outcropping lithology, distinguished in the four classes (Fig. 3). This processing was analyzed in terms of percentage, in order to evaluate the entity of the changes made by the various proposals for morphological reclamation.

As regards the underground levels, they have been identified the accesses of different levels, and, thereafter, were materialized the underground galleries in 2D, through a georeferenced shapefile for each tunnel. For the modeling of the floors and the pillars, they were made of 3D polygons in order to reflect the actual morphology of exploitation levels. Lines and polygons were extruded to obtain visually realistic 3D volumes according to the measured height of each roof. Thereafter, the single parts of the quarry levels were distinguished with different colors depending on the status of critical aspects (Fig. 4).

Definitely, 3D view allows a much more intuitive perception of the problems, both on surface than in depth, and it permits to express a general view of the different situations understandable also to non-experts.

The study continued with the development of different assumptions of reshaping the site. In particular, we paid attentions to maximize slope stability concentrating portions of exceeded slope (class IV> 35 °) in new stepped sectors and eliminating a large part of the galleries in critical conditions (Fig. 5). This re-profiling hypothesis could obtain a final status suitable for a possible accessibility and re-use of recovered places, not allowable at present for reasons of safety and security.
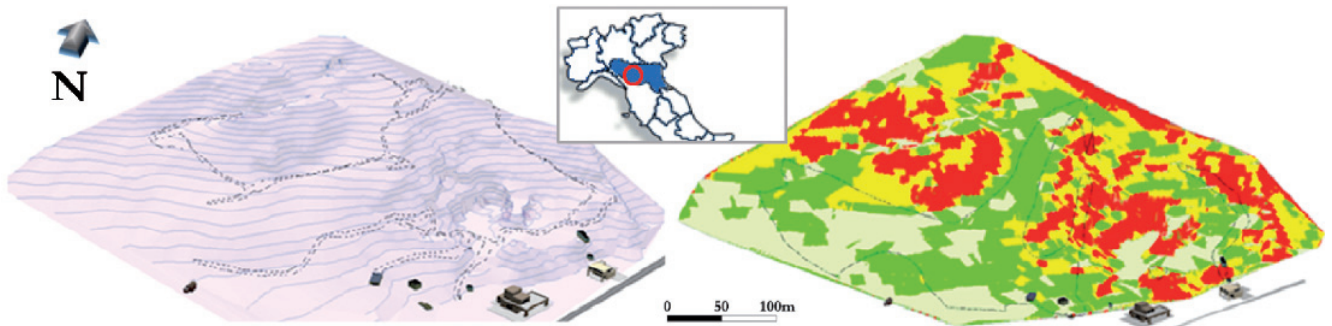
Fig. 3 - *Hill shade of the area of interest (left) and representation of classes' steepness of the slopes (right) (Class I: 0-15° ivory, 15-25° green, 25-35° yellow, > 35° red)*
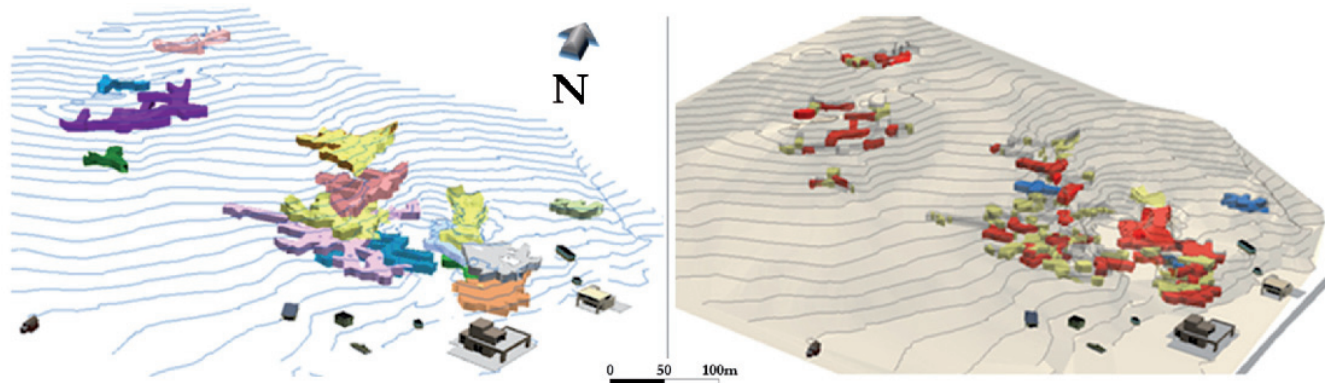

Fig. 4 - *3D GIS representation of the exploited layers (Legend: gray - no problems, yellow - moderate hazard, red - high hazard, blue - unexplored sector) at left, and related critical issues using a semaphoric sketch, at right*
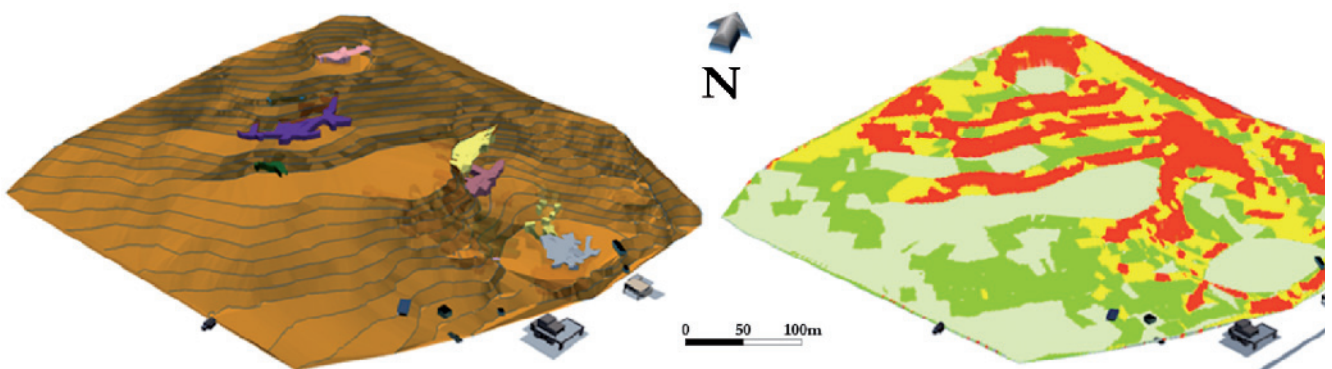

Fig. 5 - *Hypothesis of environmental recovery with galleries obliterated put in evidence (left) and representation of classes' steepness of the slopes (right)*

VISUALIZATION OF GEOPHYSICS INVESTIGATIONS AND CORRELATION TO GEOLOGICAL SURVEYS

Geological surveys and geophysical investigations are commonly used in exploration of potentially useful deposits, especially during first phase of a mining project. In fact, the cost of this kind of investigation is lower if compared to drilling, but very useful to a general understanding of geological setting also in depth. Some important information from geophysical surveys can regard rock type, kind of weathering/rock covers, rock stress, presence of water, geometries of ore bodies and major faults, purity for industrial minerals and so on. Geophysical data need to be always confirmed and compared with geological field mapping results. Better results are obtained if prognosis could be dynamic: as soon as results from new investigations become available to operators that can check previous geological model and – eventually - decide about further investigation guided by up-to-date information.
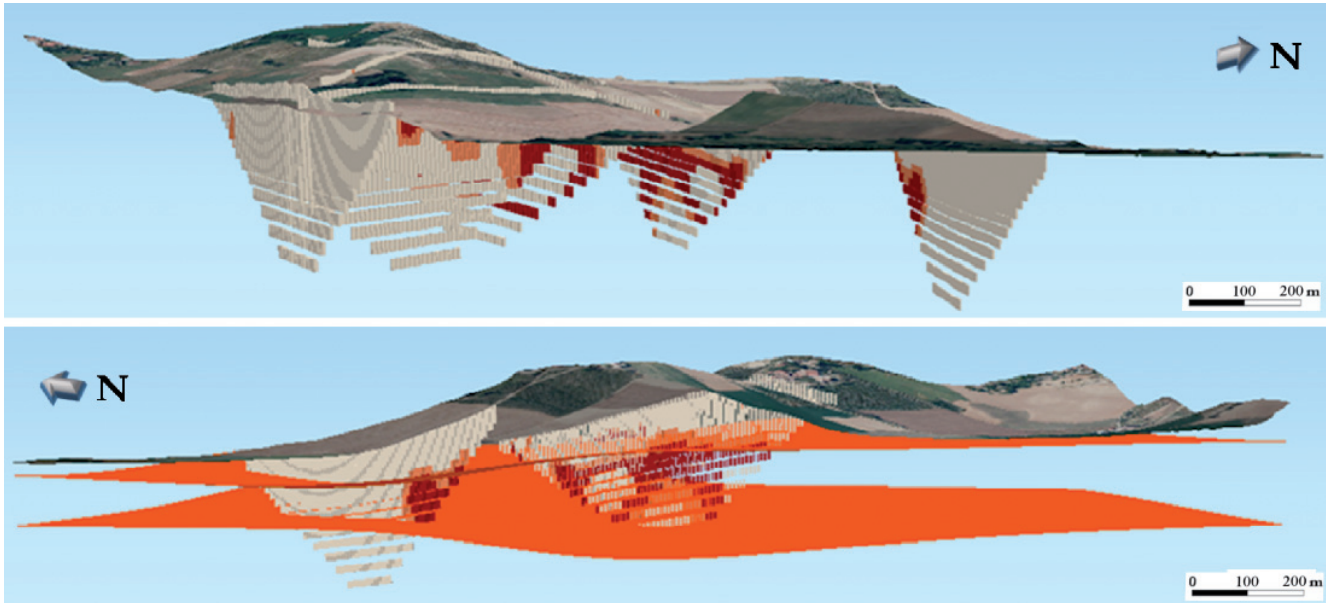
Fig. 6 - *3D browser visualization of geophysical sections (on the top) and with the addition of an interpretation of the deposit extension (bottom). The top surface is the DEM draped with orthophoto*

Data analysis require high interactivity and clarity of visualization leading to boost the decision-making efficiency. This can be obtained in a GIS framework, essential for manage large amounts of data from different sources. Geophysical surveys are generally located in a map following a rough georeferencing procedure. For this reason, some instruments incorporate GPS receivers for data positioning. However, the results are often presented by drawing a line in a topographic map, which refers to a cross section of seismic or electrical results. They are rarely reproduced in a GIS framework or in a 3D platform for a better visualization. Of course, interpretation of geophysical surveys for geological analysis became more complicated when the number of sections increases.

The procedure is based on the popular software QGIS (QGIS DEVELOPMENT TEAM, 2015), user friendly Open Source Geographic Information System (GIS), licensed under the GNU General Public License, and on a plugin Qgis2threejs, used for 3D visualization. First of all, we introduce geologic field data, collected by traditional methods (map and field surveys) or, better, by using field digital mapping techniques using mobile devices (in last years a lot of software solutions were developed to allow this task, for example ArcPad, Geopaparazzi, QGIS for Android). Then every point of geophysical measurement is located with GPS and insert into a QGIS project as point vector layer.

After geophysical data processing, we obtain a cross section with x, y, z and R field, where x, y, z are the geographic coordinates and R is the geophysical parameter result (i.e., resistivity or seismic velocity). Usually this result consists in a text data file that can be directly loaded into QGIS. The visualization is in

2D, and we used the plugin Qgis2threejs for a 3D visualization. Qgis2threejs is based on 3D Web Graphics Library (WebGL). WebGL is one of the most important new technologies facilitating 3D visualization on the browser platform (Wüest, 2012). WebGL is a JavaScript API for the rendering of 3D graphics and it is natively supported in most of the modern Web browsers. With WebGL it is possible to display interactive 3D graphics, if the graphics board and the related drivers on the host computer provide support for it (Krooks *et alii*, 2014; Comina *et alii*, 2015). However, programming in WebGL is quite complicated. Several higher level libraries have been developed to help the application developer in this task. One of these is the Three.js library. Three.js is a JavaScript library that makes the use of WebGL easier by offering to the developer a set of high level graphic objects and concepts that simplify the creation of 3D scenes. Three.js renders into HTML5 canvas element using either Scalable Vector Graphics (SVG) or WebGL.

In our example (Fig. 6), the visualization process was conducted in QGIS 2.8 with Qgis2threejs plugin (QGIS PLUG-INS, 2014) which allows user to automatically create three.js based 3D visualization. Both geologic map and aerial photo were used to drape over DEM (a 5x5 m of resolution). Geophysical data are visualized as a cubic box located at a depth equal to z value. Geophysical data are rendered with a scale of colors according to the ranges of values of resistivity or seismic velocity. 3D visualizations allowed to define the characteristic values of resistivity and of seismic velocity for the deposit so that points of top and bottom are extracted from every geophysical cross sections.
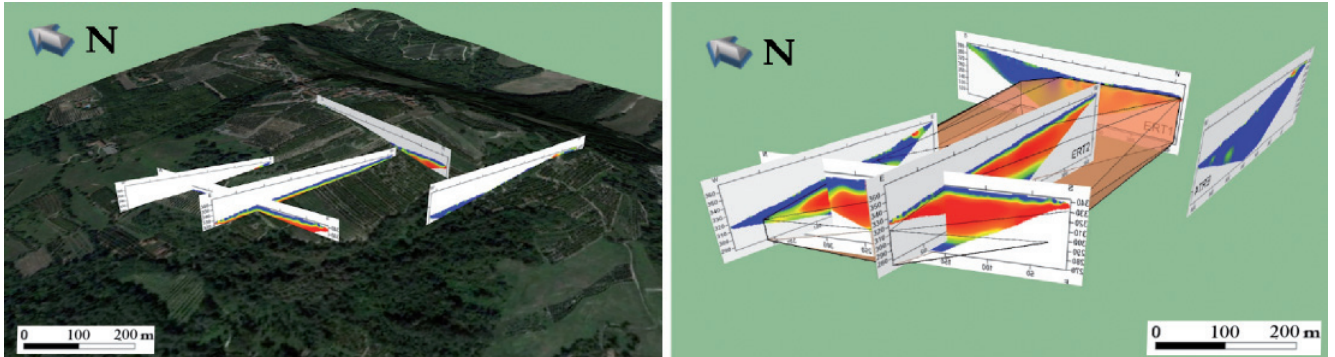
Fig. 7 - Geo-referencing of geophysical surveys (left) and graphical operations for volume plot (right)

Directly into QGIS, grid cell (raster) matrix were filled with interpolated z values generated from the geophysical data points of the top and of the bottom. For the interpolation was used a numerical approximation technique based on distance squared weighting of the values of nearest data points.

The definition of top and bottom of the reservoir is achieved by joining directly in 3D points with similar values of electrical resistivity, closing laterally the solid identified (Fig. 7). The QGIS raster calculator allows performing mathematical operations on each cell in raster. Subtraction between DEM and top raster layer give an indication of the depth of deposit, while volume of deposit is obtained by the subtraction between top and bottom surfaces.

Unlikely, when two reference surfaces (top and bottom) are not regular, the GIS software is not able to calculate included volume. The use of other software that works in 3D environment solved this problem by rebuilding irregular pattern of top and bottom and calculating with precision volume delimited by them. In our case, SketchUp by Trimble automatically calculated volume of identified solid (Fig. 8).

DISCUSSION AND CONCLUSION

Geological mapping and surface investigations are the most employed methods to get an overview of the geological conditions controlling bodies of mining interest (JIN *et alii*, 2011). One of the fastest ways to get an insight of the geology in the subsurface is to collect all the available data to create 3D geological models.
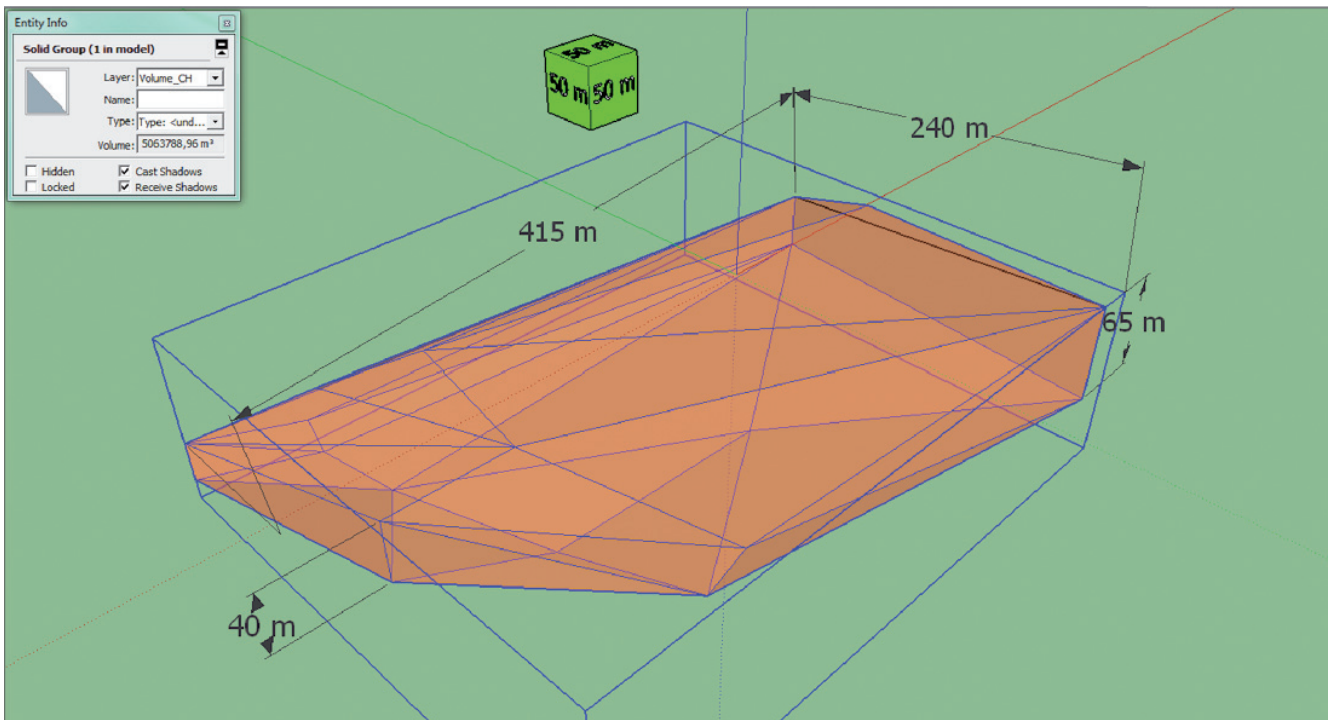

Fig. 8 - Result of orebody reconstruction with volume computation

Building 3D geological models not only allows visualizing the geometries of the geological bodies in three dimensions but also aims at understanding and constraining these geometries in the subsurface in respect to geological observations and interpretations, geophysical and borehole data and mathematical and geometrical rules. 3D geological models can be used as a tool to plan further explorations, such as geophysics or drilling, which data can then be used to further validate and calibrate the models. The interpolation of potential field-data is a common method to create 3D implicit models starting from sparse and scarce data (CALCAGNO *et alii*, 2000). In other words, we added field measurements of geological structures to constrain the interpolation of the model.

The main data needed to compute a model are the topographic surface (e.g. a Digital Terrain Model DTM), which represents the upper border of the model, contact points or interfaces (representative of the geological limit of each formation) and dip data (named foliations in the software) which can be obtained from field observations and geological maps. More needed information are the stratigraphic sequence, the reference of the pile specifying if the data points define the top or the bottom of the formation.

In this paper, there are three different example of visualization, interpretations a reconstruction of geological subsurface bodies using free - or cheap - software. Results have been checked by our commitment (both private and public companies) and they appreciate both graphical visualizations and scientific contents. Of course, there are many other ways to reach these results, but - in our opinion - it is possible to obtain good results thinking from the beginning to the purpose of the project and to the better integrated solution. It is very common that one single software is not able to satisfy all our needs, but now there is a huge amount of solutions and most of them can share data easily.

First examples show how it is possible to reconstruct a complex system of tunnels under the Alps (more than 45 km on many levels) and exploitations panels aimed to planning further explorations, assessing ore deposits contents, plan strategies of exploitations.

The second one is an example in which 3D techniques are used to plan and optimize rehabilitation of a dismissed quarry in the Apennines made of different open pit and big underground spaces. Thanks to our approach, different risk maps and solution of mitigation or protection have been evaluated and shared with public managers.

In last case, it is shown how state-to-the-art direct and indirect investigations can be integrated and implemented thanks to 3D visualization. This approach revealed its usefulness in modeling geological bodies through multiple step models: every time new data are available, model will receive confirmation or will be changed according new information. Eventually, 3D model was build and thickness of ore bodies, depths from surface, quality of mineral were highlighted so contractors could do their choice having a better perception of resources and problems.

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