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1. 3D Geological Model of the Turčianska kotlina Depression at Scale 1: 50,000

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Abstract: 3D modelling of the Turčianska kotlina Depression was elaborated within the project Turčianska kotlina Depression - three-dimensional geological modelling in 2013 and 2014 (Nagy et al., 2014) in order to create a quality regional model at a scale of 1: 50,000, which could also be used as an input data for hydrogeological modelling, etc.

To create a 3D geological model of the area, data from published works were used, such as analog geological profiles from the geological map at a scale of 1: 50,000 (Gašparik & Halouzka, 1993), maps of the pre-Tertiary basement of the Atlas of Geothermal Energy (Franko et al., 2010) and geophysical works (Bielik et al., 2013), but for the required quality it was also necessary to use data from 1,300 VES probes that were interpreted in 34 profiles. The creation of the model itself would still not be possible without the external intervention of an experienced geologist, so it is possible to say that the so-called an explicit approach was applied, where a geologist and a 3D expert interactively co-create a 3D model using computer technology.

In this work we present a methodical procedure for solving the problem, i.e. the exact procedure from the creation of a catalog of modelled layers/formations and processing of input data, through the creation of a tectonic model to the creation of 3D surfaces with respect to the tectonic structure.

The results of modelling are documented by individual modelled formations and layers and in a separate chapter also by individual tectonic segments, where the projection areas and cubatures of individual modelled bodies are calculated. Both the procedure and the modelling results are documented by tables and a number of figures.

The conclusions provide a summary of the work and recommendations for modelling other regions of the Slovak Republic.

The work used a 3D modelling package Petrel® in version 8.4 from the company Schlumberger.

Keywords: 3D modelling, geological model, sedimentary basin, vertical electrical sounding

1.1 Introduction

Already at the beginning of the computer age, after mastering elementary computational operations and verifying the speed of computations for a larger amount of input data, effective algorithms began to be developed and subsequently applied, which helped to perform demanding tasks in a reasonable time. In addition to the great interest of the military, new opportunities have opened up for science and research and the application of their results in various areas of human activity, not excluding geology.

From the beginning, the investments in geological prospecting and of mining companies have pushed the development forward, from various 2D interpolation methods (kriging, splines), through simulations, mining optimization to the current state with fantastic possibilities in 3D (calculations, visualizations) and virtual reality. Such tools, robust 3D packages, were gradually available to the wider professional public, and thus enabled also SGIDŠ to participate in the field of 3D model creation more than ten years ago.

The first task in this area was the project "Upper Nitra Basin - three-dimensional geological modelling of the exposed area" (Kotuľová et al., 2010). The methodological results of this project were followed by the task "3D geological model of the Turčianska kotlina Depression at a scale of 1: 50,000" (Nagy et. al., 2014) in order to create a three-dimensional geological model of the area and other superstructure 3D models of the basin together with morphology and lithological content of the pre-Cenozoic bedrock and the overlying Cenozoic sedimentary fill.

1.2 Sequence of the 3D model creation

At work, we relied on previous experience and know-how. We have already solved the problems of calculating the reserves of mineral resources, or solving the spatial distribution of useful components in the magnesite deposit of the Dúbrava Massif, but these problems were solved mainly in a 2D way along individual mining horizons and profiles.

The use of the Petrel® 8.4 program from the Schlumberger Company enabled us to create a geological model in a truly spatial way, assuming we are based on the methodological procedure and philosophy of the Petrel® program model creating.

Since our task was to create a 3D model of the sedimentary filling of the depression, we did not have to create new procedures, it was enough to prepare as much relevant input data as possible and proceed exactly within the defined methodology.

We proceeded from the creation of a tectonic structure, the selection of modelled interfaces, the creation of catalogs and databases, through the generalization and interpretation of input data to the actual modelling of individual 3D bodies (complexes). The resulting 3D model formed a set of 3D surfaces, including the tectonic structure of the area.

How did we proceed?

3D modelling was preceded by the preparation of input data (engineering geological boreholes, hydrogeological wells, deep boreholes, analog data from existing geological maps and geochemical atlas data, analog profiles from maps at a scale of 1: 50,000 (Fig. 1.1), existing digital data on the basement from geophysics results and the others, which we will present hereinafter).

The comparison of some existing models of the basement of the Turčianska kotlina Depression (geophysical model or data from the Atlas of Geothermal Energy, Fig. 1.2) showed that the situation was not unambiguous and we

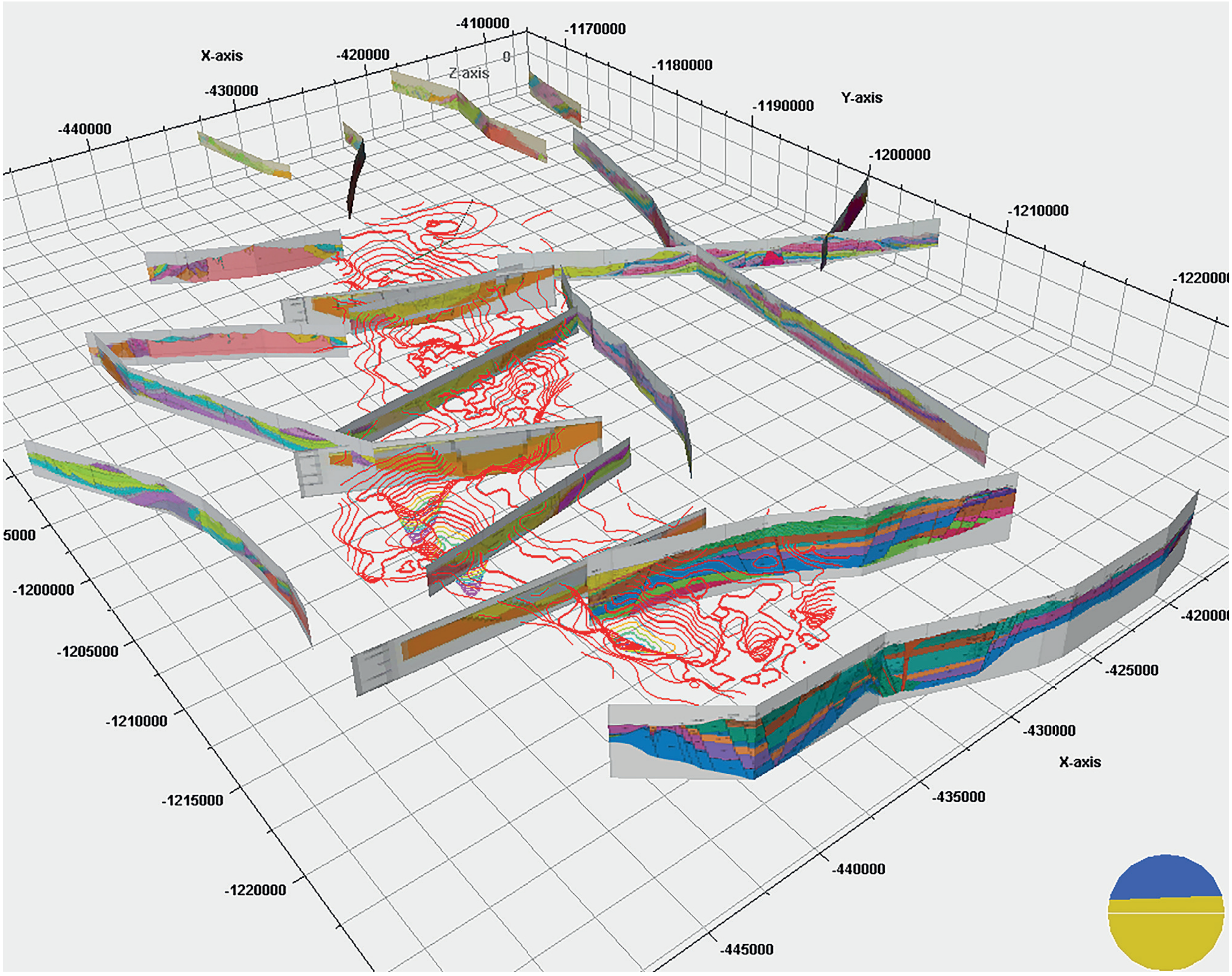

Fig. 1.1. *3D geological profiles from geological maps and basement depth (basement depth according to Bielik et al., 2013)*

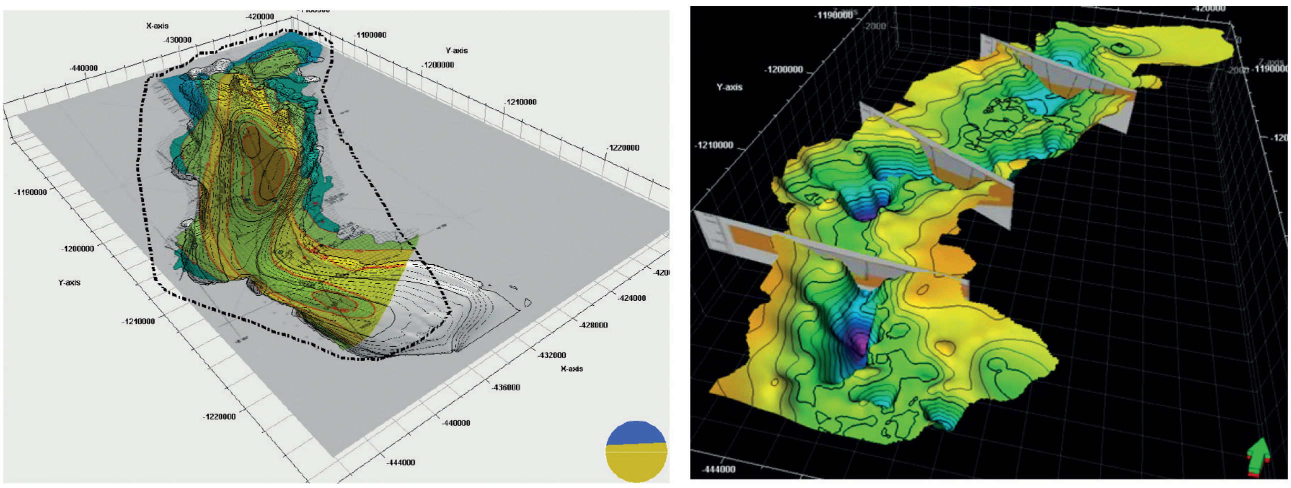

Fig. 1.2. *left: Basement depth according to data from the Atlas of Geothermal Energy, right: Basement depth according to (Bielik et al., 2013) and selected 3D geological profiles.*

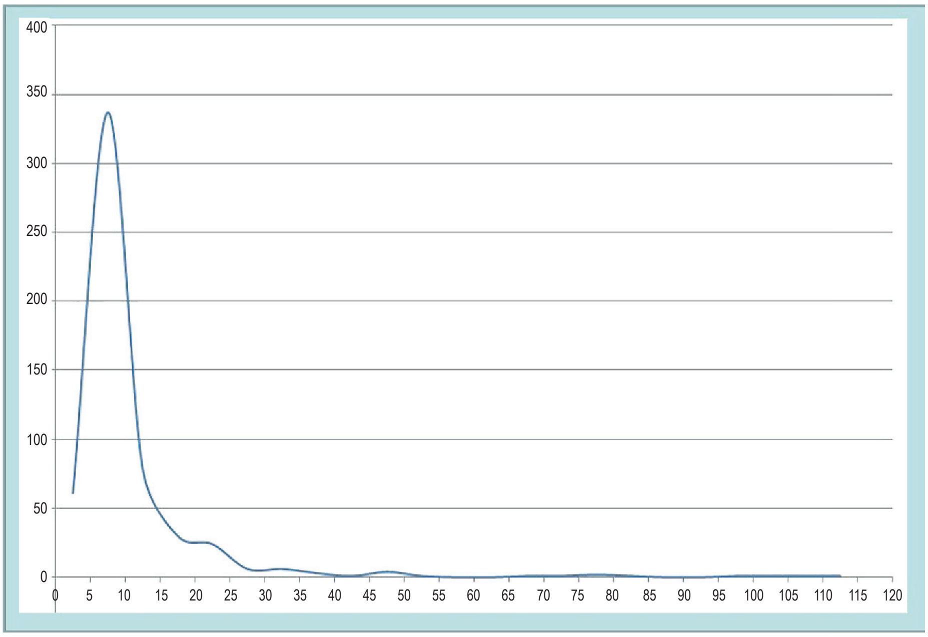

Fig. 1.3. *Number of boreholes depending on depth (histogram/distribution). Existing, mostly shallow engineering geological and hydrogeological boreholes did not allow to model the area of the Turčianska kotlina Depression basin to a depth greater than 10-15 m.*

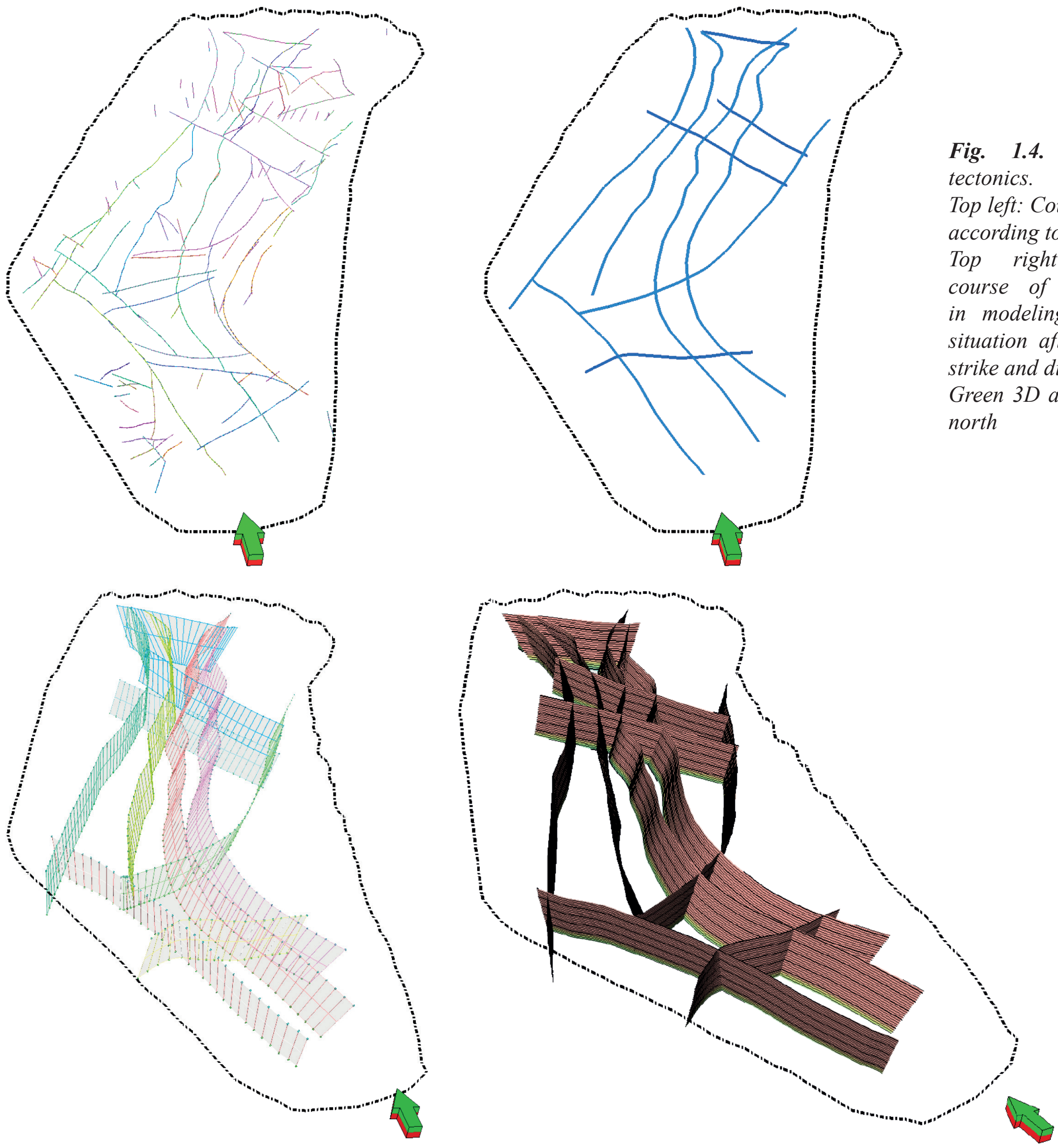

Fig. 1.4. *Modelling of tectonics.*
Top left: Course of all faults according to geologic maps, Top right: Generalizrd course of faults applied in modeling. Bottom: 3D situation after defining the strike and dip of the faults. Green 3D arrow pointed to north

had to critically evaluate the previously published results or create a basement model in a new way.

In addition, due to the spatial distribution of the above-mentioned input data (Figs. 1.1, 1.2, 1.3), it was not possible to create a more detailed, or sufficiently deep 3D geological model at a scale of 1: 50,000.

We proceeded to thicken the input data with data from existing VES profiles, which were obtained from company Geocomplex, a.s. Subsequently, more than 1,300 VES probes were processed and 34 *interpreted* geophysical profiles were created. From such 3D input data (i.e. from a sufficiently detailed set of geological profiles), it was already possible to create a sufficiently representative 3D model of the Turčianska kotlina Depression. This model was subsequently used as an input for the creation of a hydrogeological model of the area.

In the initial phase of the model creation, a legend was prepared, or the catalog in which the codes for the modelled layers and formations were defined (Tab.1.1).

Tab. 1.1. Explanations for the processed VES probes. We list the names of the layers and formations ("Original Name", the "Simplified name", and the "Code" used in the database).

Original Name	Simplified name	Code
Quaternary	Quaternary	0
orthogneiss	Granitoids/Crystalline complex	2
granitoid		
weathered granitoid		
Ramsau dolomite	Mesozoic	4-7
dolomitic limestone		
marly limestone, marl		
Algau+Gresten Members		
Borové Formation	Borové Fm.	10
Huty Formation	Huty Fm.	11
Rakša Formation	Rakša Fm.	14
fine grained tuff and tuffite	Fine grained tuff(ite)	16
epiclastic volcanic conglomerate	Epicl.conglom.	17
lava flow 1	Turčok Fm.	18.1
lava flow 2	Jastrabie Fm.	18.2
Bystričany Formation	Bystričany Fm.	19
Budiš Formation	Budiš Fm.	20
Abramovce Member	Abramovce Mb.	21
sandstone	>> Martin Fm.	22

The top boundary surface of the 3D model was created from the existing high-precision DMR in a 20x20 m grid (source: GeoIS SGIDŠ), which was recalculated and generalized to a 100x100 m network. This regular grid was used for all 3D visualizations.

The boundary of the modelled area and the geological map of the area at a scale of 1: 50,000 were digitally processed and georeferenced into 3D. Above the georeferenced map of the Turčianska kotlina Depression and the adjacent regions (Veľká Fatra, Malá Fatra, Kremnické vrchy Mts.), the faults were digitized, the most significant were selected for modelling purposes and they were generalized (Fig. 1.4).

Based on the VES probes (1,340 pcs.), 34 interpreted profiles with a legend (explanations) were created in accord with Tab.1.1. Subsequently, the slope of the individual faults was modelled according to the interpreted VES profiles so that it corresponded as accurately as possible to the geological and interpreted situation (Fig. 1.5).

The modelling of the tectonic structure completed the first stage of creating a 3D model, the so-called *fault modelling* - creation of model structural frame. In the next stages, this tectonic structure formed a skeleton not only for the subsequent creation of a 3D model, but also provided a solid structure during the interpretation and digitization of the input data. The space was divided into 14 segments by generalized faults (Fig. 1.6).

Originally nonlinear raster geological profiles were digitized with respect to generalized tectonics. The interfaces of the individual interpreted VES profiles were vectorized taking into account the created spatial faults and the existing legend of the individual complexes (i.e. their mutual stratigraphic position, Figs. 1.7, 8).

Tab. 1.2. Final explanations (catalog, database) for the processed VES probes from overburden to basement.

Simplified name	Code
Quaternary	0
Bystričany Fm.	19
Jastrabie Fm.	18.2
Martin Fm.	16-24
Abramovce Mb.	21
Epiclastic conglomerates	17
Turčok Fm.	18.1
Budiš Fm.	20
Rakša Fm.	14
Huty Fm.	11
Borové Fm.	10
Mesozoic undivided	4-7
Granitoids/Crystalline complex	2

Selected modelled complexes description:

Crystalline (code 2)

Crystalline rocks are involved in the geological structure of NW slopes of the Žiar mountain range, the western slopes of Lúčanská Malá Fatra Mts. and on the S slopes of Krivánska Malá Fatra Mts. The crystalline rocks of the Žiar and Malá Fatra core mountains are made of magmatites mainly, dominantly granitoid rocks. Metamorphic rocks, with the exception of Lúčanská Malá Fatra Mts., where paragneiss predominatea, are inferiorly represented in the Žiar Mts. and are absent in Krivánska Malá Fatra Mts.

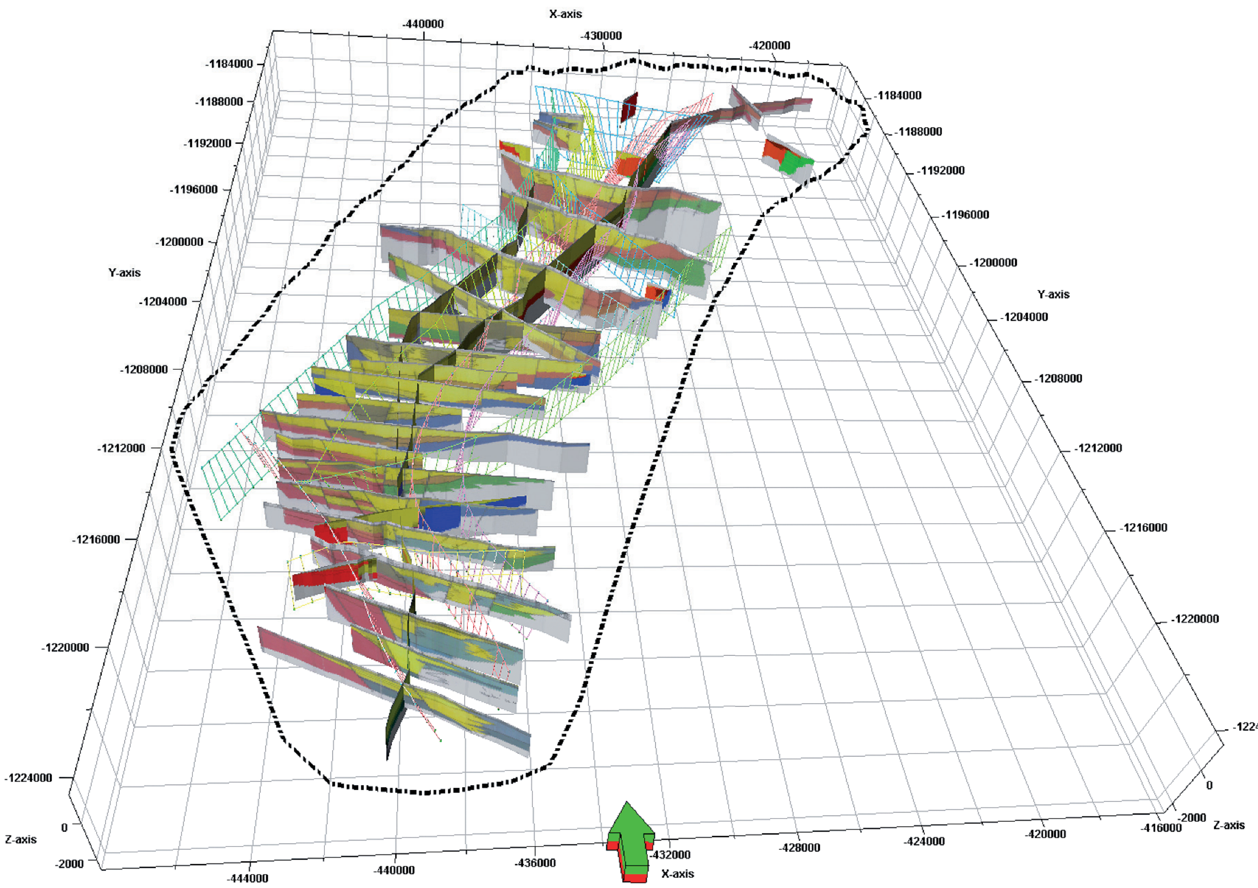

Fig. 1.5. *Resulting georeferenced interpreted 3D VES profiles with territory delineation and faults course depiction.*

Mesozoic undivided (code 4-7)

In the segment 1, only Hronicum rocks (age range Cretaceous-Valanginian to Triassic-Fasanian) represented by dolomites and marly shales of the Mráznica Formation, Gader Limestone and Wetterstein Dolomite.

The segment **2** includes Tatricum and Fatricum outcrops. The **Tatricum** (age range of the Early Triassic to the Cretaceous-*Early Albian-Middle Turonian* is represented by sedimentary clastic, carbonatic and shale rocks in the form of narrow strips (Lúžna Formation Gutenstein Mb., Ramsau Dolomite, Carpathian Keuper, Trlenský potok Fm., Allgäu Mb., Lučivná and Poruba Fms.).

The largest areas of Mesozoic **Fatricum** units (age range Triassic-*Anisian* to Cretaceous-*Early Cenomanian*) are made of calcareous rocks of the Mráznica Fm., then the Ramsau Dolomite and the least represented sediments of the Carpathian Keuper. The remaining sediments (Gutenstein Limestone, Podhradie Limestone, Lunz Mb., Haupt Dolomite, Fatra Mb., Kopienec Fm., Allgäu Mb., silica-rich Fleckenmergel, variegated radiolarian limestones and radiolarites, Jasenie Fm., Osnica Fm., organodetritic limestones, Nolčovo Mb. And Poruba Fm.) occupy an incomparably smaller area representing mostly occurrences in the form of strips.

The sgment **3** consists only of the **Hronicum** rocks (age range Triassic-*Anisian* to *Late Carnian-Norian*), of which the Wetterstein Dolomite, Gader Limestone and Ramsau Dolomite occupy the largest surface area. Others (Gutenstein Limestone, Wetterstein Limestone, Lunz Mb. and Haupt Dolomite) are represented to a much lesser extent.

The whole area of the segment 4 is represented by Fatricum rocks (age range Triassic-*Norian* to Cretaceous-*Early Cenomanian*) of which (Ramsau Dolomite, Carpathian Keuper, Fatra Mb., Allgäu Mb., variegated radiolarian limestones, Poruba Fm.) almost the entire territory is represented by dolomites and marly shales of the Mráznica Fm.

In the segment **5** of the edge of the basin of the pre-Cenozoic age, the Mesozoic rocks belong mainly to the Tatricum Žiar Succession. In the lithostratigraphic sequence (age range from the Early Triassic to the Cretaceous), larger continuous areas are formed only by clastic sediments of the Lúžna Formation, Gutenstein Limestone and limestones and claystones of the Allgäu Mb. Distribution of other carbonatic, shale and clastic sediments (Werfenian Mb., Carpathian Keuper, Kopienec Fm., Trlenský potok Fm., Hierlatz Limestone, siliceous Fleckenmergel, siliceous limestones and radiolarian limestones, Lučivná Fm. and conglomerates occurs in the form of relatively thin strips.

The Fatricum in the segment **6** is represented by the Zliechov Sequence (age range from the Middle Triassic to the Middle Cretaceous). The situation is complicated by a duplex structure, where on a Cretaceous flysch there

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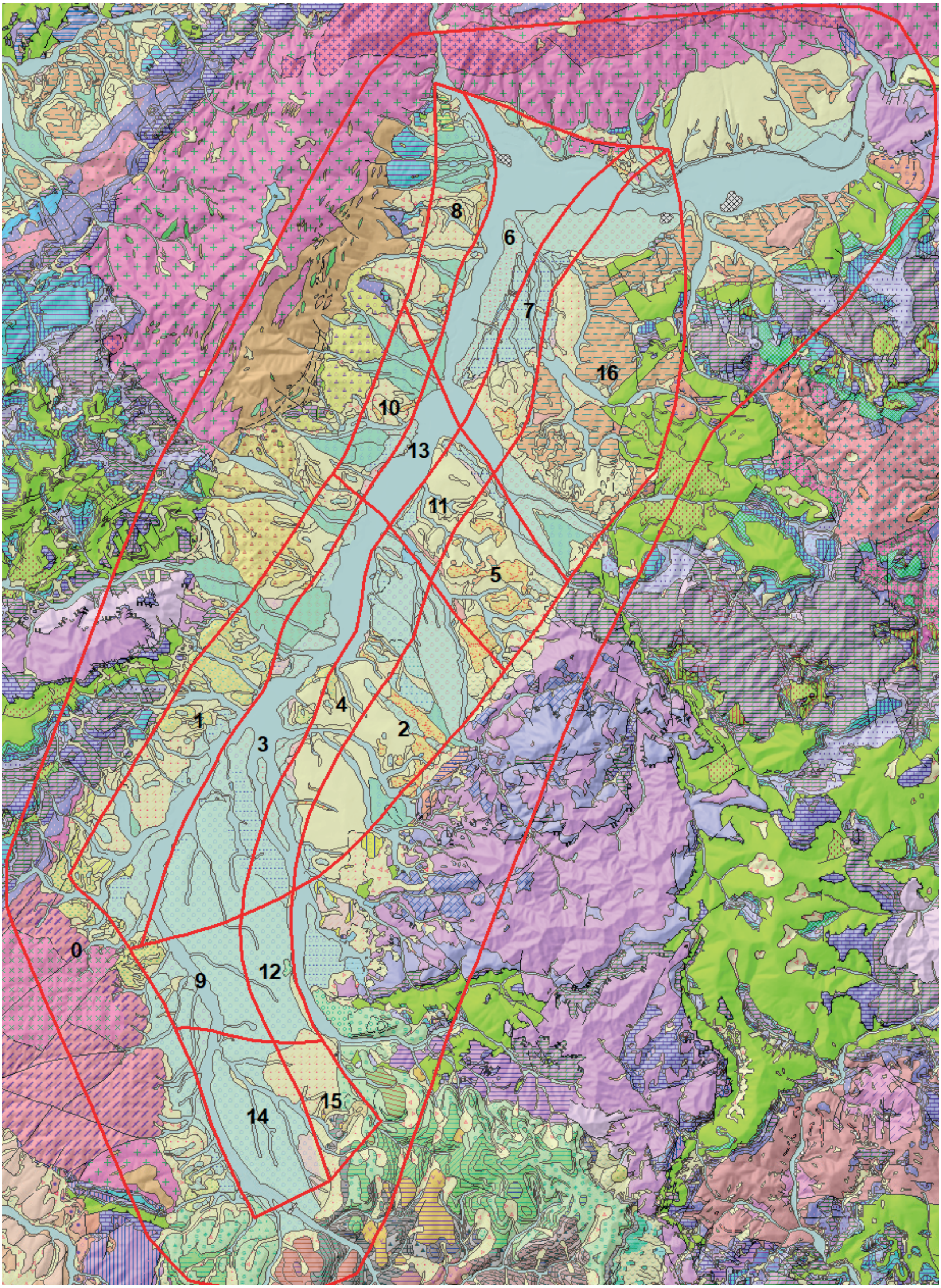

Fig. 1.6. *Area segmentation (according to generalized faults).*
Segments 2 to 14 are bound by tectonics from all sides, segments 91-93 form auxilliary segments, bound by tectonics from three sides. segment 1 forms an boundary area on the digital geological map at a scale 1: 50 000, map portal SGIDŠ [online].

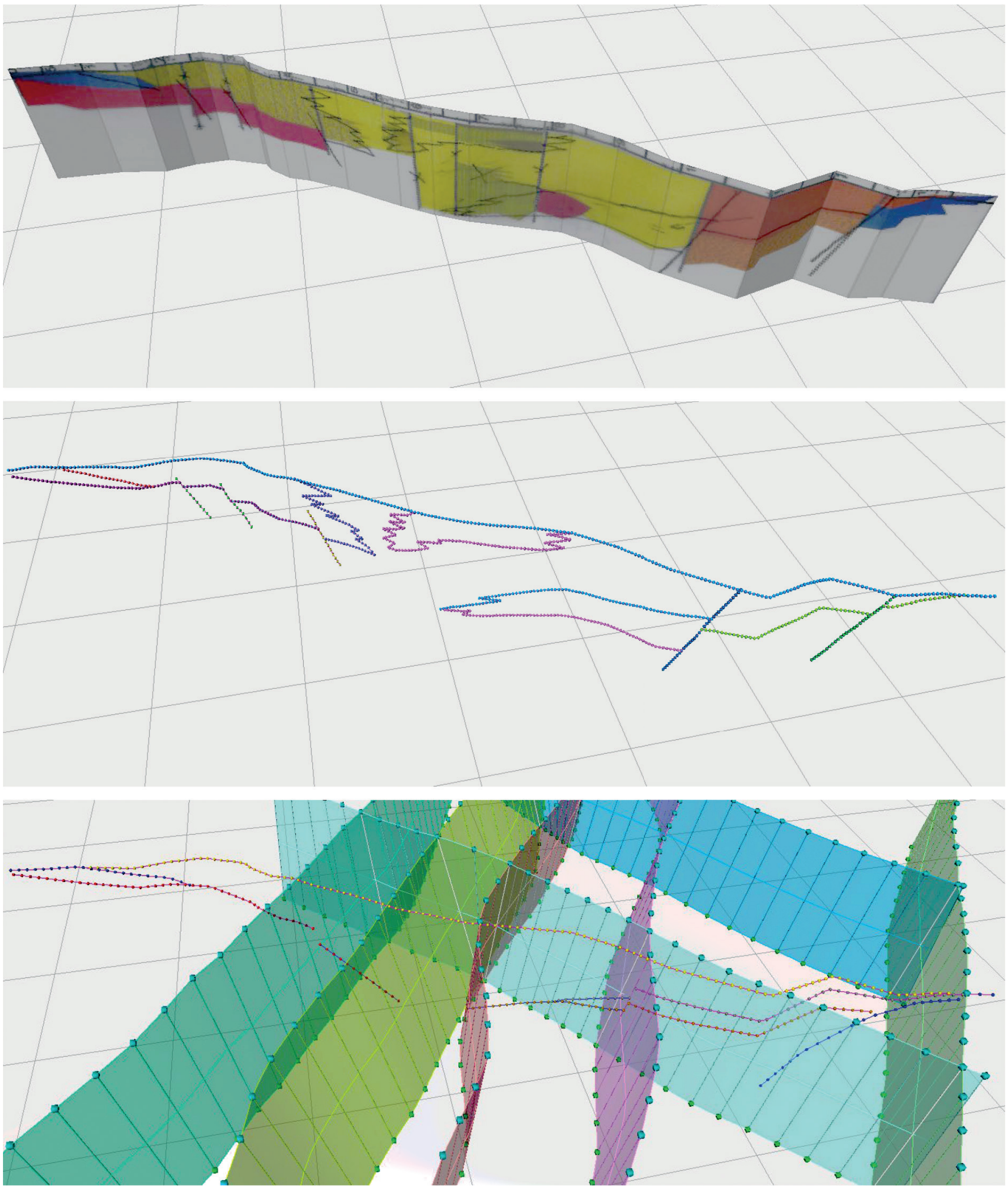

Fig. 1.7. *Digitization of raster 3D profiles - detail of works.*
Top: Raster interpreted VES profile georeferenced in 3D (1st stage)
In the centre: Digitization of interfaces into vector form in space (2nd stage).
Bottom: Final interpretation (stage 3).

is again a layered sequence of Neocomian age overlain by the Hronicum tectonic outliers. Larger continuous areas consist only of Ramsau Dolomite and Cretaceous carbonates. The remaining carbonatic, clayey and clastic sediments (Gutenstein-type limestone, Podhradie Limestone, Carpathian Keuper, Kopienec Fm, Allgäu Mb., siliceous Fleckenmergel, radiolarans and flyschoid formation) occur in the form of relatively thin stripes.

The Hronicum rocks (age range Triassic-Anisian to Norian) in the segment **7**, consist of two elements. The lower structure is composed of Gutenstein Limestone, Ramsau Dolomite and Haupt Dolomite and marginally by Lunz Mb. The upper one is formed by the so-called tectonic outlier "Studenec", represented by Gutenstein Limestone and Wetterstein Dolomite, marginally also by Schreyaralm Limestone. The Wetterstein and then the Haupt Dolomite occupy the largest area.

The segment **8** is formed by rocks of the Fatricum and Hronicum. The oldest and at the same time the lowest parts of the Fatricum belong to the Middle Triassic sequences. The setting is complicated by the unevenly developed duplex structure, in which the sequence of the Middle Cretaceous age lies again on the Early Cretaceous. The Fatricum sediments are also exposed in small isolated islands between the Valčianska dolina Valley and Lázky in the narrow strip of NE direction.

The Fatricum sediments (age range of Triassic-*Anisian* to Cretaceous-*Aptian*) are represented by carbonatic, clastic and clayey rocks (Ramsau Dolomite, Lunz Shale, Carpathian Keuper, Kössen Mb., Kopienec Fm., Allgäu Mb., siliceous limestones, radiolarian limestones, marls and marly limestones).

The minor tectonic outliers of the Mesozoic Hronicum units, represented by the Ramsau Dolomite and the Gutenstein Limestone, rest either on the first thrust slice or on the duplex block.

In the segment **9**, the Mesozoic Tatricum units are situated in small occurrences on the SE slopes of Lúčanská Malá Fatra Mts. They overlie directly the crystalline rocks. They consist only of clastic sediments of the

Lúžna Formation and of Gutenstein Limestone (age range Triassic-*Scythian* to *Anisian*).

Among the Mesozoic formations of the Fatricum (age range from Triassic-*Rhethian* to the Cretaceous-*Hauterivian*), the Allgäu Mb. is the most widespread. In addition to it, there are also carbonatic, organodetritic and shale sediments (Kopienec Fm., Fatra Mb.).

Borové Fm. (Lutetian, code 10)

It consists of conglomerates, breccias and organogenic limestones.

Huty Fm. (Priabonian, code 11)

It is made of shales, sandstones and menilite claystones.

Rakša Fm. (Eggenburgian, code 14)

The Rakša Fm. is the oldest Neogene sediments complex, formed by brecciated conglomerates of carbonate rocks and layers of sandy limestones with a fauna of molluscs.

Budiš Fm. (Sarmatian-Pannonian, code 20)

The formation occurs only in the southern part of the basin, in forefront of the Žiar mountain range. The deposits have the character of a flood cone (sediments of planar torrents or a braided river). The main rock component are washed-out granite deluvia transported over short distances and erosion products of the packaging Mesozoic. They are mainly sands - sandstones of arkose-like character with varying degrees of lithifying from loose to dense or slightly cemented.

Turčok Fm. (code 18.1)

The Turčok Fm. (*Late Badenian*) is made of epiclastic conglomerates, tuffs, pyroclastic breccias and lava flows of various varieties of andesite volcanism.

Abramovce Mb. (Pannonian-Pontian, code 21)

The main rock type are gravel - gravel sands of exclusively carbonate composition. These are sediments of dense gravitational flows (debris flow) settled in the form of fans.

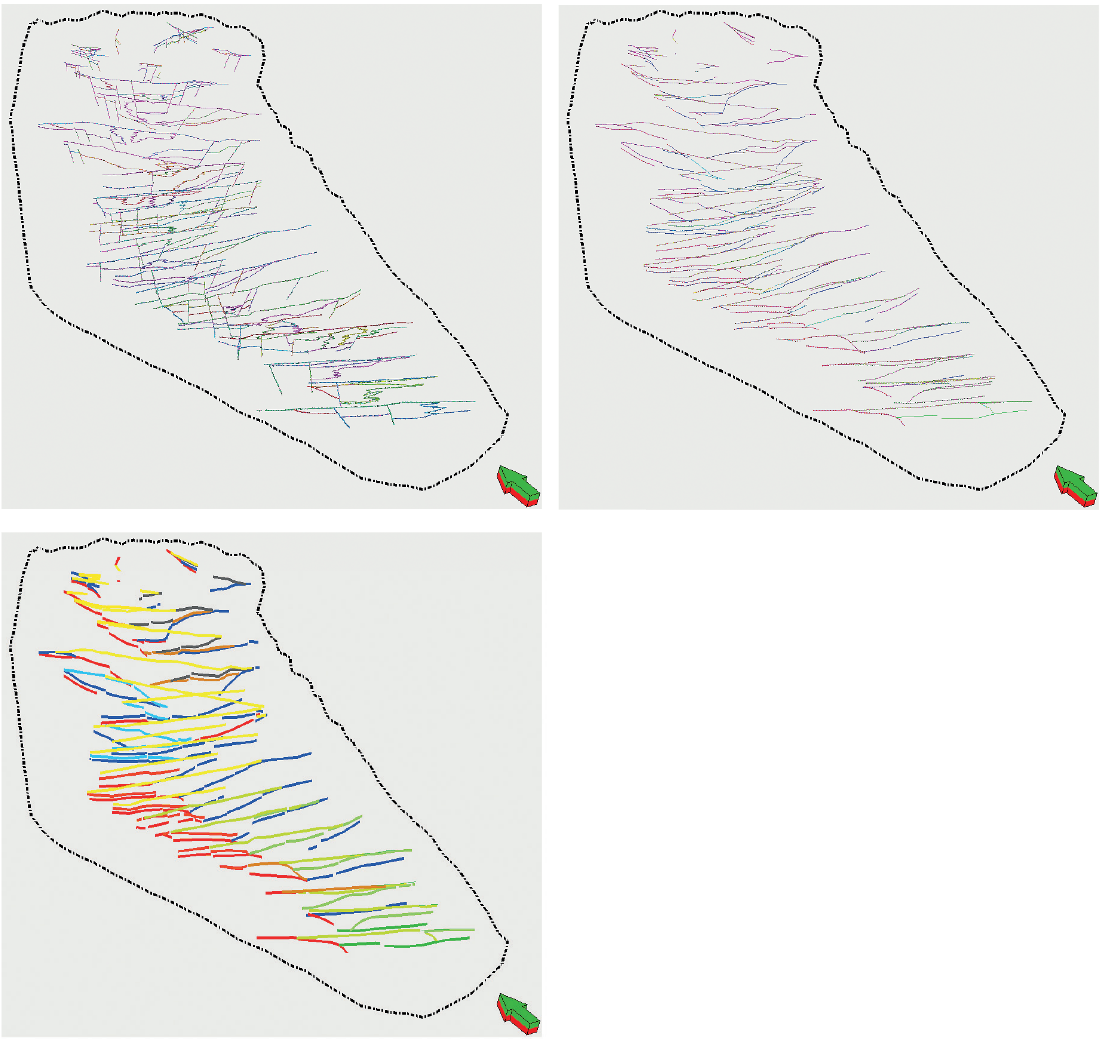

Fig. 1.8. *From digitization to 3D database.*
Top left: vector interfaces by profiles 2nd stage.
Top right: vector interfaces by profiles 3rd stage.
Below: Colour-indicated interfaces of overburdens of selected complexes (see Tab. 1.2).

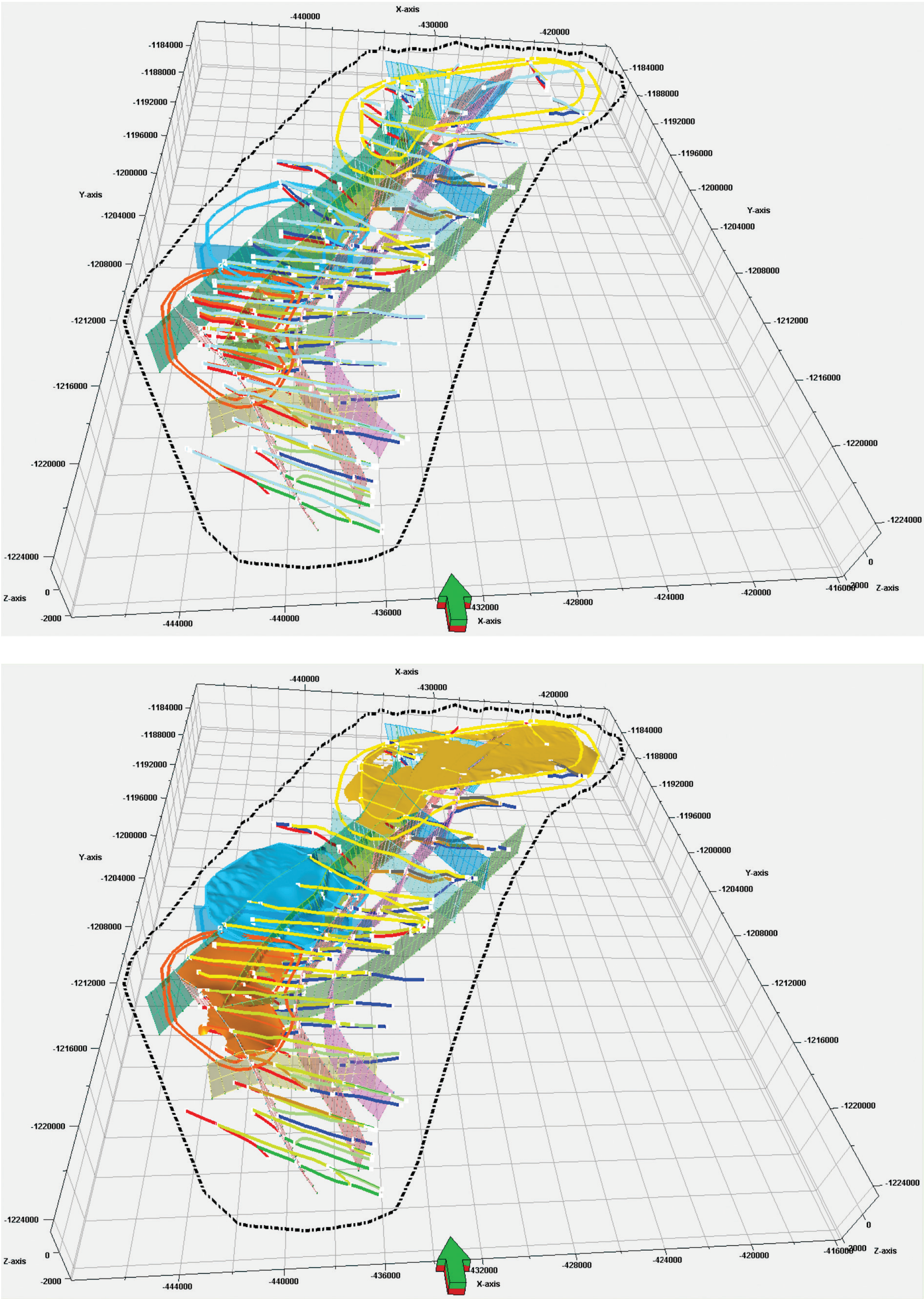

Fig. 1.9. Interfaces and their occurrence.
Above: 3 selected complexes are displayed: Budiš Fm., Abramovce Mb. and Bystričany Fm. and their probable wedging out. The selected units are shown below as a 3D modelled surface.

Martin Fm. (Sarmatian-Pontian, code 16-24)

The formation forms the main part of the Neogene filling of the basin. In terms of lithofacies it is variable, with the main component being clays with different proportions of sandy admixture. Furthermore, there occur so-called coaly clays, lignite seams, clayey sands to sands, rare sandstones, fine to medium-grained carbonate conglomerates and freshwater limestones and occasionally tuffites.

Jastrabská Fm. (code 18.2)

The Jastrabie Fm. (*Late Sarmatian-Early Pannonian*) consists of rhyolite epiclastic sandstones and breccias, tuffs, extrusions of rhyolites and their breccias and lava flows.

Bystričany Fm. (Pliocene, code 19)

It consists of coarse sediments of subaerial and subaquatic gravitational flows (debris flow) deposited in the form of fans. In contact with the crystalline massif of Lúčanská Malá Fatra Mts., these are rather breccias and boulder conglomerates with blocks of several m^3 in volume, made of dolomites and limestones. From the edge, the size of the pebbles gradually decreases. Unlike the Slovany and Abramovce Mbs., their composition is varied.

Quaternary (code 0)

Quaternary sediments have the largest area distribution in the Turčianska kotlina Depression. In the past, they were most completely studied by Halouzka (in Gašparik et al., 1995), according to whom the determining genotype of the Quaternary alluvial sediments in this basin are terrace-type sediments.

To each of the individual 3D boundary lines an attribute was assigned which characterized the modelled complex. These objects were grouped according to the modelled horizon (Tab. 1.2). Models of individual horizons were formed gradually from the base (granitoids). The 3D boundaries created faithfully corresponded to the data from the profiles (where they were at hand), but in areas where there was no data, their extrapolation was challenging (Fig 1.9). For this reason, it was necessary to include other expert information in the modelling, such as the probable wedging out of the layers, which was performed in a similar way as in the calculation of mineral reserves. (In the construction of 3D polygons, the wedging out was inserted within 1/2 of the distance between positive and negative occurrence in the profiles, respecting the morphology between the profiles and stratigraphy (Fig. 1.9).

Progressing from the base to the overburden, the errors of topological connections between objects, or various interpolation artifacts (extrapolation of the Mesozoic below the granitoids, the outcrop of a layer at the surface where it was not possible according to the geological map and interpreted profiles, etc.). Gradually, all modelled units were created in the form of 3D surfaces in this way (Figs. 1.10, 1.11).

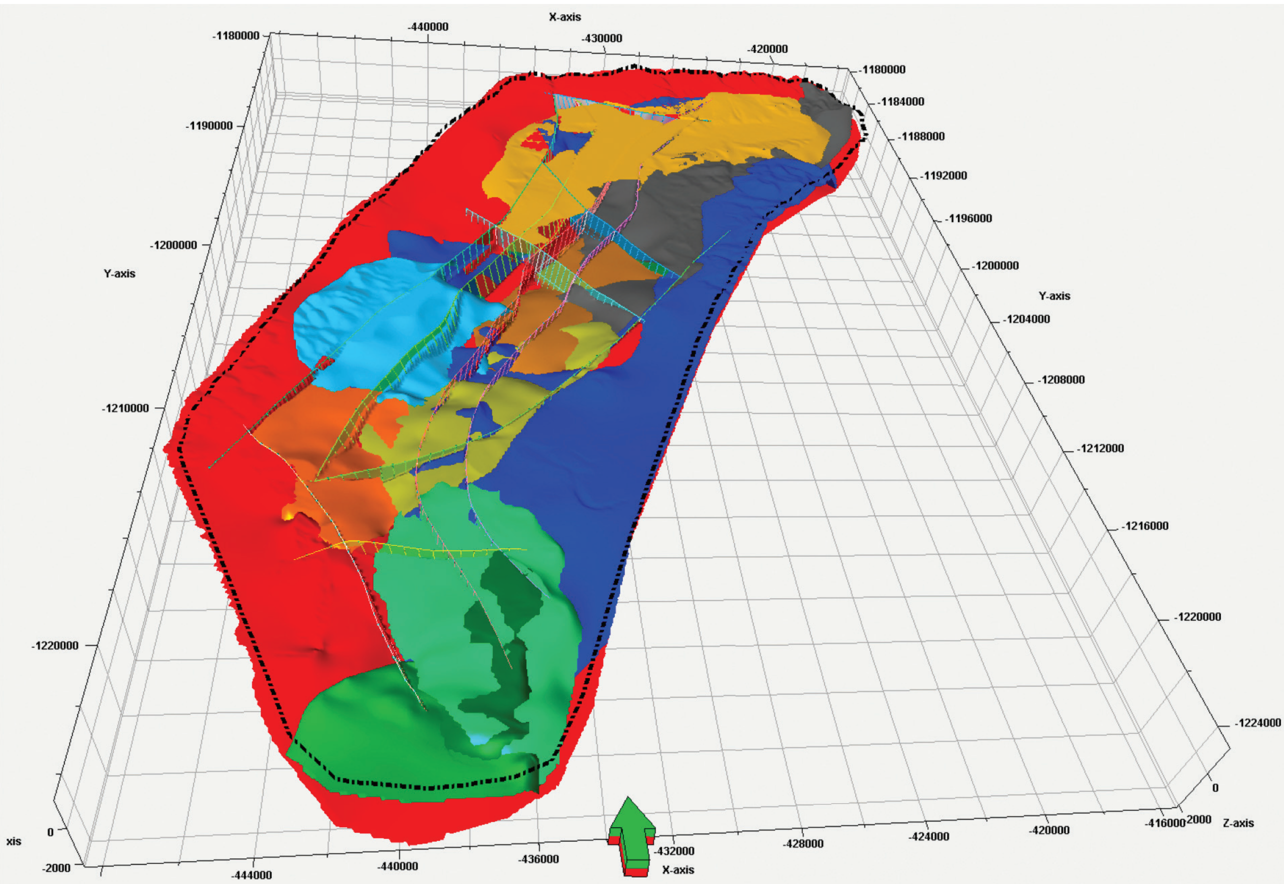

Fig. 1.10. *3D geological model (except for the Martin Formation and the surface) and faults in the Turčianska kotlina Depression.*

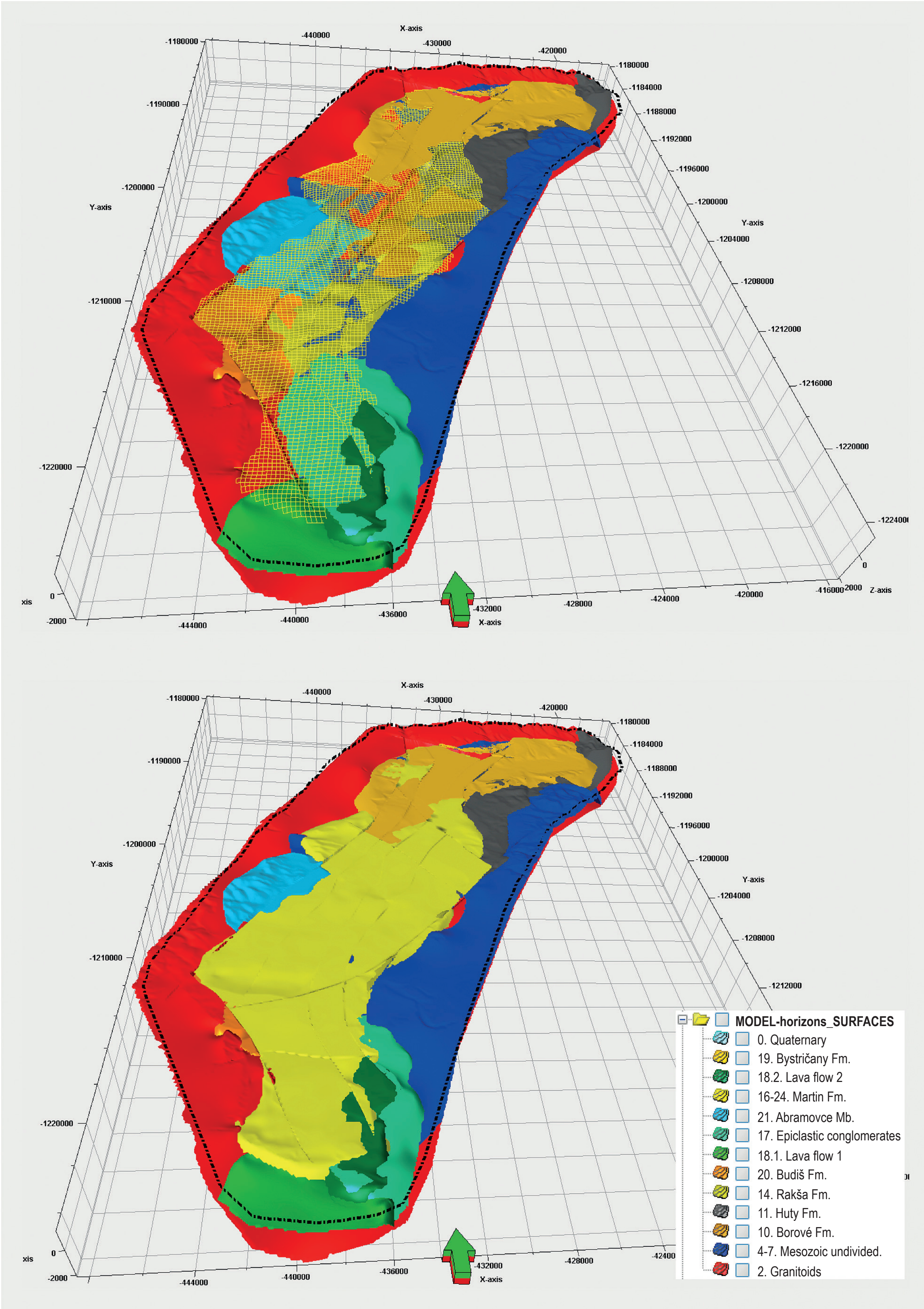

Fig. 1.11. *3D geological model of the Turčianska kotlina Depression.*
Above: exposed model (Martin Formation is shown in the form of a hatch).
Bottom: 3D geological model with legend (without Quaternary).

1.3 Results of the 3D modelling reflecting individual formations

In the following text, for the sake of clarity, the individual modelled complexes (except for granitoids) are shown as follows (Figs. 1.12-1.23).

At the top left is a view of the modelled unit (formation, layer) from SW, at the top right is a modelled unit loaded on the ***cumulative*** surface of the underlying layers. The bottom left shows the unit thickness in [m] and the bottom right its approximate modelled range projected onto the surface of the area with DMR and topography.

MESOZOIC

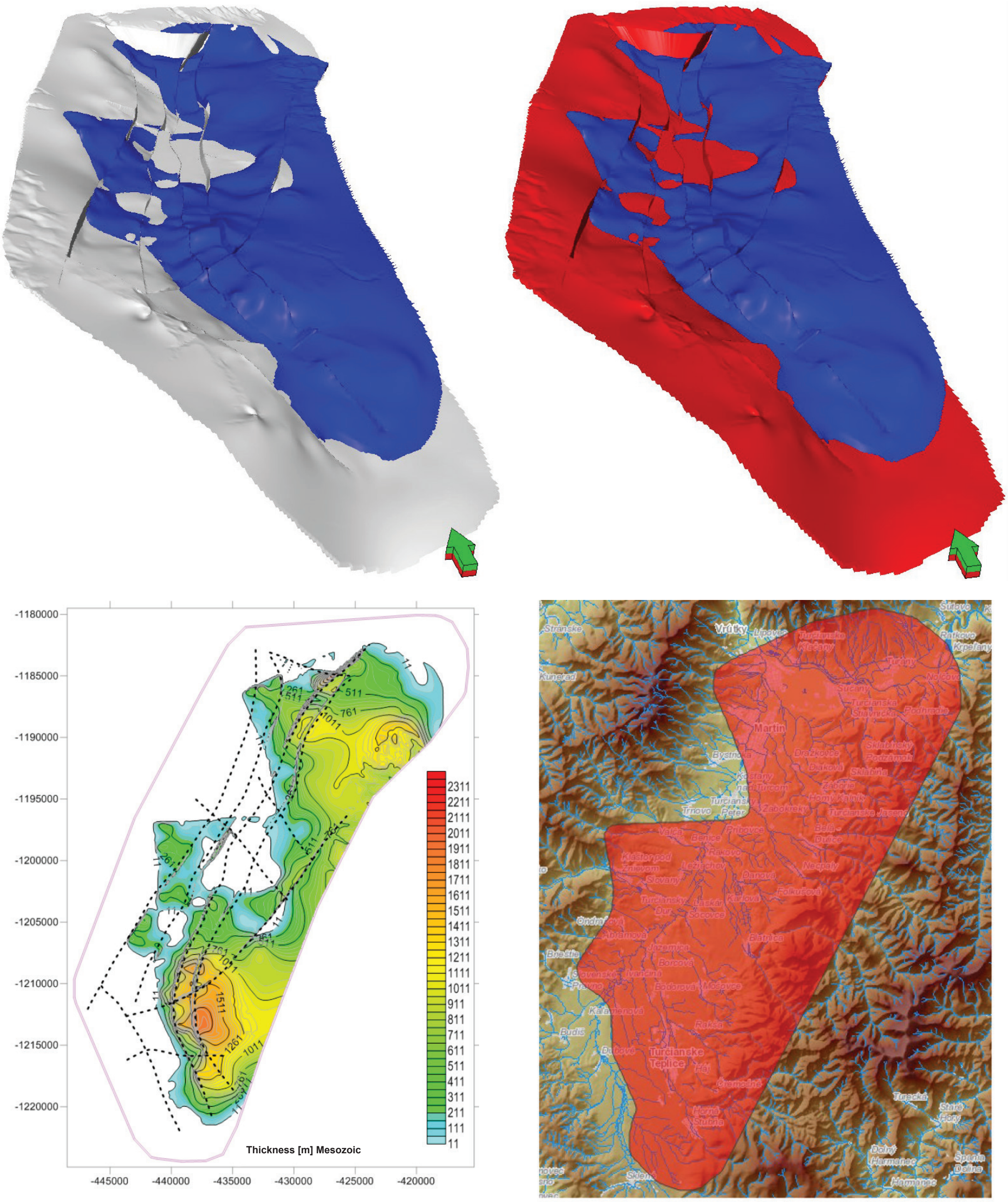

Fig. 1.12. *Mesozoic.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (here: granite), bottom left: thickness [m],bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

BOROVÉ FORMATION

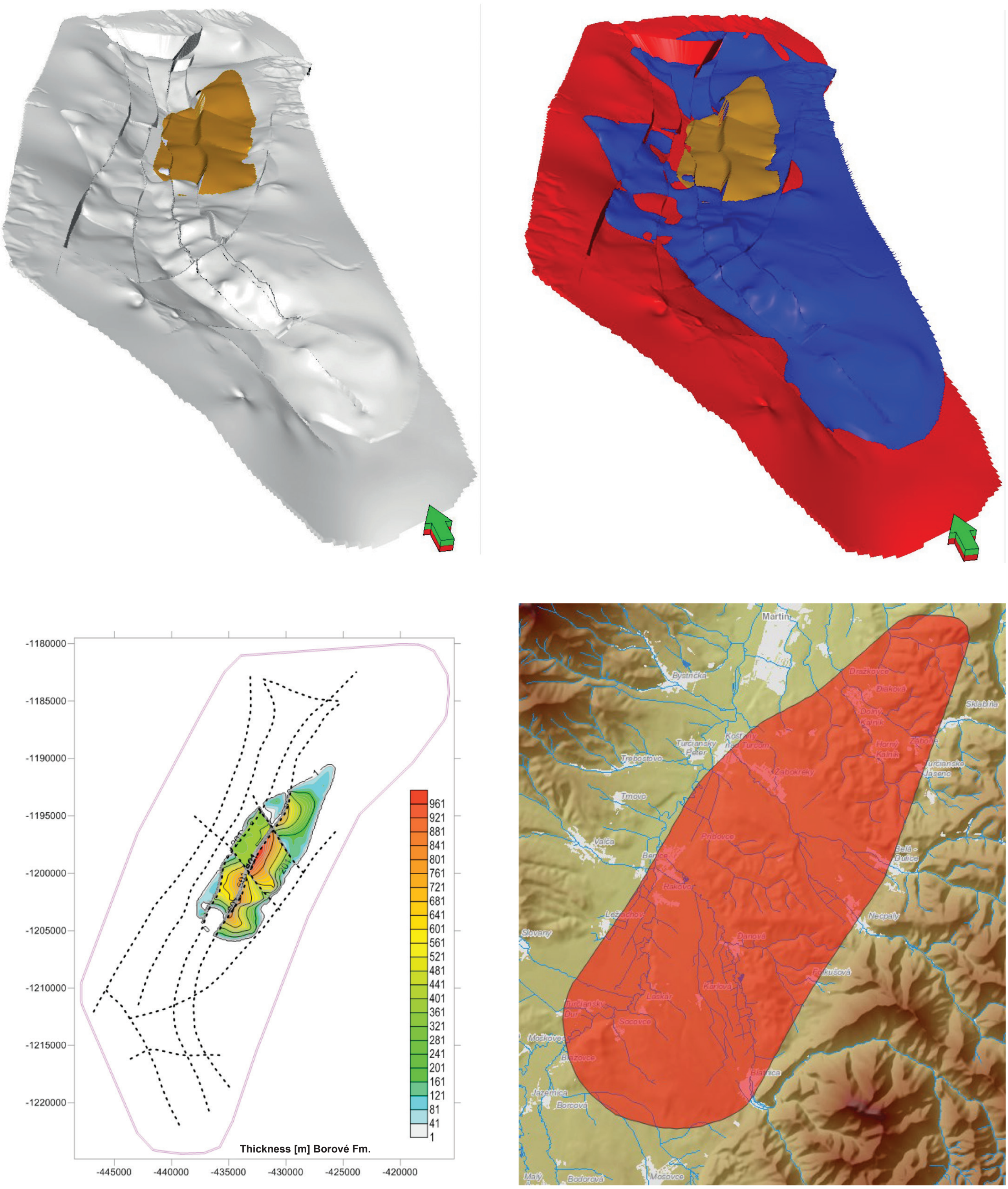

Fig. 1.13. *Borové Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the underlying formations (in this case: granite and Mesozoic), bottom left: thickness in [m],bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

HUTY FORMATION

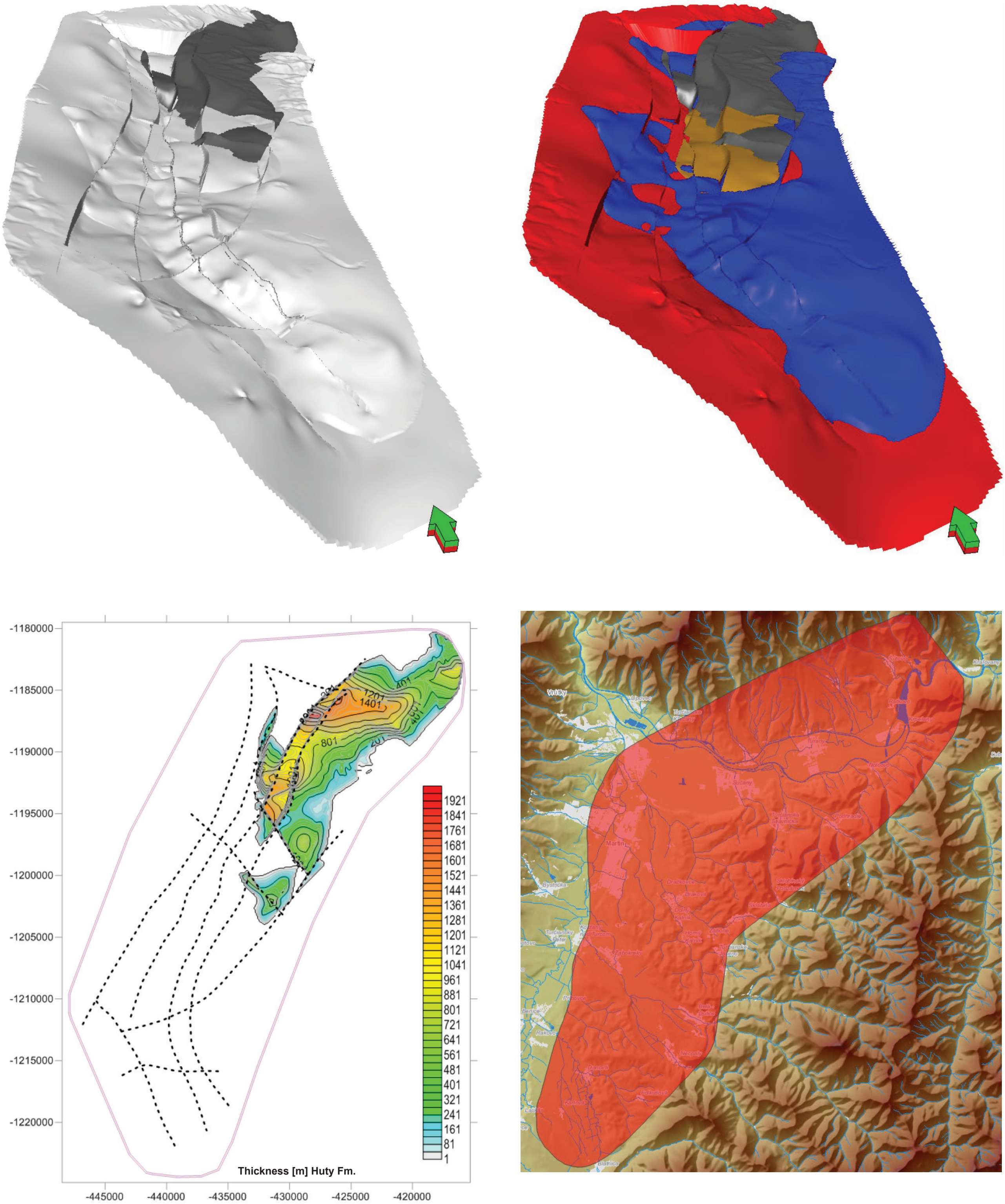

Fig. 1.14. Huty Formation.
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

RAKŠA FORMATION

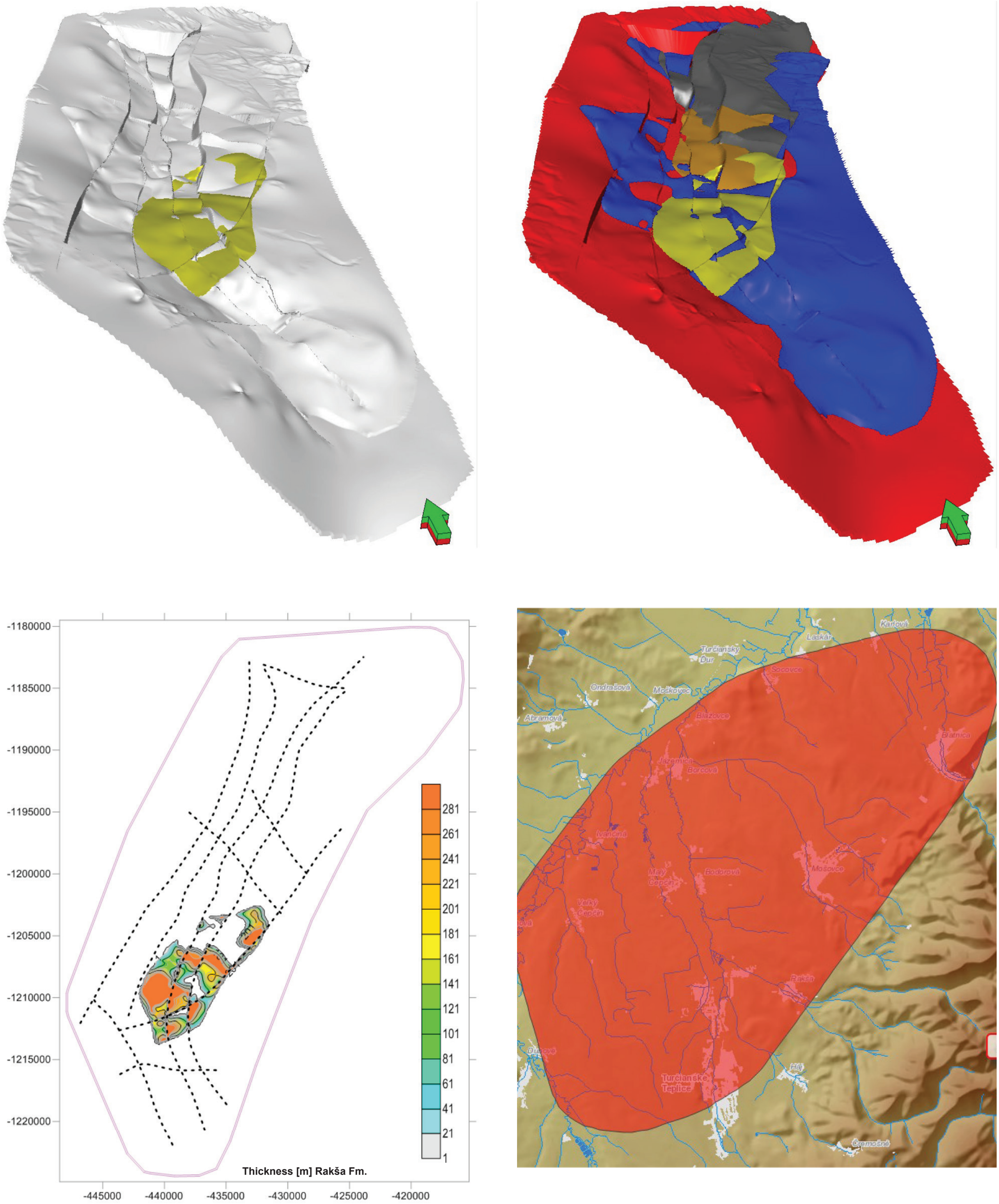

Fig. 1.15. *Rakša Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

BUDIŠ FORMATION

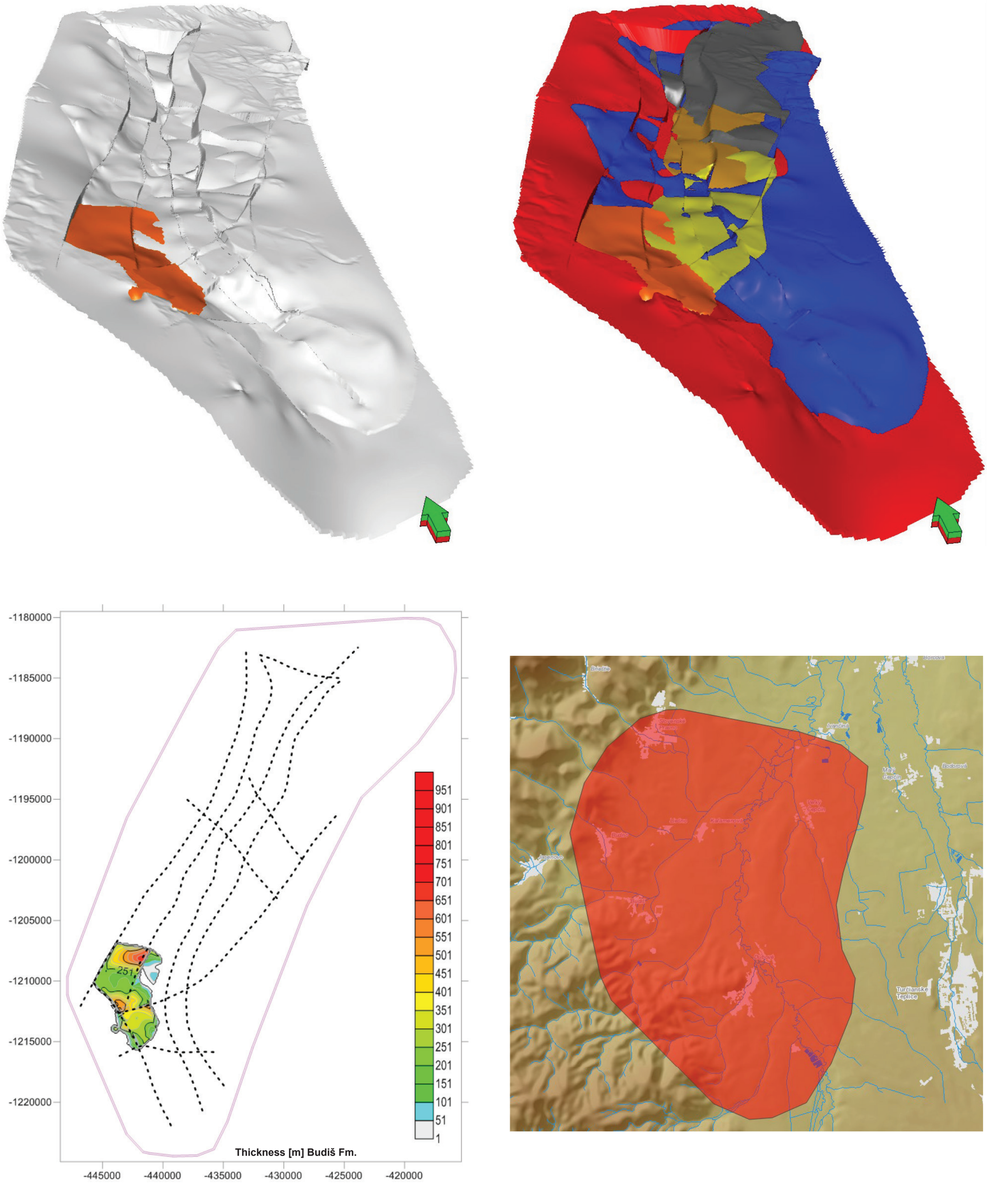

Fig. 1.16. *Budiš Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

TURČOK FORMATION

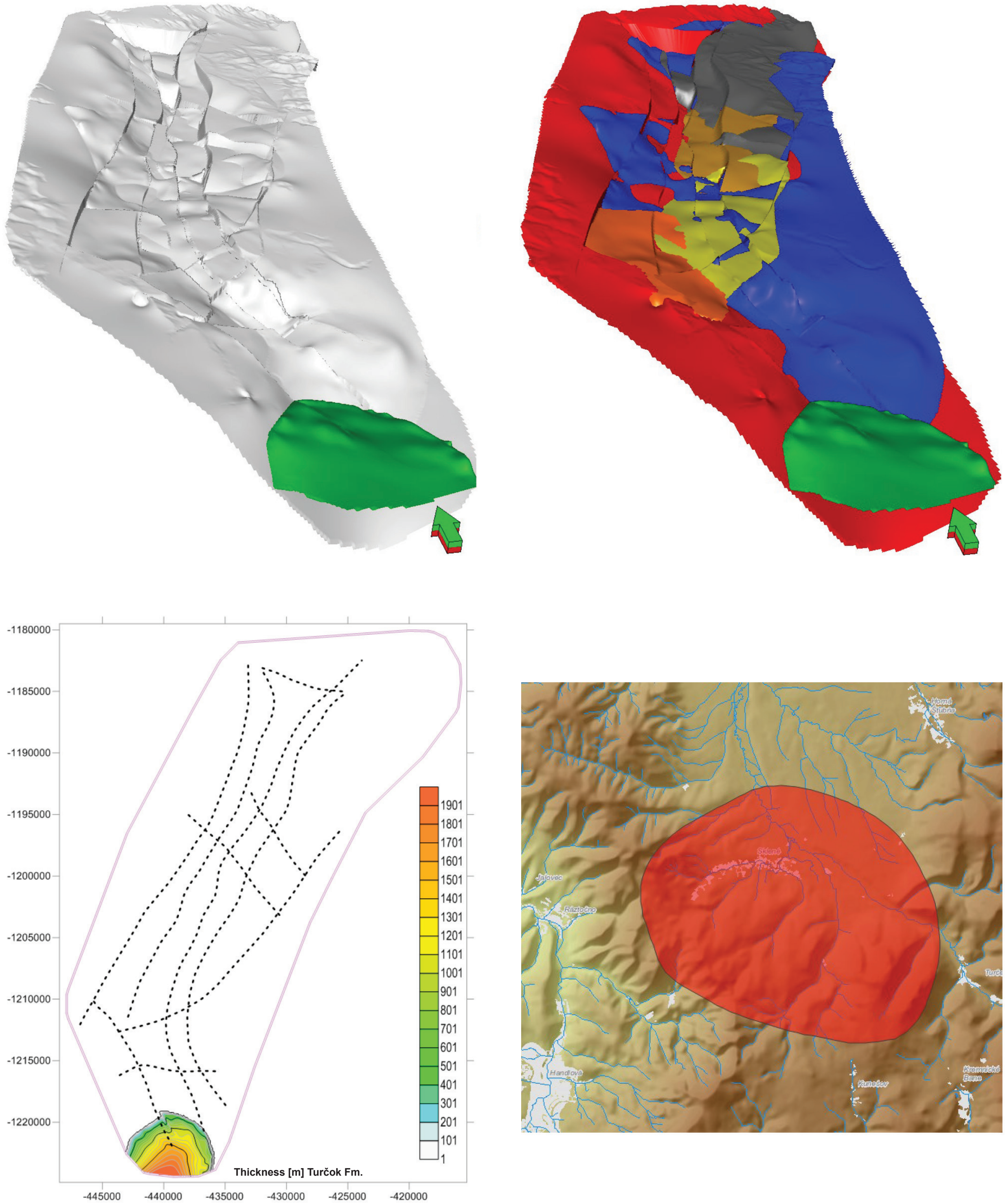

Fig. 1.17. *Turčok Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

EPICLASTIC CONGLOMERATES

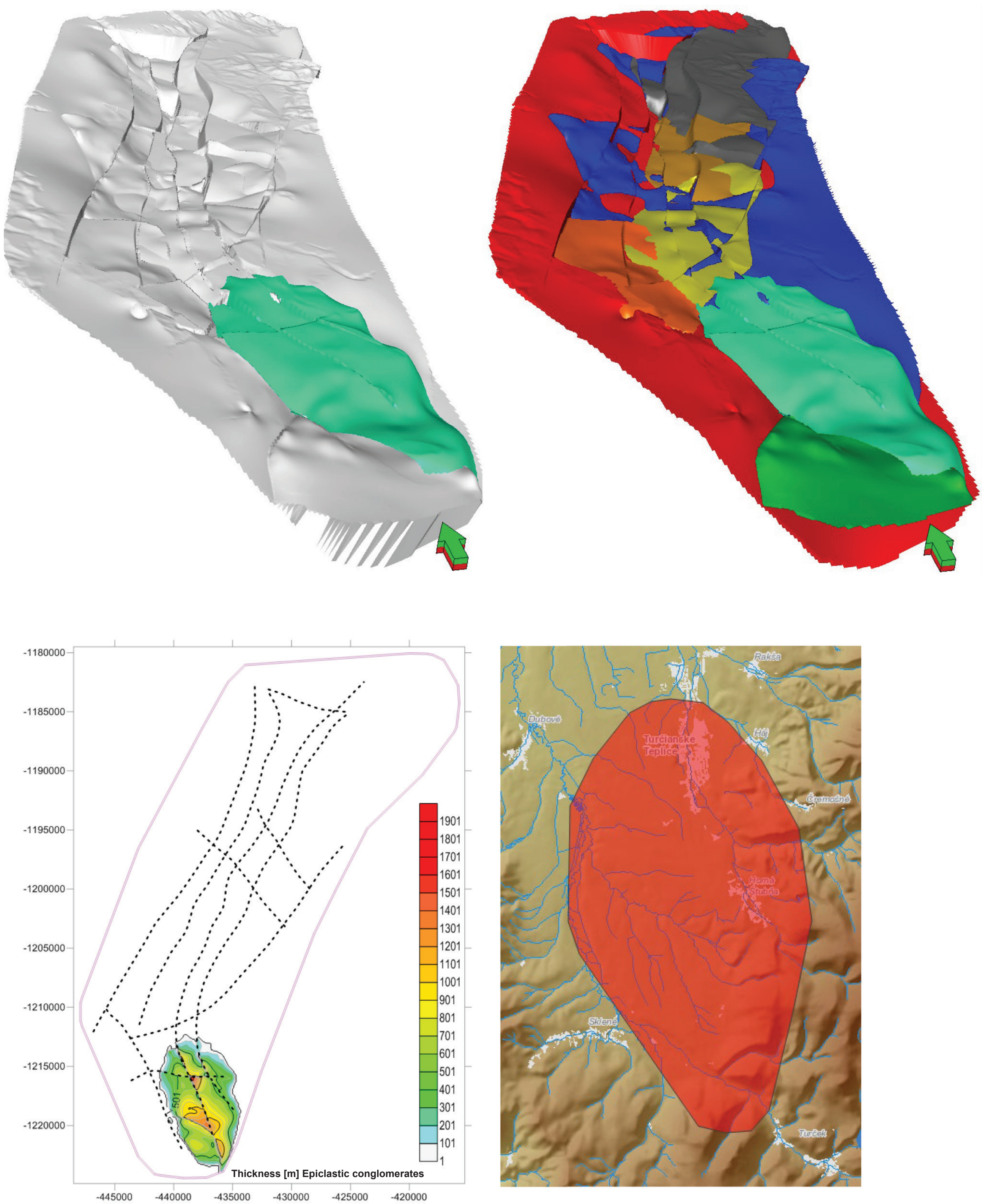

Fig. 1.18. *Epiclastic conglomerates.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

ABRAMOVCE MEMBER

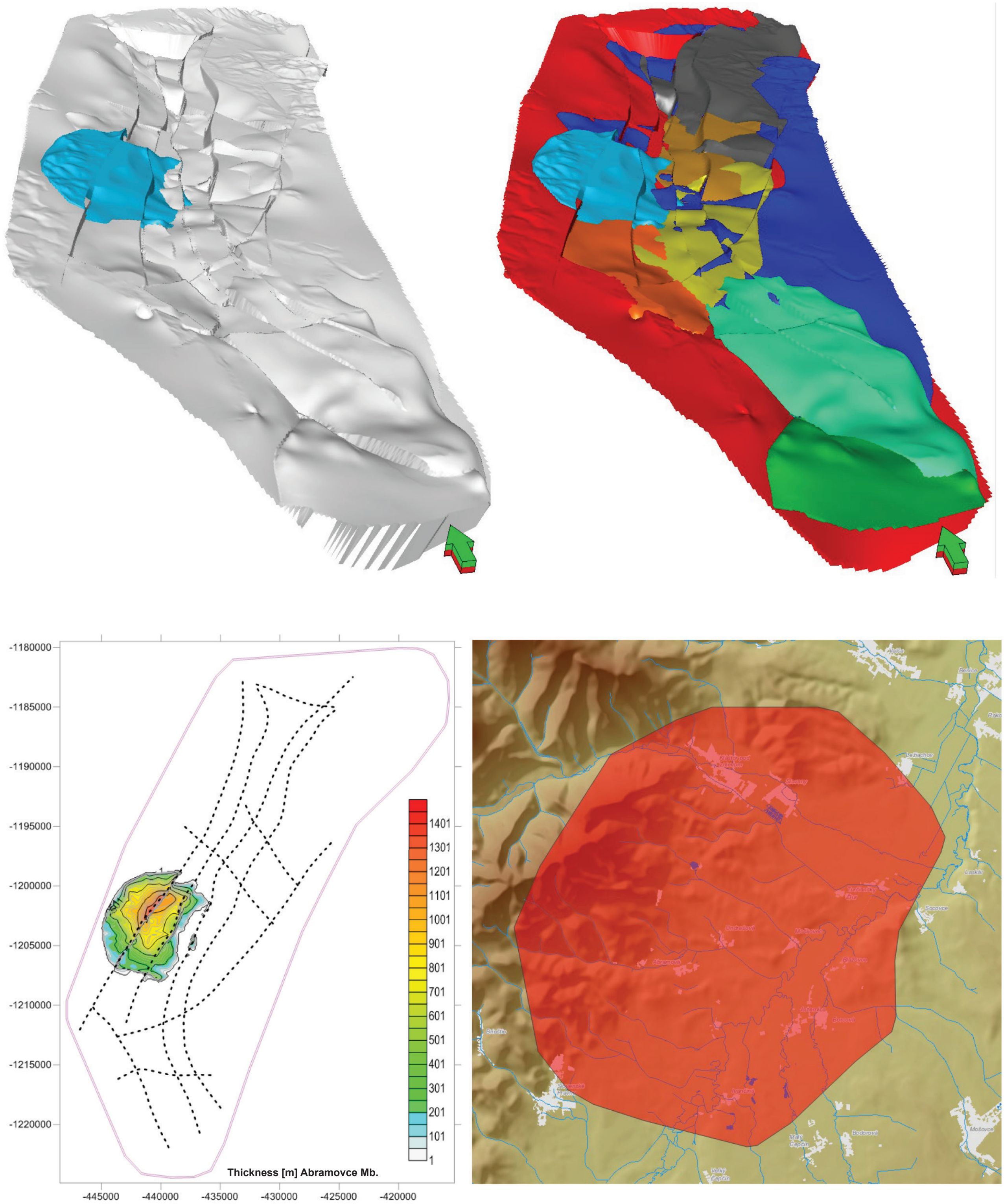

Fig. 1.19. *Abramovce Member.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

MARTIN FORMATION

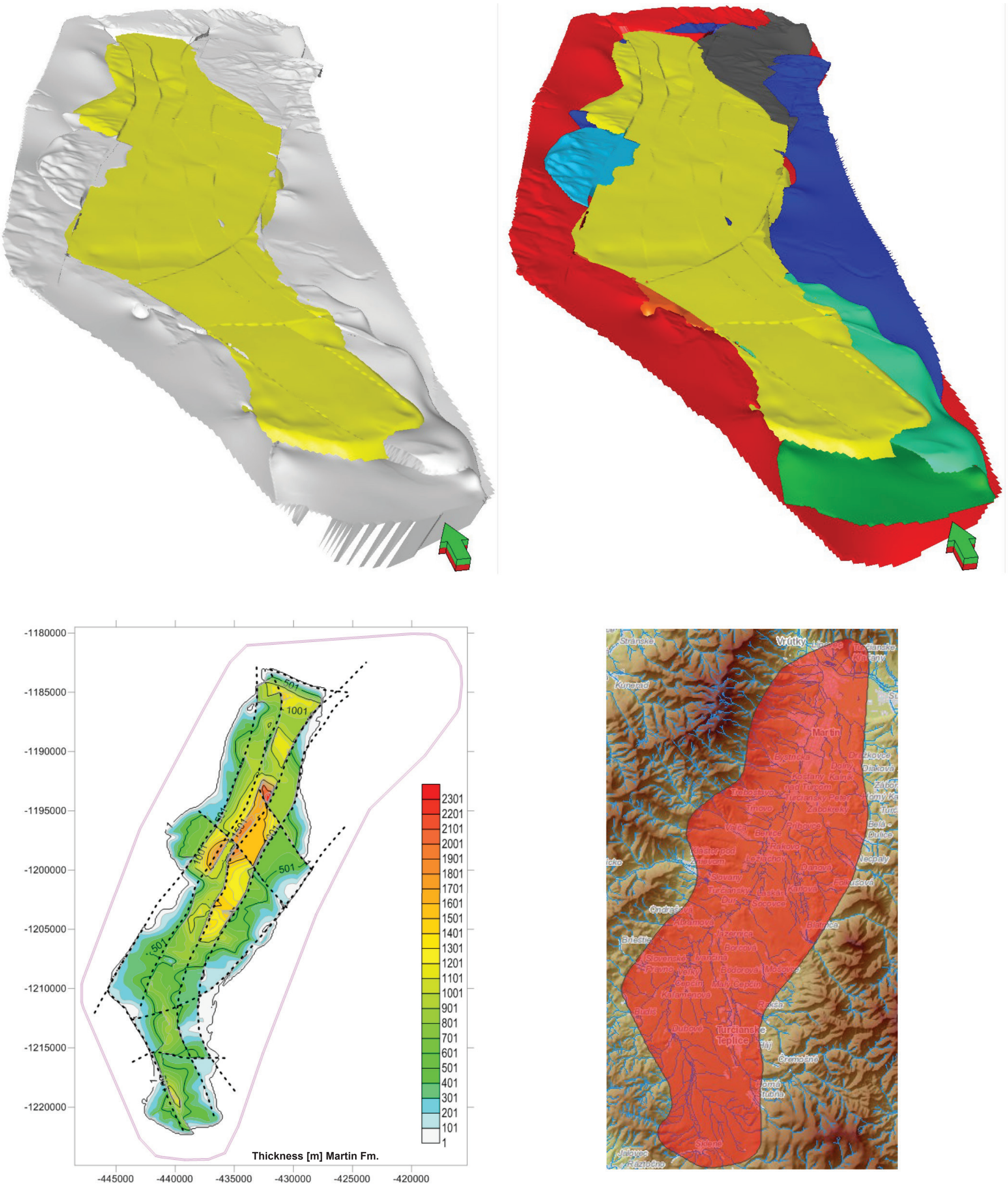

Fig. 1.20. *Martin Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

JASTRABIE FORMATION

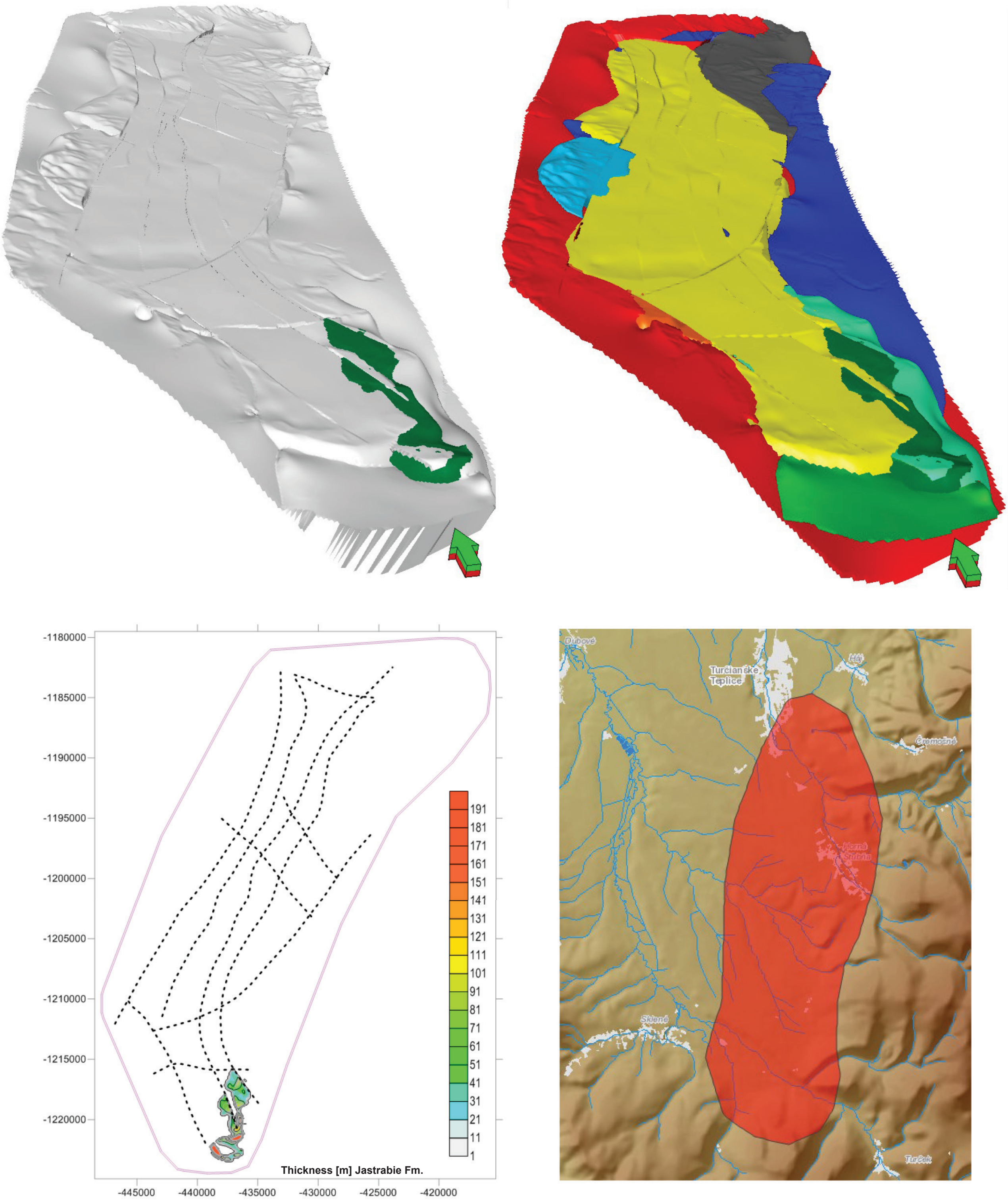

Fig. 1.21. *Jastrabie Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

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BYSTRIČANY FORMATION

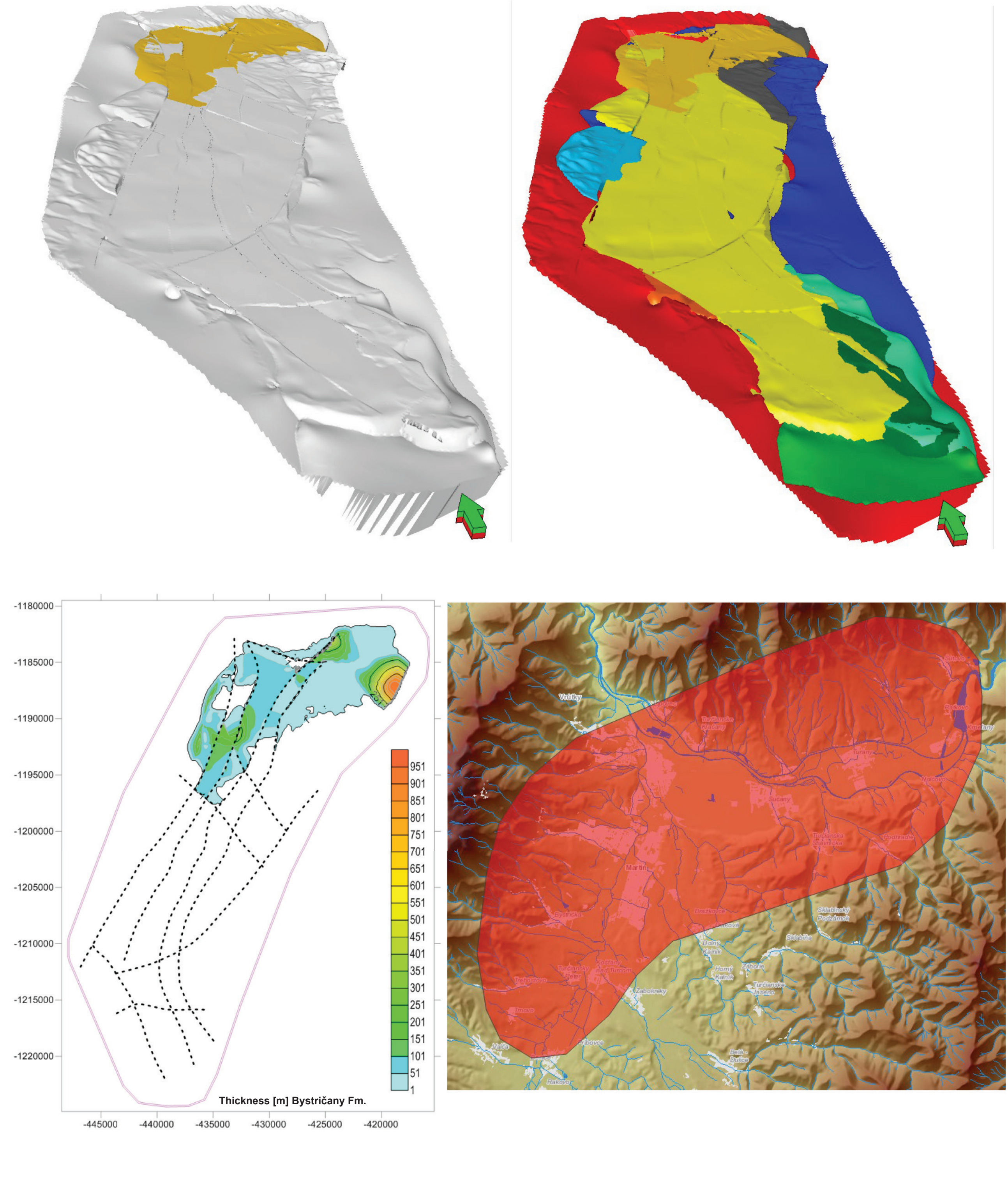

Fig. 1.22. *Bystričany Formation.*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m], bottom right: approximate extent projected onto the surface of the area with DMR and topography (display without scale).

QUATERNARY

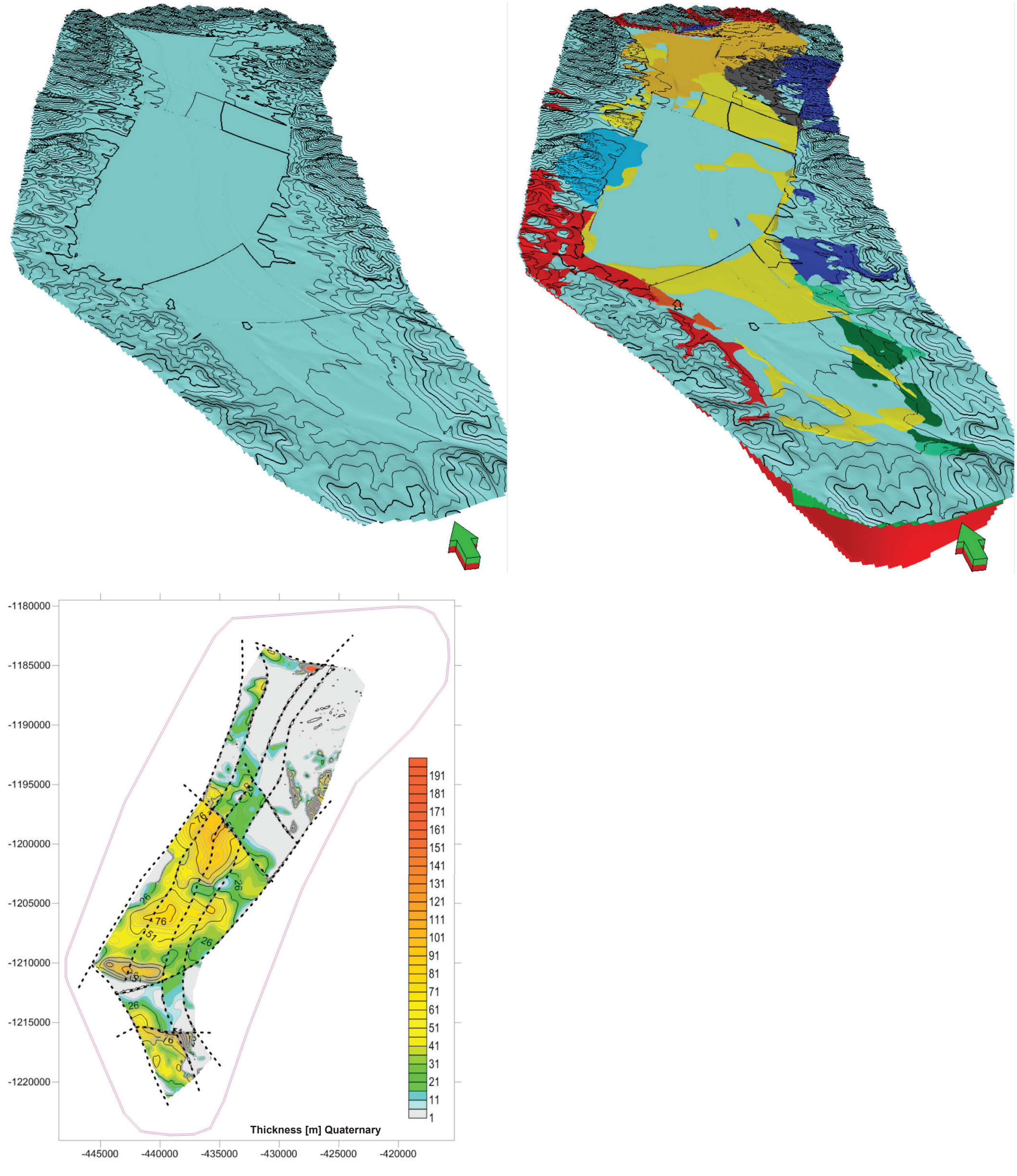

Fig. 1.23. *Quaternary (DEM).*
Top left: view from SW, top right: loaded on the cumulative surface of the bedrock (in this case: previous complexes), bottom left: thickness in [m].

1.4 Results by individual segments

As we mentioned above, the 3D space of studied area was divided by generalized faults to tectonic segments (see Fig 1.24).

SEGMENT 1: The Segment 1 forms a marginal zone outside the central part up to the edge of the study area. It covers an area of 420.7 km^2 and contains all modelled complexes /formations, except the Borové and Rakša Fms.

SEGMENT 2: It covers an area of 37.36 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Martin Fm., Budiš Fm. and Abramovce Mb.

SEGMENT 3: It covers an area of 26.45 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Borové Fm., Huty Fm., Rakša Fm. and Martin Fm.

SEGMENT 4: It covers an area of 34.92 km^2 and contains complexes/formations:

Granitoids/Crystalline complex, Mesozoic undivided, Borové Fm., Rakša Fm., Martin Fm., Budiš Fm. and Abramovce Mb.

SEGMENT 5: It covers an area of 22.07 km^2 and contains complexes/formations:

Granitoids/Crystalline complex, Mesozoic undivided, Borové Fm., Huty Fm., Rakša Fm., Martin Fm. and Abramovce Mb.

SEGMENT 6: It covers an area of 16.43 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Borové Fm., Huty Fm. and Martin Fm.

SEGMENT 7: It covers an area of 25.86 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Huty Fm., Martin Fm. and Bystričany Fm.

SEGMENT 8: It covers an area of 16.52 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Huty Fm., Martin Fm. and Bystričany Fm.

SEGMENT 9: It covers an area of 14.7 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Huty Fm., Martin Fm. and Bystričany Fm.

SEGMENT 10: It covers an area of 11.9 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Rakša Fm., Martin Fm., epiclastic conglomerates and Budiš Fm.

SEGMENT 11: It covers an area of 9.08 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Martin Fm. and Bystričany Fm.

SEGMENT 12: It covers an area of 8.05 km^2 and contains complexes/formations: Granitoids/Crystalline

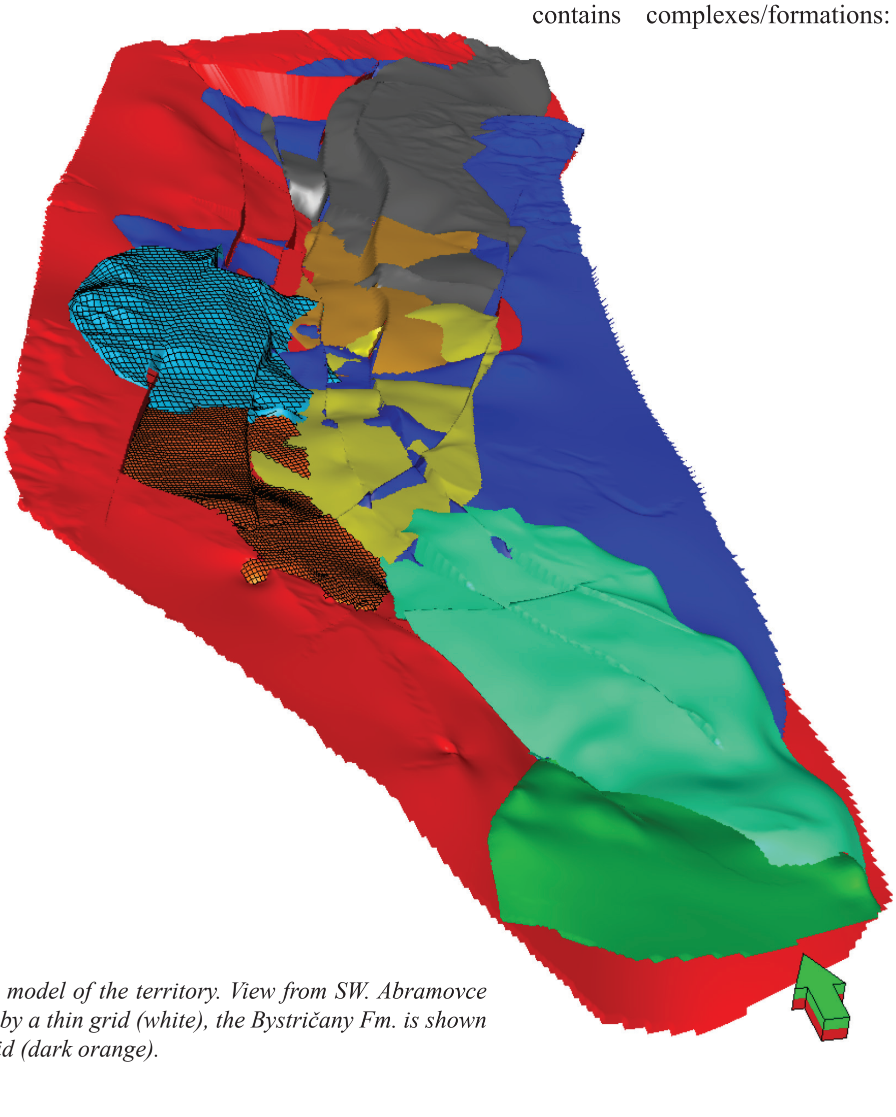

Fig. 1.24. *3D model of the territory. View from SW. Abramovce Mb. is shown by a thin grid (white), the Bystričany Fm. is shown by a dense grid (dark orange).*

complex, Mesozoic undivided, Borové Fm., Huty Fm. and Martin Fm.

SEGMENT 13: It covers an area of 8.15 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Rakša Fm., Martin Fm. and epiclastic conglomerates and Budiš Fm.

SEGMENT 14: It covers an area of 6.97 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Borové Fm., Martin Fm. and Bystričany Fm.

AUXILLIARY SEGMENT 91: It covers an area of 18.94 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Martin Fm., epiclastic conglomerates, Turčok Fm., and Jastrabie Fm.

AUXILLIARY SEGMENT 92: It covers an area of 8.09 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Martin Fm., epiclastic conglomerates and Jastrabie Fm.

AUXILLIARY SEGMENT 93: It covers an area of 54.60 km^2 and contains complexes/formations: Granitoids/Crystalline complex, Mesozoic undivided, Borové Fm., Huty Fm., Martin Fm. and Bystričany Fm.

The area and volume of individual modelled complexes were calculated for each of the 14 tectonic segments of the Turčianska kotlina Depression area delineated. The results are shown in Tab. no. 1.3.

Tab. 1.3. Representation of modelled complexes in individual segments. Material volume in km^3. The modelled complexes are defined with the help of database code for the sake of clarity of the table, the names are assigned to the codes below.

Row	Segment \ formation	2 [km^3]	4-7	10	11	14	16-24	17	19	20	21	18-1	18-2
1	2 [code]	74.55	3.63	-	-	-	14.84	-	-	4.50	12.48	-	-
2	3	45.98	12.82	5.71	0.84	2.35	10.41	-	-	-	-	-	-
3	4	60.69	6.10	0.58	-	2.94	27.14	-	-	1.56	3.22	-	-
4	5	25.38	10.82	5.01	0.09	1.67	21.80	-	-	-	0.03	-	-
5	6	29.12	4.02	7.43	1.39	-	7.26	-	-	-	-	-	-
6	7	35.47	8.92	-	4.85	-	23.80	-	2.12	-	-	-	-
7	8	11.92	8.60	-	19.34	-	7.57	-	0.46	-	-	-	-
8	9	28.94	2.22	-	0.15	-	10.28	-	0.51	-	-	-	-
9	10	24.41	1.27	-	-	0.36	6.42	1.30	-	1.91	-	-	-
10	11	17.61	0.01	-	-	-	7.86	-	12.63	-	-	-	-
11	12	8.56	0.05	3.32	0.42	-	11.33	-	-	-	-	-	-
12	13	8.96	9.85	-	-	0.49	2.50	2.56	-	-	-	-	-
13	14	9.06	0.03	0.46	-	-	10.52	-	0.15	-	-	-	-
14	91	30.05	3.04	-	-	-	9.45	9.88	-	-	-	4.33	0.09
15	92	9.54	8.08	-	-	-	0.57	6.46	-	-	-	-	0.20
16	93	85.80	42.09	4.57	27.21	-	2.45	-	0.06	-	-	-	-
17	Sum1 [r. 1 to 16]	506.06	121.55	37.07	65.29	21.80	174.23	37.19	34.94	27.96	36.73	4.33	0.30
18	continuation		block 1		block 1		block 1	block 1	block 1		block 1	block 1	block 1
19	In directions		NW		NW		W	E	W, NW		W	W, S	S
20	1 - edge	1,000.65	130.90	-	33.07	-	13.55	9.15	8.33	0.36	13.30	26.31	0.35
21	Sum2 [r. 17 + 20]	1,506.71	252.45	37.07	98.37	21.80	187.78	46.35	43.27	28.32	50.02	30.63	0.64

Formation [code]	Name
2	Granitoids/Crystalline complex
4-7	Mesozoic undivided
10	Borové Fm.
11	Huty Fm.
14	Rakša Fm.
16-24	Martin Fm.

Formation [code]	Name
17	Epiclastic conglomerates
19	Bystričany Fm.
20	Budiš Fm.
21	Abramovce Mb.
18.1	Turčok Fm.
18.2	Jastrabie Fm.

Explanations to the Tab. 1.3:
Interpretation in rows: e.g. Segment 6 involves 29.12 km^3 of the Crystalline rocks (code 2), 4.02 km^3 Mesozoic rocks (code 4-7), 7.43 km^3 rocks of Borové Fm. (code 10), 1.39 km^3 rocks of Huty Fm. (code 11) and 7.26 km^3 rocks of Martin Fm. (code 16-24),
Interpretation in columns: e.g. epiclastic conglomerates (code 17) are present in segments 10 (volume 1.3 km^3), 13 (volume 2.56 km^3), 91 (volume 9.88 km^3) and 92 (volume 6.46 km^3).

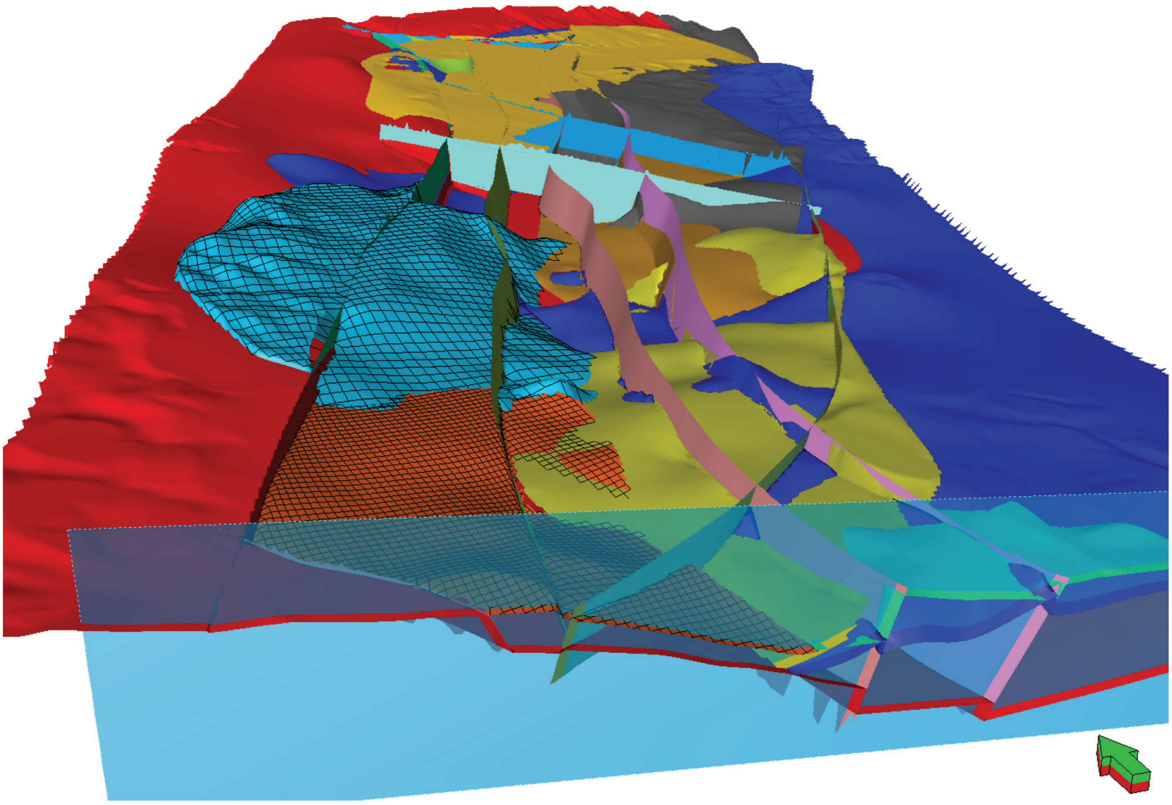

Fig. 1.26. *3D model of the territory. Transverse profile in the central part of the territory through the Budiš Fm. View from S.*

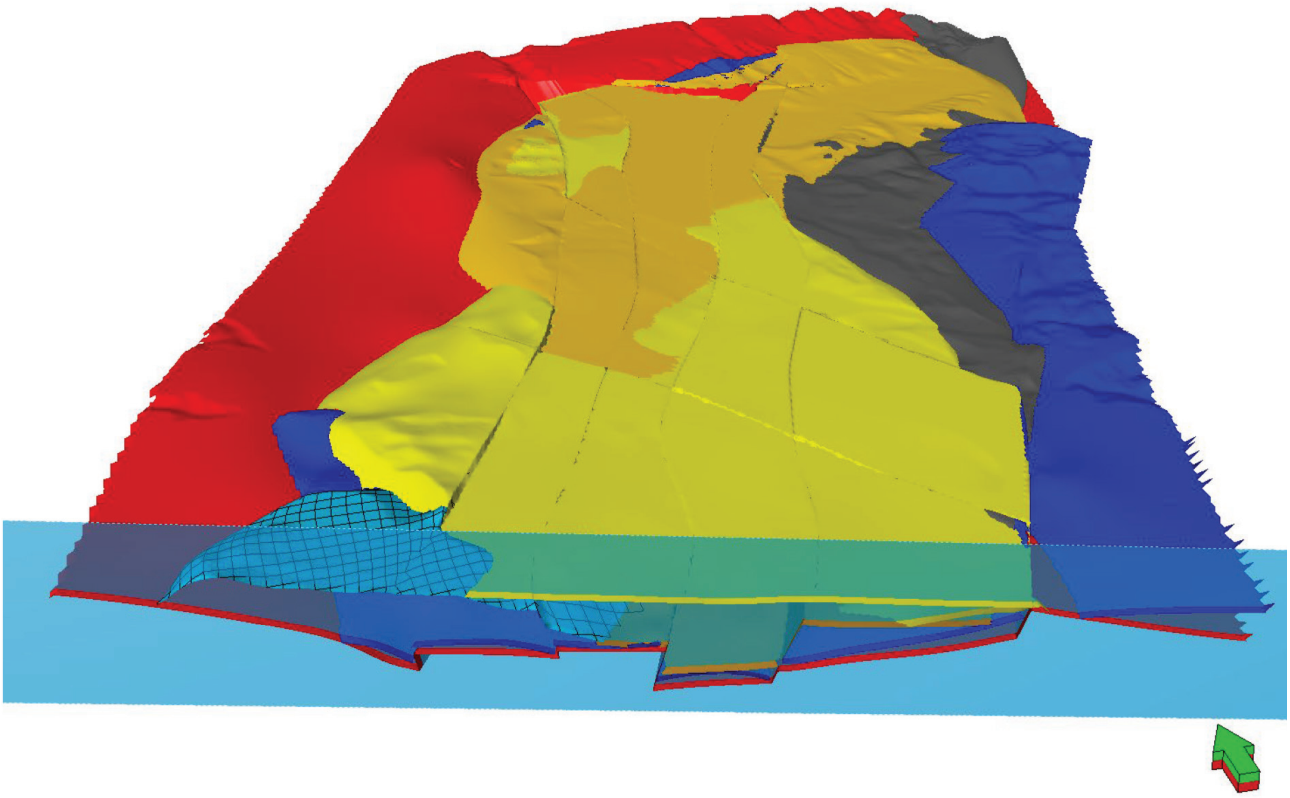

Fig. 1.27. *3D model of the territory. Transverse profile in the central part of the territory through the Abramovce Mb. View from S.*

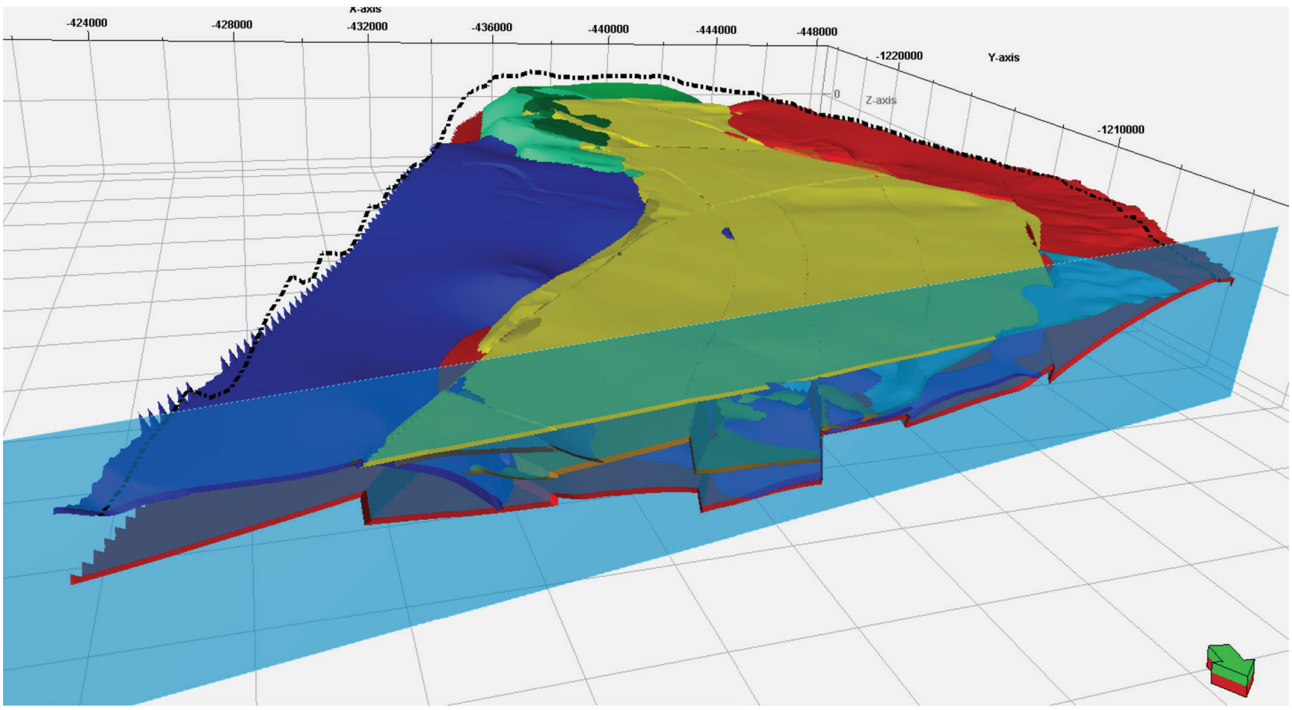

Fig. 1.28. *3D model of the territory. Transverse profile in the central part of the territory through the southern part of the Bystričany Fm. View from N.*

1.5 Visualization options for the 3D model

The visualization options are demonstrated in Figs. 1.24 to 1.28. In 3D models, it is possible to turn on and off individual layers, change their colour, transparency, display method (fill, grid, iso-planes, etc.). In the 3D model, it is possible to create a profile in any direction, a dynamic profile (gradual display of the following profiles with a defined step). The 3D model can be freely rotated, zoomed in/out. Above the created map view, it is possible to create various map compositions after adding a north, scale, legend.

1.6 Conclusion

3D modelling of the Turčianska kotlina Depression took place in several stages. The input data for modelling were deep boreholes and analog geological profiles of the area. When creating the model, it turned out that on the basis of such data it was not possible to model the volume of the basin with sufficient credibility (the quality of the model depends on the quality of input data, which is all the more true in multidimensional modelling) and it was necessary to thicken the input data based on the interpretation of VES profiles. Information from deeper boreholes for calibration of modelled curves was also taken into account in their interpretation. Despite the fact that we did not have any seismic data and the spatial distribution of boreholes and VES probes was not sufficiently uniform, using interpolation and extrapolation techniques, the 3D model of the entire Turčianska kotlina Depression with a depth range of approximately 2 km was created.

In comparison with the pioneer model of the area of the Upper Nitra Basin, where the area of interest occupied an area of 290 km^2 and the model area for 3D output about a quarter, in the Turčianska kotlina Depression the area subjected to three-dimensional geological modelling represented about 750 km^2. In addition to the 3D geological model, other models were created: a geological-geomorphological model of the whole area together with engineering geological characteristics of the rocks and a static hydrogeological model. For the first time in Slovakia, 3D modelling was applied to the basin development of a complete and delimited sedimentary pool.

Since this was the first task of this type, several procedures and algorithms were tested in the 3D modelling. The result of this research was the creation of a comprehensive ***methodological procedure*** for processing geological spatial data for sedimentary basins modelling. The process has been integrated into licensed software products such as ESRI® ArcGIS™ and Petrel® from Schlumberger. The spatial data processing (3D) methodology applied the following processing methods in consecutive steps:

- 3D georeferencing of objects (rasters);
- 3D vectorization (creation of polygons in space by 2D digitization and snapping to the corresponding spatial plane);
- 3D import of objects;
- 3D (spatial) modelling of the distribution of the observed phenomenon;
- 3D modelling of objects (vectors);
- 3D volume modelling;
- 3D visualization and 3D animation.

The resulting ***spatial model of the Turčianska kotlina Depression*** reflects, on the basis of currently known facts, all spatial relationships between the modelled complexes, while the main tectonic lines are also reflected in it - which needs to be emphasized. From the created model, the volumes of individual modelled complexes were calculated, which can be used for further geological analyzes.

The Petrel® software package from Schlumberger was very suitable for the purposes of modelling the sedimentary basin and can be recommended for use in such areas in the future. All modelled objects in the form of 3D vector objects can be easily exported in ASCII format with coordinates and used directly as inputs for specialized programs (e.g. for hydrogeological modelling) or after simple modifications as inputs for other GIS programs, such as ESRI® ArcGIS™ or display some layers in Google Earth™, etc. This procedure was later used in the creation of a 3D geological model of the Slovak Republic at a scale of 1: 500,000, the results of which are presented in a separate article in this issue of the Slovak Geological Magazine (Zlocha et al., 2020, in press).

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