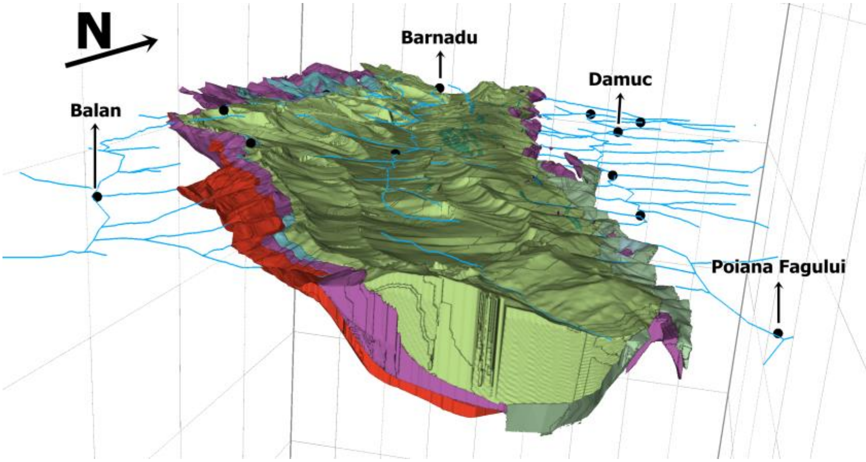
„ALEXANDRU IOAN CUZA" UNIVERSITY, IAȘI
FACULTY OF GEOGRAPHY AND GEOLOGY
DOCTORAL SCHOOL OF CHEMISTRY AND LIFE AND EARTH SCIENCE

3-D geological model for Tulgheș-Hășmaș-Ciuc Mesozoic Syncline between Bicaz and Javardi rivers



PhD Thesis Summary

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CONTENTS OF THE DOCTORAL THESIS

Key words: 3D geological modelling, volume calculation, Move3D, the Ceahlău Nappe, the sub-Bukovinian Nappe, the Bukovinian Nappe, the Hășmaș Nappe, Hășmaș Mountains, Eastern Carpathians, 3-D virtual environment, Virtual Terrain Project, Unity3D, „Structure from Motion” photogrammetry, 3-D outcrops, 3-D samples, digital database.

INTRODUCTION

This thesis stands for the continuation, complement and completion of studies that formed the basis of the graduation and dissertation thesis. The large amount of data, the geological and 3-D modelling knowledge accumulated during this period of time (2009-2014) have led to the creation of a complete image of the studied area geology, by the performance for the first time of a 3-D structural and physical-geographical model of this one. This model provides a general and 3-D overview of the tectonic structures and faults from the Mesozoic sedimentary suite of the Tulgheș – Hășmaș – Ciuc Syncline.

MATERIALS AND METHODS USED IN THE 3D GEOLOGICAL MODELLING OF THE HĂȘMAȘ MOUNTAINS

For the modelling of the region, with a total area of 411.3 km^2, I chose 11 software which fulfil the necessary functions (data collection and processing, modelling and distribution) and by which the performed 3-D model correspond (as much as possible) to the internal and external structure of the studied zone.

Whereas for the validation of the research performed it is needed the rallying to western standards, it was needed, in relation to the ages of the described deposits, the introduction of the terminology used by Cohen et al. (2014) in the International Stratigraphic Chart. However, in order to avoid the possible confusions, the terms used until now have also been kept between brackets, where appropriate.

DATA COLLECTION

For the performance of the Hășmaș mountains 3-D modelling, the following materials have been used:

- Bibliographic materials (books and articles used for the documentation regarding the geological structure of the region);
- Published graphical data (Dămuc map sheet 1:50.000 <Săndulescu et al, 1975>, Toplița map sheet 1:200.000 <Alexandrescu et al., 1968>, Odorhei map sheet 1:200.000 <Săndulescu et al., 1968> and the geological section A-12 1:200.000 <Ștefănescu, 1986>);
- Published digital data (the DTM with a 5 m resolution for 96,4 % from the total area, the ASTER GDEM <Advanced Spaceborne Thermal Emission and Reflection Radiometer for Global Elevation Map> with a 30 m resolution for 3,6 % from the total area, the aerial imagery made in 2012 for 91,3 % from the total area and the aerial imagery made in 2008 for 8,7 % from the total area).

In order to check and confirm the already existent geological information (maps and geological sections), a series of field campaigns have been performed in the mentioned region, during 2009-2014, using equipment such as the geological compass, Garmin GPS, photo camera, video camera, smartphone and the software products Locus Free and Move Clino and the sampling equipment.

At the end of the 6 years, after a first inventory, the information collected during the field campaigns is represented by:

- 290 points with geographical coordinates (figure1);
- 48 strike and dip measurements;
- 50 collected samples (for which I have made a set of photos in order to obtain 3-D models for seven of them);
- 2800 photos (from which 1576 photos made for the 3D modelling of the outcrops), 15 video recordings, 50 photos of a panoramic type (180°, 240°, 360°), 40 3-D Anaglyph photos, all largely corresponding to the previously mentioned 290 points.

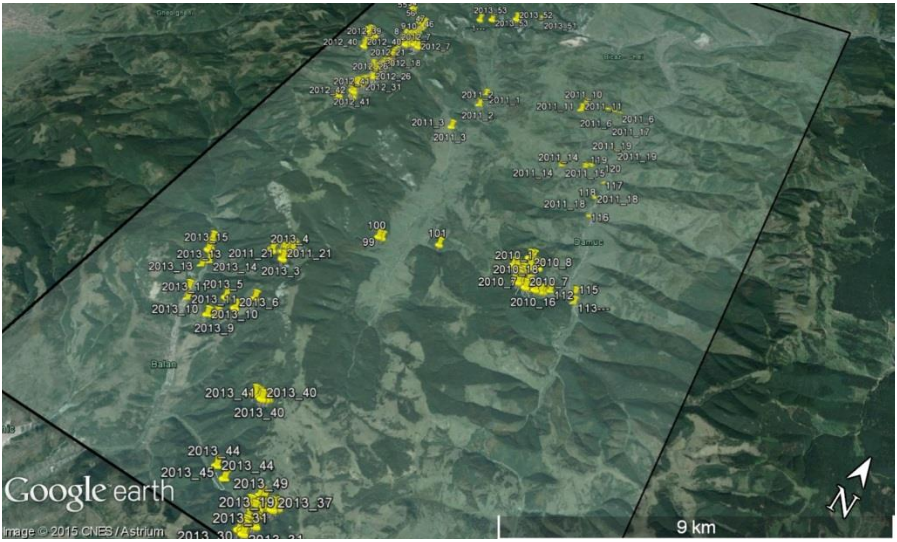

Figure1 Distribution of the 290 points with geographical coordinates.

DATA PROCESSING

The data processing was made by using a computer with a AMD FX 6100 processor, 16 GB RAM, MSI R9 290X graphic card.

I started by making the 3-D models for outcrops (78 3-D models <figure.2>) and the 3-D models for the samples (7 3-D models) by using the previously mentioned photos and the software products RecapPhoto (Dumitriu, 2013), Project Memento and MeshLab.

The next step was to check the information provided by the used cartographic materials and to draw-up the geological map for the studied region by using it. The colours used for the formations (on the map and on the 3-D geological model) have been taken from the International Stratigraphic Chart <Cohen et al, 2014>, and for the faults from the 3-D model (purple, dark blue and yellow), have been selected according to the phase in which these ones were formed (pre-paroxysmal or post-paroxysmal) and to the one in which they were reactivated, as the case may be.

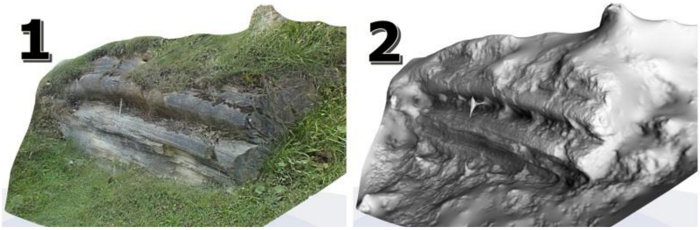

Figure 2 3-D models examples of the outcrops
The crystalline basement outcrop near the Dămuc River (1 – geometry/morphology with texture and 2 –geometry/morphology)
The Mid-Jurassic limestones outcrops near Lacul Roșu (3 – geometry/morphology with texture and 4 –geometry/morphology

THE 3D GEOLOGICAL MODELLING

The 3-D geological modelling was based on the mentioned cartographic materials (subsequently georeferenced) and was made with the help of the Move 3-D software (obtained from the Midland Valley Ltd company) being able to be divided in four stages: performance of the faults areas, performance of the geological sections (respectively of 5978 geological sections), generation of the limits areas between the formations, generation of the formations volumes.

ERRORS ESTIMATION

For the errors estimation, I have used and improved two tests proposed by Smith et al. (2005). The first test refers to the statistic calculation based on the „fish" type diagram belonging to Kaoru Ishikawa (1968), and the second test is in fact a graphical representation (of a chart type) of the distribution and density of the information used for the 3D geological model performance.

From the performed calculation, we have obtained 82,2085% from a total of 100%, for the 3D geological model validity.

FINAL MODEL (SHAPE AND DISTRIBUTION)

After the 3D geological and surface models have been performed, they must be made available to the entire scientific community, but, as the modelling is still at its beginning, there is no default and standardized distribution mode.

For the 3D geological model I have chosen the MoveViewer software offered by the same company, MidlandValley.

For the surface models, some software products that allow their representation individually or next to the depth ones in virtual interactive environments had to be identified.

The first virtual environment was achieved with the help of the Virtual Terrain Project software, which was upgraded during 2012-2014 by collaborating with its author, with functions that allow the study of the elements beneath the surface and by accessing the graphical materials collected during the field campaign.

The second virtual environment was achieved with the help of the Unity3D software and allows the user to interact and to explore the region Bălan-Piatra Singuratică.

GEOLOGICAL FRAME

In terms of geology, the researched area belongs to the „Eastern Carpathian Marginal Syncline" (Uhlig, 1903), which has a basement made of crystalline schists covered by Mesozoic sedimentary deposits.

The internal structure of the region, known in the specialized literature as the Tulgheș-Hășmaș-Ciuc Mesozoic Syncline (Grasu et al., 2012), is made of a complex system of pre-alpine and alpine thrust nappes (the sub-Bukovinian nappe, the Bukovinian nappe, the Hășmaș nappe) covered by post-tectonic formations (Bârnadu Conglomerates).

For the performance of the 3D geological model, it was also required the representation of another five structures that have been identified in the region modelled both at the surface and in depth (the Ceahlău nappe) or only in depth (Pietrosu Bistriței Nappe, Rodna Nappe, Baraolt Nappe, the Black flysch Nappe), using the graphical materials from the bibliography, respectively the geological section A-12, SCALE 1:200.000 (Ștefănescu, 1986).

Concerning the personal field observations on every formation, they are broadly described within the thesis.

STRATIGRAPHY

The sub-Bukovinian nappe – Induan-Hauterivian (Seisian-Neocomian)

The sub-Bukovinian nappe is only found in the form of some thrust klippes represented by sandstones and conglomerates of an induan (seisian) age, anisian dolomites, lower Jurassic breccia deposits, Middle Jurassic limestone rocks and tithonian-hauterivian rudites, found between the Bukovinian Nappe and the Ceahlău Nappe, that can be identified near the area where Dămuc river flows into Bicaz river.

The crystalline basement of Bukovinian Nappe – Middle Proterozoic-Ordovician

The crystalline basement can be divided in three levels: Tulgheș Group, Bretila-Rarău Group and Dămuc Formation.

The Bukovinian Nappe – Upper Paleozoic -Albian

According to Grasu et al. (2012), the sedimentary suite of the Bukovinian Nappe (autochthonous both in Rarău Syncline and in Tulgheș- Hășmaș-Ciuc Syncline) starts with the Hășmaș Breccia of an Upper Paleozoic age and includes Triassic formations (Induan <Seisian> conglomerates and sandstones, Induan-Olenekian <Campilian> grey limestones, Olenekian-Anisian <Upper Campilian-Anisian> massive dolomites, Ladinian limestones with *Diplopora annulata*, Upper Triassic limestones and dolomites), Jurassic formations (Sinemurian- Upper

Pliensbachian <Sinemurian-Domerian> limestone-dolomites and sandstones, Middle Jurassic limestones, Callovian-oxfordian jaspers and radiolarites, Kimmeridgian-Hauterivian <Kimmeridgian-Neocomian> *Aptychus* formation) and Cretaceous formations (Wildflysch formation Upper Barremian-Albian), standing for the most complex stratigraphic suite in the area.

Hăşmaş Nappe – Triassic- Lower Aptian

This nappe is characterized by the allochthonous sediments from the Hăşmaş Syncline in the form of sedimentary klippes incorporated in the Wildflysch Formation (Triassic limestones and sandstone-limestones, Kimmeridgian limestones), or in the form of some covering flaps (Tithonian-Hauterivian <Tithonian-Neocomian> limestones and mudstone-limestones, Valanginian- Lower Aptian limestone).

Post-tectonic deposits – Upper Albian -Cenomanian (Vraconian-Cenomanian)

These deposits were separated from the Wildflysch Formation in 1969 by Săndulescu (who also proves their post-tectonic nature), and according to Săndulescu (1975) these ones are made of polymictic conglomerates with elements from the Bukovinian Nappe, but also from the Hăşmaş Nappe, to which it is added, with a much lower rate, sandstones.

TECTONICS

In Romania, we may distinguish, according to Săndulescu (1984), two types of major geotectonic structures: Alpine orogen and Pre-alpine platforms. The studied region represents only a small sector from the orogen, containing important parts from its subunits.

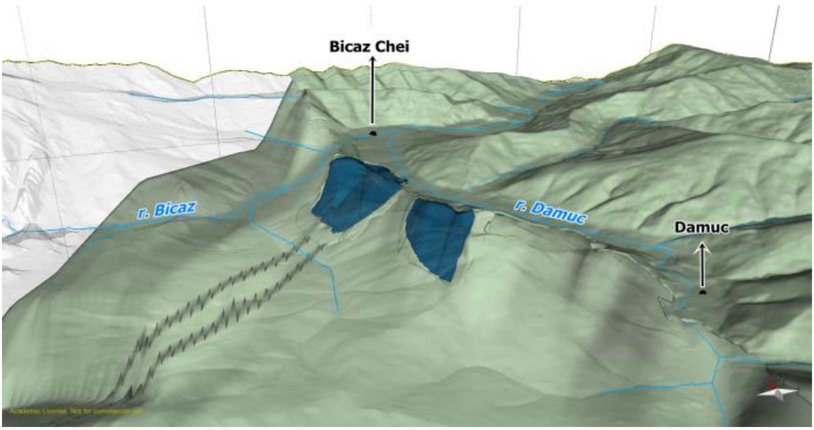

Figure 3 3-D representation of the sub-Bukovinian deposits (dark blue colour) near the estuary of the Dămuc River, located on the flysch deposits (green-grey)

The Flysch Nappe

The modelled area includes also a sector of the Carpathian flysch represented here by the Ceahlău nappe (with an overthrust that corresponds to the Laramic phase), the Black Flysch Nappe and the Baraolt nappe (with a Mid-cretaceous overthrust).

The Sub-Bukovinian Nappe

In the studied region, the Sub-Bukovinian Nappe is present by means of the thrust klippe (figure.3). According to Săndulescu (1975), the formation age of these klippe is Austrian-Alpine, framing thus within the pre-paroxysmal deformations.

The Bukovinian Nappe

The Bukovinian Nappe (figure 4) represents a socle nappe, which together with the Sub-Bukovinian Nappe and the Infra-Bukovinian Nappes, forms the system of the Central-Eastern-Carpathian nappes from the Median Dacides. The nappe overthrust existed before the Bârnadu Conglomerates formation and after the sedimentation of the Wildflysch Formation, corresponding to the Austrian tectogenetic phase.

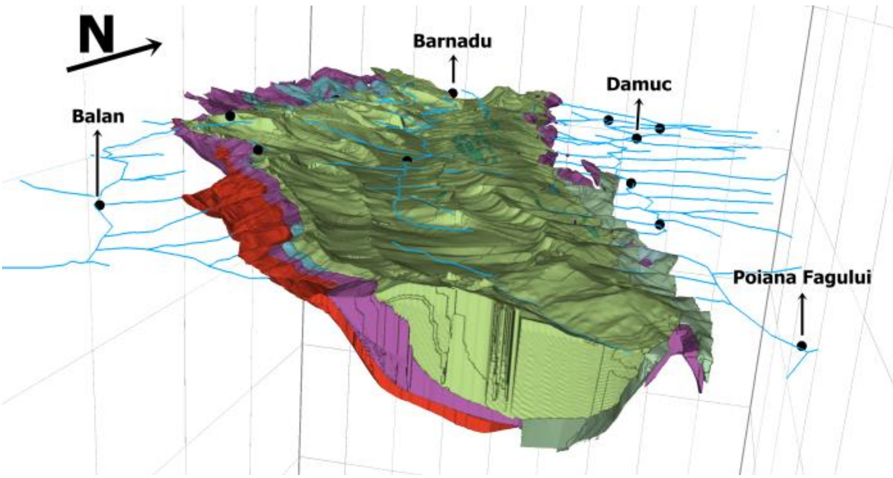

Figure 4 3-D representation of the sedimentary formations from the Bukovinian Nappe (e.g.: green represents the Wilsdlfysch formation, purple, the formation of the Olenekian – Anisian massive dolomites, orange, the Hășmaș Breccias and blue, the Mid-Jurassic limestones).

Hășmaș Nappe

Alongside the other Transylvanian nappes, the Hășmaș nappe (figure 5) corresponded to the main ophiolitic suture of the Carpathians, which was situated west from the current area and was formed by an expanding ocean area. Its movement took place during the Middle Cretaceous period, the Austrian phase, by an initial process of obduction and a secondary one of gravitational sliding. (Săndulescu, 1984)

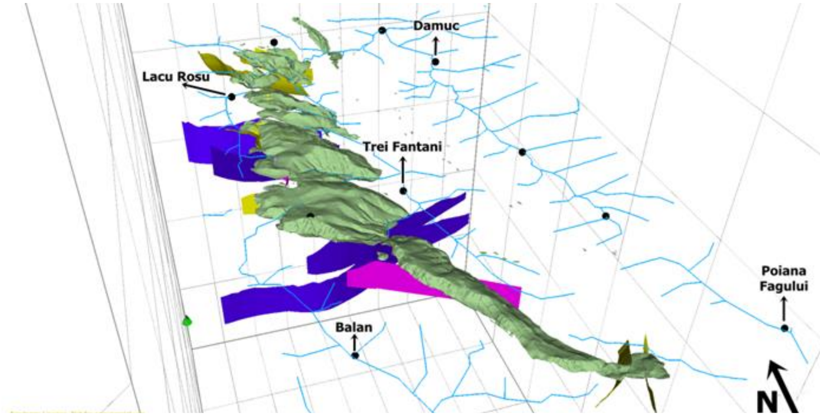

Figure 5 3-D representation of the Hășmaș Nappe and the faults affecting its deposits.

Deformations of the post-paroxysmal tectogenesis

The post-paroxysmal deformations affected the Bukovinian Nappe deposits, the Hășmaș Nappe deposits and the post-tectonic deposits. The structures formed during this stage belong, according to Săndulescu (1975), to the Laramic phase or to the Savic or Stiric phases, are of the reverse faults type and have a reverse vergence comparing to the ones previously formed.

We may also frame within this stage the structures formed as a result of erosion, whereas at least a part of them represent a consequence of the post-paroxysmal deformations.

RESULTS AND CONCLUSIONS

The thesis objective is the performance of a 3D structural model of the Tulgheș-Hămaș-Ciuc Syncline (figure 6), with the tectonic accidents specific to the post-tectonic deposits and to the Mesozoic sedimentary formations from the Bukovinian Nappe and the Hășmaș Nappe.

Alongside these geotectonic units, a part of the Carpathian Flysch, the Sub-Bukovinian Nappe deposits, deposits of the Bukovinian Nappe Crystalline basement and even the deposits of the alluviums, terraces and landslides have also been approached for modelling. Finally, the 3-D geological model performed is framed within a parallelepiped with a volume of 3085.35 km3 (area <411.38 km2> ; hight <7,5 km>).

The 3D geological model has been performed with the help of the Move3D software by performing and interpreting 5798 geological sections, having as support the geological maps, the geological cross-sections and the digital materials mentioned in chapter „MATERIALS AND METHODS...”. To all these, it was also added the measurements made during the field campaigns between 2009-2014. The field measurements have most of the times confirmed the presence of the structures from the materials previously mentioned and only in few cases, they were amended or modified. The modifications proposed for the geological map are:

- Redimensioning of the Lower Jurassic on the Ghilcoș stream with a thickness of 70 m;
- Removal of the Ladinian limestones opening and of the buttonhole containing Triassic and Lower Jurassic deposits from the arrangement „reverse fault-stall” from the western side of the Oii stream basin, represented on the Dămuc geological map;
- Introduction of some big-sized rudites, within the Oii stream basin (Dumitriu și Huțu, 2013);
- Removal of the normal fault from the superior side of Mâțul stream, represented on the Dămuc geological map;
- Introduction of a basal horizon with jaspers from the Wildflysch Formation, within the Lazăr stream basin.

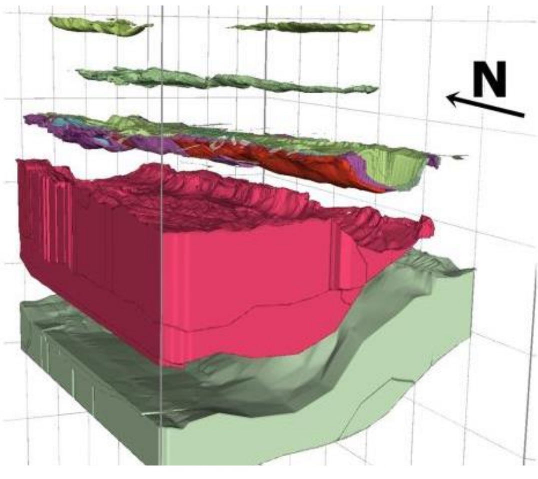

Figure 6 The 3-D structural model of the Tulgheș – Hășmaș – Ciuc Synclined (exploded).

The other notes and measurements which confirmed the elements from the used geological maps contain geographical coordinates collected during the field campaigns with the help of a high accuracy GPS type system. Moreover, in case of the concerned points and of the outcrops identified, some simple photos, 3-D photos of anaglyph type and in some cases video records and panorama photos have been taken with the mentioned geographical coordinates. From the processing of a large amount of photos (by means of the „Structure from Motion" type photogrammetry method), for some outcrops it was also possible the performance of some 3-D models for these ones (78 3-D models). Both the mentioned photos and the 3-D models for the outcrops can be viewed on the DVDs 2 and 3.

From the interpretation and processing of all this information it was possible the drawing-up of the improved geological map for the studied region, map that represented the base of the 3-D structural model performance concerning the Tulgheș-Hășmaș-Ciuc Syncline region, located between the Bicaz river and the Javardi river.

The performed 3-D geological model:

- Allows the study of the entire assembly underneath the region surface;
- Facilitates the interpretation in real time of any point within the modelled space. Replaces the need to perform geological sections by the possibility to make some direct observations on the three-dimensional structures;
- Provides the possibility to automatically perform some geological vertical or horizontal sections, in any selected direction;
- Provides the possibility to calculate the faults throw or the thickness of a formation between two points chosen at random, in a quick and easy manner;
- Shows both the areal expansion of each formation and the actual dimensions of the tectonic accidents covered by the Wildflysch Formation (drawings 17-37 from the doctoral thesis).
- Allows the measurement and viewing of the Hășmaș Nappe thrust plane and of the elements that could only be studied cartographically, such as the tectonic windows, klippe and the thrust klippe.

Moreover, by the performance of this model it was also possible the calculation of the faults areas and every rock package volumes, data presented within the tables from the thesis, pages 97 - 103.

One issue that can be studied only by using the 3-D model and consequently the calculated volumes is the one of the faults throw variation throughout the entire length of their surface (figure7) and the amount of rocks dislocated from these ones during the tectonic moves.

Thus, from the evaluation of the obtained volumes values, there can be observed all the dislocated sections for all the modelled faults. One example for this situation is the area of the Piatra Singuratică Peak, where the pre-paroxysmal faults 1.2.5 and 1.2.6 are forming a horst type structure, moving in a positive direction a rock volume of 4.310.958.976 m^3, from which 602.110.218 m^3 Middle Jurassic limestones (M18.13), 15.128.753 m^3 deposits belonging to the Lower Jurassic (M 19.5), 452.509.107 m^3 Upper Triassic limestones and dolomites (M 20.10), 523.494.220 m^3 Ladinian limestones (M 21.10) , 2.634.991.364 Anisian-

Olenekian massive dolomites (M 22.27) and 82.725.314 m^3 Hăşmaş Breccias (M 25.4).

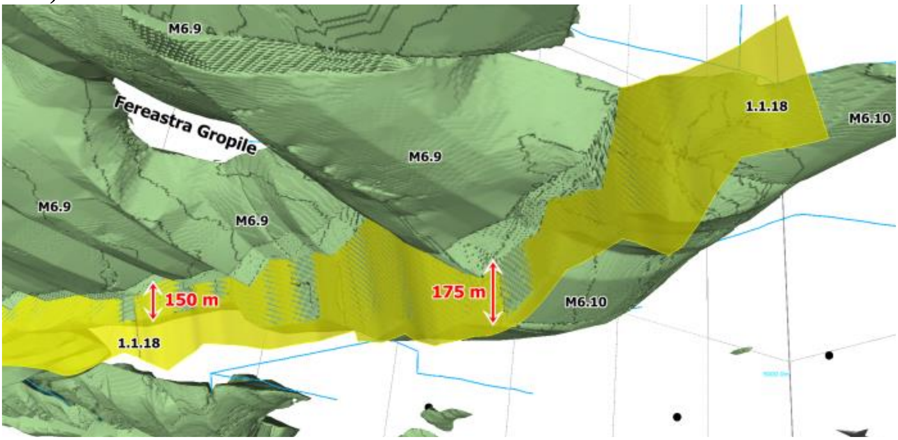

Fig.7 3-D representation of the fault 1.1.18 with the throw calculation performed in two chosen regions (red arrows) by means of the Move3D software.

Using the obtained volumes, the mas of every rock package can be calculated, by means of the known average densities. For example, knowing that the Hăşmaş Nappe is only made of limestones, the average density of the limestone being of 2611 kg/m^3 and the total volume of the nappe is of 16.017.031.640 m^3, there will be obtained a mass of 41.820.469.612.040 kg. The obtained mas may be introduced in various calculations that could highlight the necessary forces in case of some compression movements, to move and deform the studied deposits.

The values obtained from such a model can also be used for simplifying the reserves calculation during the prospecting and exploration phase of a concerned area and consequently for reducing the costs related to these operations.

In order to experiment some theories regarding the evolution of the tectonic structures and accidents from the studied area, the obtained model can be used within the Move3D software as a base for the creation of a set of equilibrated sections or of an equilibrated 3-D models sequence.

As I have already mentioned above, alongside the 3-D structural model (DVD 1), a number of 78 outcrops have also been modelled using the „Structure from Motion" type photogrammetry technique and various photos and records have been taken. Whereas the information volume collected during the field campaigns is quite high, a digital database was created related to the studied area (DVD 2 and DVD 3). Moreover, for all these elements to be studied in only one context, it was tried their introduction in a single virtual environment (figure 8) with real geographical coordinates (DVD 4). The mentioned virtual environment was performed with the help of the Virtual Terrain Project software, improved by the option to introduce the elements underneath the surface, by collaborating with the author Ben Discoe from the United States of America. Moreover, in order to induce the user the sensation of direct exploration of the region, being thus able to interact with the surrounding environment, it was also performed a virtual environment (figure 8) of the surface elements, for the region Bălan – Piatra Singuratică Peak, with the help of the Unity3D software (DVD 4).

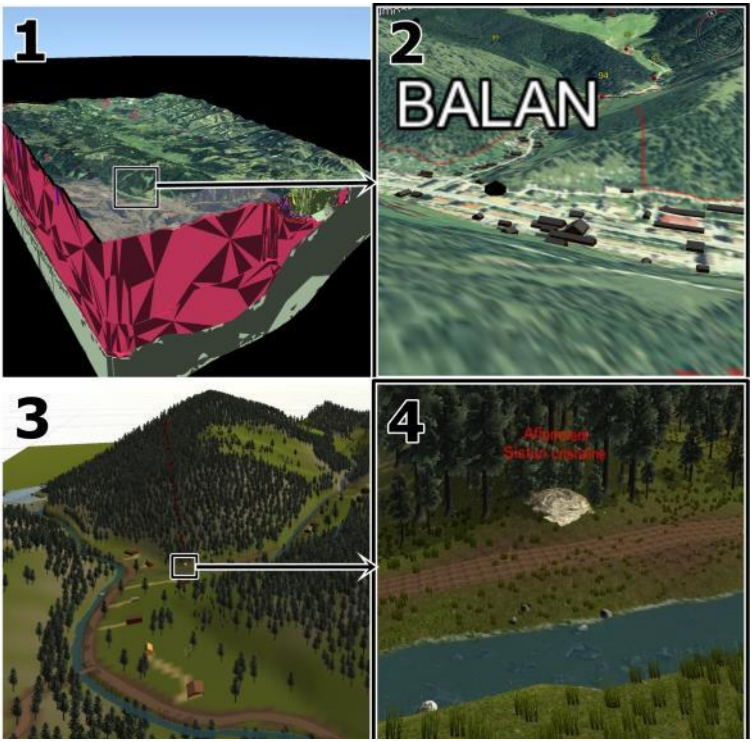

Figure 8 The virtual environments performed within Virtual Terrain Project (1, 2) and Unity3D (3, 4)
1 - overall view; 2-detailed view
3 - overall view; 4-detailed view

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