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Development and application of a mathematical-cartographical model to sand / gravel deposits and prospective areas

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The modelling of mineral deposits is a complex process. The paper presents a new automated 3D geological modelling system applied, as an example, to the Rūsteikiai marginal glaciofluvial sediments of Zarasai District (North Lithuania). The model was adapted to analyse the structure and formation of the Rūsteikiai mineral deposit, as well as for estimating the geological reserves of mineral deposits, and finally it was used for design solution, i. e. assessment of the recoverable reserves and the automated designing of quarrying.

Key words: marginal glaciofluvial ridge, 3D modelling, 3D visualization, GRID method

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INTRODUCTION

The 3D modelling of mineral deposits and its application in practice is a complex problem (Kessler et al., 2009; David, Theobald, 2007). A mathematical-cartographical 3D model enables to draft the geological structure of deposits in a comprehensive visualized way. Application of the 3D approach infers volumetric geological mapping. The 3D model can be turned about, cut in any direction, or presented as a block-diagram.

The final goal of the modelling is to handle all parameters of a geological body in the most accurate way in order to obtain a detailed structure of a mineral deposit, its formation conditions, and finally to apply the model for assessing mineral resources in an automated way. It is also crucial for designing the mineral deposit development.

The UAB "GJ Magma" and the UAB "Infoera" have been developing an automated 3D modelling system since 2006. It is supported by the EU funding since 2009.

The study case concerns the Rūsteikiai area (607.5 ha) which includes the proved mineral area of 20.4 ha. The study area is located 0.6 km east of Rūsteikiai Village in the eastern part of the Zarasai District (Northeast Lithuania).

METHODS

The Geomap 3D 2010 software (based on Autodesk Civil) was used to construct the mathematical cartographical model of the mineral deposit. The model was adapted for the analysis of the structure, formation conditions and estimation of geological reserves of the mineral deposits and, finally, for achieving design solutions for the study area. The designing was performed using the 3D Deposit Modelling supplementary software developed by the UAB "GJ Magma" in cooperation with the software author – the UAB Infoera. This supplementary software was elaborated for an automated evaluation of geological prospecting and other data, as well as for assessing geological reserves to be developed later, the compilation of geological profiles in a selected direction and charting 3D block diagrams. It is also used to design the cover (overburden) and production stage slopes according to the pit mine outer side non-production stage inclination angles and to determine automatically the restricted zone allocated for recultivation of the quarry. With the production rate and trend of production given, the system enables calculating and drafting mining timetables. The automated designing can be done for two-slope ground dams, dumps and storages. All this is calculated and modelled in a 3D space.

To build the mathematical cartographical model, the following instruments and data have been used: Digital Terrain Model, data of prospecting and detailed exploration (borehole co-ordinates and altitudes), laboratory (analytical) data. The information was accumulated from 196 boreholes of prospecting and detailed exploration.

The contours of sand and gravel deposits and their prognostic areas were defined in the area studied (Fig. 1); also, the property data (logs and sediment composition) of boreholes were compiled. To build the digital topography model, the surface levelling data stored at LTDBK50000 (© National Agricultural Service at the Agriculture Ministry) were used.

Based on borehole data, the deposit bed thicknesses and altitudes of deposit bottom levels were determined. The grain-size analysis results enabled to distinguish four glaciofluvial lithofacies: 1 – coarse gravel, 2 – fine gravel, 3 – low-sorted coarse and medium-grained sand, 4 – fine sand. Based on this material, frame models were built for the tops and bottoms of the lithofacies. The frame models of the surfaces were built by means of triangulation. For this purpose, the Delauney trian-

Fig. 1. Location of the study area. *1* – area under investigation

1 pav. Tirto ploto (*1*) situacijos planas

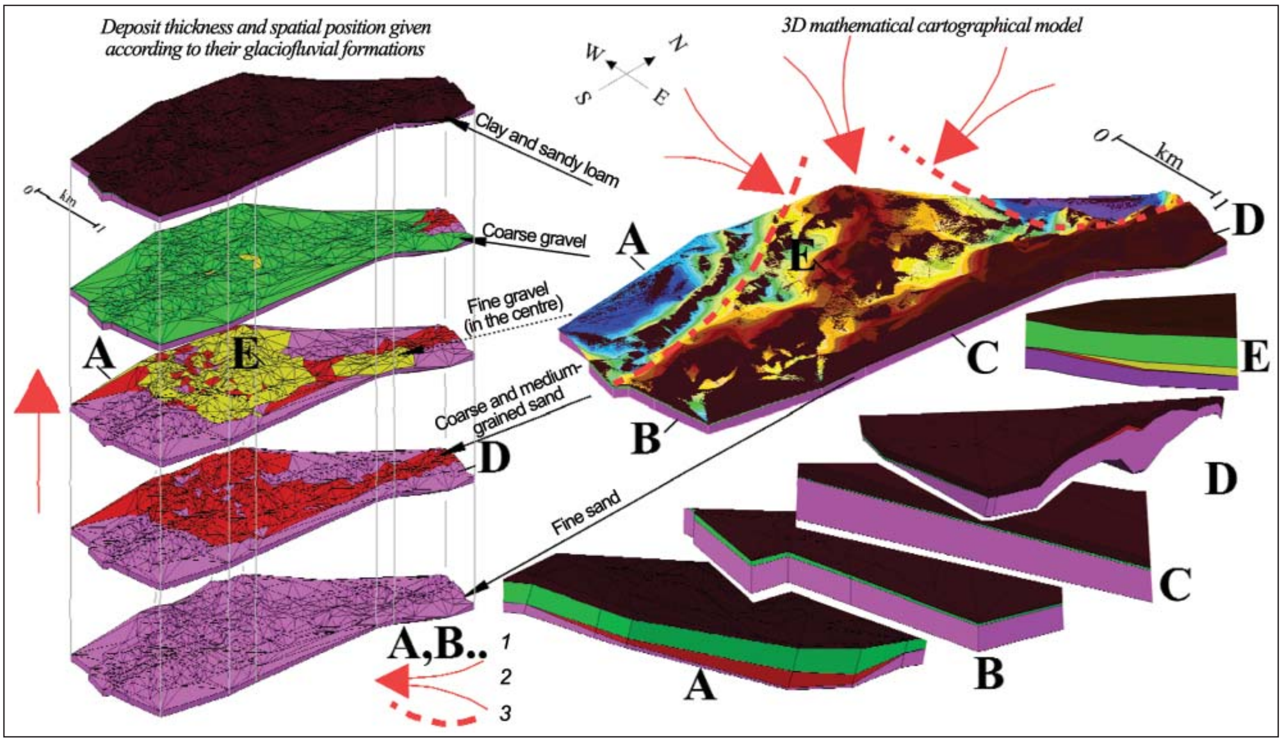

Fig. 2. The 3D mathematical cartographical model built for the Rūsteikiai zone in Zarasai District with deposit thickness and spatial position given according to their glaciofluvial formations:

1 – geological model projections: *A* – view from the west, *B* – view from the south, *C* – view from the east, *D* – view from the north, *E* – view of centre-cut model, *2* – main direction of outwash fan formation, *3* – probable sites of glacier tongue margins

2 pav. Zarasų rajono Rūsteikių zonos 3D matematinis kartografinis modelis; nuogulų storiai ir jų erdvinė padėtis pagal litologines atmainas: *1* – geologinio modelio projekcijos:

A – vaizdas iš vakarų, *B* – vaizdas iš pietų, *C* – vaizdas iš rytų, *D* – vaizdas iš šiaurės, *E* – vaizdas perpjovus sukurtą modelį per centrinę dalį, *2* – pagrindinė išnašų kūgio formavimosi kryptis, *3* – tikėtinos ledyno liežuvių pakraščių vietos gulation algorithm (Avdonin et al., 2007) integrated into the Geomap 3D 2010 software was used. By joining all the surface frame models built into one entity, a geological 3D model was obtained for the zone studied (Fig. 2).

During the field investigations of the Rūsteikiai marginal ridge, data on cross-bedding dip angles and directions were collected in a local pit. Based on these data, the circle and rose diagrams were built, which additionally enabled to make conclusions about the hydrodynamical activity of the streams that had formed the deposits of the glaciofluvial ridges and determined the direction of sediment transport; moreover, they confirmed the assumptions accepted for the mathematical model. All in all, 30 different beds were measured.

The dug-out pit model presented here was constructed taking into account all wastes of useful minerals at the top, bottom, untouched strip, on the slopes and underneath. It was assumed that the excavation would be carried out only in the part of the area explored in detail, with a restricted zone at the left boundary of agricultural and mining plots for flattening slopes by pushing the ground. The angles for stable slopes were calculated based on laboratory data. For testing, according to the standard (GOST 12071-72), four undisturbed soil monoliths were taken from different layers and nine samples were collected for trial studies. Laboratory investigations and trials determined the necessary geotechnical properties for the pit slopes – specific weight γ [kN/m^3], internal friction angle φ [°], total cohesion c [kPa]). Accordingly, the design parameters ensuring the pit slope stability were calculated (Mik ys, 2008). For this purpose, the slope steepness safety factor (k_s) was applied and assumed to be equal to 1.10, i. e. with a 10% reserve. Thus, the stable slope angles were suggested as follows: 40° in the glaciofluvial deposits (sand, gravel) and 45° for glacial deposits (loam, sandy loam), which meet the recommended values (*Metodiniai nurodymai,* 1982).

APPLICATION

Analysis of the occurrence and lithofacies composition of marginal glaciofluvial deposits in the Rūsteikiai zone

Four main layers of glaciofluvial formations were distinguished in the study area: 1 – coarse gravel, 2 – fine gravel, 3 – low-sorted coarse and medium-grained sand, 4 – fine sand (Figs. 2 and 3). The thickness of the deposits ranged from 1 to 30 m (Fig. 4). Furthermore, the layers of silt and loam / sandy loam covering and basing the glaciofluvial deposits were identified (Figs. 2 and 3). The silt and loam / sandy loam occurring at the bottom and reached only in local plots did not provide a complete view of the distribution of these deposits, therefore they are not depicted in the 3D geological model. Nevertheless, although silt is identified only locally, it indicates the beginning of the formation of glaciofluvial deposits under the basin conditions.

The glaciofluvial deposits overlay the marginal Upper Pleistocene glaciolacustrine and glacial deposits of the Baltija stage of the Nemunas glaciation (Fig. 3). The marginal glaciofluvial deposits and their bottom surface were possibly

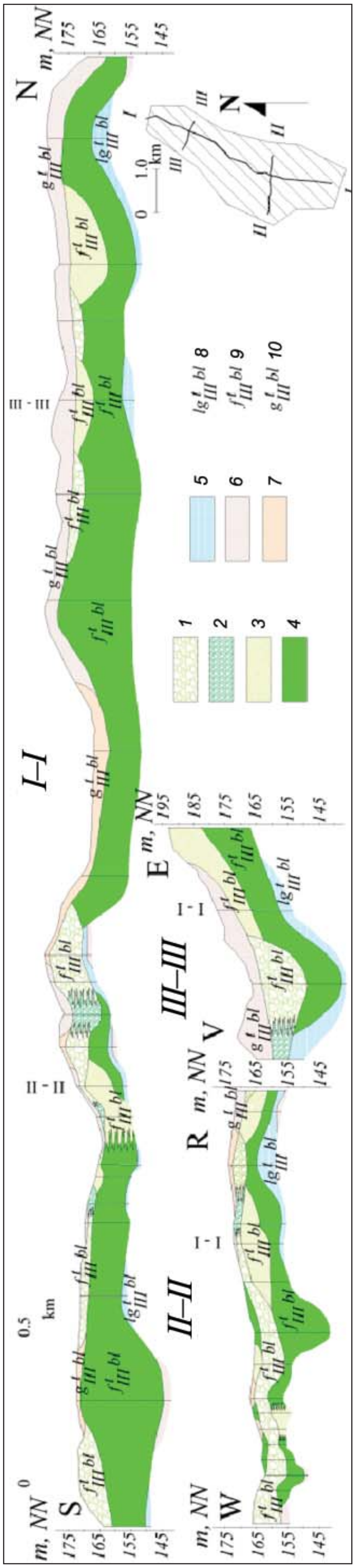

Fig. 3. Geological cross sections and their location. Lithology:
1 – coarse gravel, *2* – fine gravel, *3* – coarse and medium-grained sand, *4* – fine sand, *5* – silt, *6* – loam, *7* – sandy loam; Geological indexes: *8* – Upper Pleistocene Baltic Subformation marginal glaciolacustrine deposits, *9* – Upper Pleistocene Baltija Subformation marginal glaciofluvial deposits, *10* – Upper Pleistocene Baltija Subformation marginal glacial deposits

3 pav. Geologiniai pjūviai ir jų padėtis. Litologija:
1 – stambus žvyras, *2* – smulkus žvyras, *3* – stambus ir vidutinis smėlis, *4* – smulkus smėlis, *5* – aleuritas, *6* – priemolis, *7* – priesmėlis; geologiniai indeksai: *8* – viršutinio pleistoceno Baltijos posvitės kraštinių darinių limnoglacialinės nuogulos, *9* – viršutinio pleistoceno Baltijos posvitės kraštinių darinių fliuvioglacialinės nuogulos, *10* – viršutinio pleistoceno Baltijos posvitės kraštinių darinių glacigeninės nuogulos

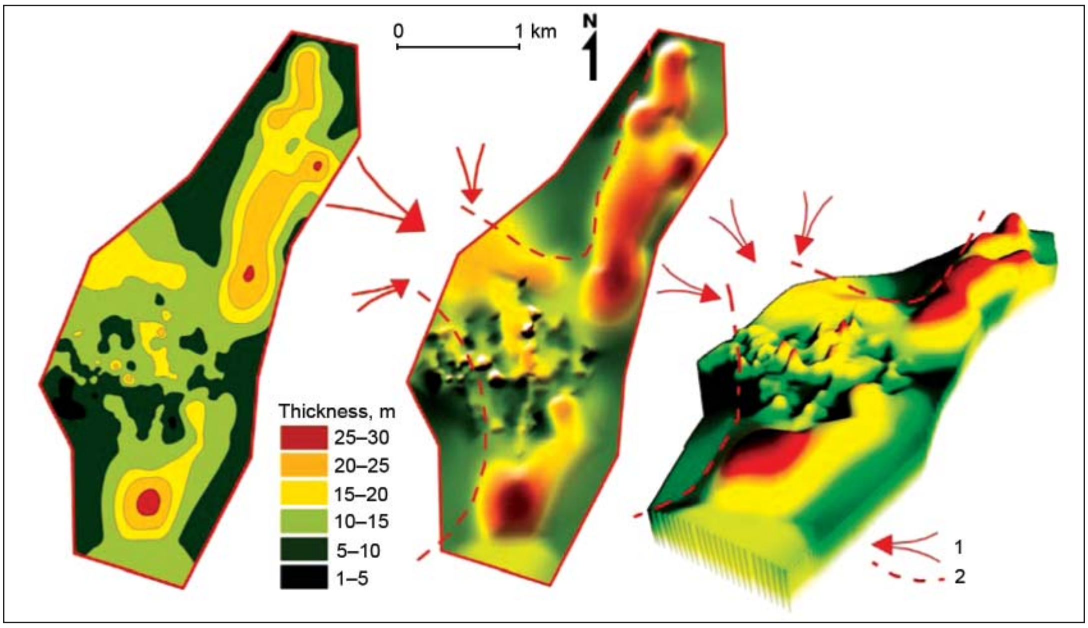

Fig. 4. 2D and 3D glaciofluvial deposit thickness models: *1* – main direction of outwash fan formation, *2* – probable sites of glacier tongue margins

4 pav. Fliuvioglacialinių nuogulų storių 2D ir 3D modeliai: *1* – pagrindinė išnašų kūgio formavimosi kryptis, *2* – tikėtinos ledyno liežuvių pakraščių vietos

formed when the traps of the former till surface had been filled with a silt layer. Silt deposition started on a till loam or sandy loam and took place in all parts of the area at the most depressed sites of glaciofluvial deposits and their bottom formed in glacial deposits. The silt layer is the deepest in the northern part of the area (Fig. 3).

Fine sand, reaching 26.6 m in thickness, overlies the till loam or silt in some places (Fig. 3). Fine sand is distributed throughout the area and represents an uninterrupted layer of varying thickness (Figs. 2 and 3).

The glaciofluvial layers overlying the fine sand comprise a coarser sand reaching 12 m in thickness. The uppermost layer of varying thickness is observed in nearly all the area, but it is absent in its southern part or rare in the north-eastern part. The main reserves of sand of this lithofacies are observed in the central and northern parts of the area, where three sand layers are isolated from each other. The northernmost part of the ridge contains the thickest (12 m) layer of sand (Fig. 3).

A fine gravel layer up to 10.6 m thick overlies the coarse sand and is distributed locally, filling in small depressions in the glaciofluvial deposits. It is distributed mainly in the central part of the area and does not form a continuous body, occurring rather as separate lenses. However, one such lens reaching 4 m in thickness is observed in the north-eastern part of the area. Fine gravel overlies the coarse and fine sand beds.

A layer of coarse gravel up to 14.8 m thick covers the glaciofluvial deposits and occurs nearly in all the study area (Figs. 2 and 3). Its thickness is the largest in the northern part of the ridge, where it exceeds 14 m. The smallest thickness (4 m) is documented in the southern part of the area. The northernmost part of the area is devoid of such deposits.

Glaciofluvial deposits in the main part of the area are overlain by marginal glacial till loam and sandy loam layers, their thickness ranging from 0.1 to 8.3 m. This marginal glacial deposit grows thicker northwards, overlying the major part of the glaciofluvial deposits. The cover thickness exceeding 8 m was reported from the north-eastern part of the area, while it is less than 2 m in the southern part where operating quarries are located and these deposits are removed.

Analysis of conditions the marginal glaciofluvial deposits are being formed in the Rūsteikiai zone

The Rūsteikiai zone is situated in the North Lithuanian Aukštaičiai Upland subdivided into 26 micro-regions. The area is located within the Salakas–Liaudėnai micro-region (Basalykas, 1965) which comprises a glacial tongue depression stretching eastwards as far as Drūkšiai Lake. This region is notable for lakes confined to large subglacial basins. Other parts of the depression contain numerous small glaciokarst depressions. The surface is undulating, with elevations exceeding 39 m. Absolute altitudes are in the range of 154–193 m. The highest hills are situated in the north-eastern part of the area and stretch in the south–north direction (Fig. 2).

The analysis of the lithofacies reflecting the sedimentation basin and the dynamics of the glaciofluvial streams enabled to distinguish the sedimentation environments of very high-rate streams, high-rate streams, medium-rate streams and basins.

Most of glaciofluvial deposits were accumulated by medium-rate streams as indicated by sand abundance in the lower part of the ridge. The upper part was formed by a significantly stronger stream, which redeposited sand and sorted the coarser deposits (coarse and fine gravel) (Fig. 2).

The direction of the streams that formed the glaciofluvial ridge deposits, as well as hydrodynamical activity and matter

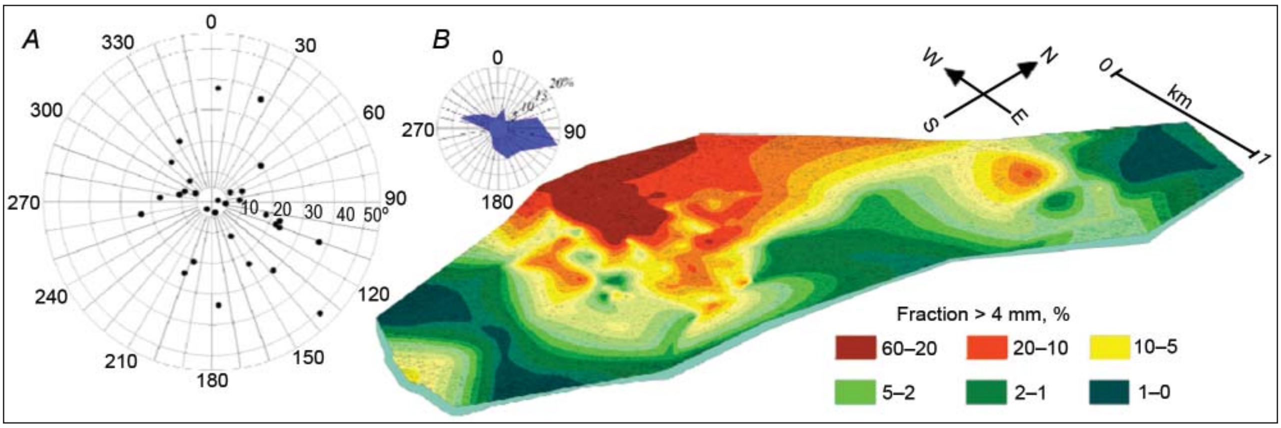

Fig. 5. Distribution of gravel and pebble (fractions >4 mm) in glaciofluvial bed, dip angle diagram (*A*) and direction rose diagram (*B*) of cross-bedding
5 pav. Žvirgždo ir gargždo (frakcijos > 4 mm) pasiskirstymas fliuvioglacialinių nuogulų storymėje ir nuogulų įstrižų sluoksnių polinkio kampų skritulinė (*A*) bei krypties (*B*) rožių diagramos

transport direction are revealed from the cross-bedding dip angles and directions in the circle and rose diagrams (Fig. 5). Thus, the biggest inclination angle is above 50°, but the majority of measured beds are inclined at the angles within the range of 0–25° (Fig. 5, *A*). This indicates that the intensity of streams varied and was not always high. The rose diagram for inclination angles of oblique beds is greatly scattered (Fig. 5, *B*), implying that the direction the matter had been brought in was not constant (Yurgaitis et al., 1982). The main direction of matter transport was from the north-west, thus confirming the main direction of outwash fan formation and the sites of glacier tongue margins presented in the mathematical cartographical model (Figs. 2, 4).

To analyse the direction of sediment transport by glaciofluvial flows, the distribution of gravel and pebble (>4 mm) grains in glaciofluvial deposits was investigated (Fig. 5). These data also confirmed the direction of the outwash fan formation. The coarser the sediments, the stronger the stream and the thicker the deposit layer.

The ridge morphology and topography were modified by the glaciokarst processes. After the retreat of the glacier, the buried ice masses melted; this deformed the overlying sediments (Fig. 6). The stratification caused by faulting indicates that the bottom and the bank of the sedimentation basin are of glacial origin.

Calculation of recoverable reserves and making design solutions in the Rūsteikiai zone

To calculate the geological, particularly the recovered reserves, the surfaces of mineral deposit base (fine sand) and top (coarse gravel) were defined (Fig. 2, Table 1). The geological reserves were calculated separately for the entire area

Table 1. **Calculation of the geological resources**
1 lentelė. **Geologinių išteklių apskaičiavimas**

Calculation area	Volume, m^3	Area, m^2	Average thickness, m
Base surface – top of the useful mineral bed, comparison surface – bottom of useful mineral bed			
Total area studied	87 917 477	6 075 000	14.5
Proved Mineral Reserve, designed mining area	1 116 000	203 600	5.5

Fig. 6. Fault system in glaciofluvial deposits (Rūsteikiai quarry)
6 pav. Sprūdžių sistema fliuvioglacialinėse nuogulose (Rūsteikių karjeras)

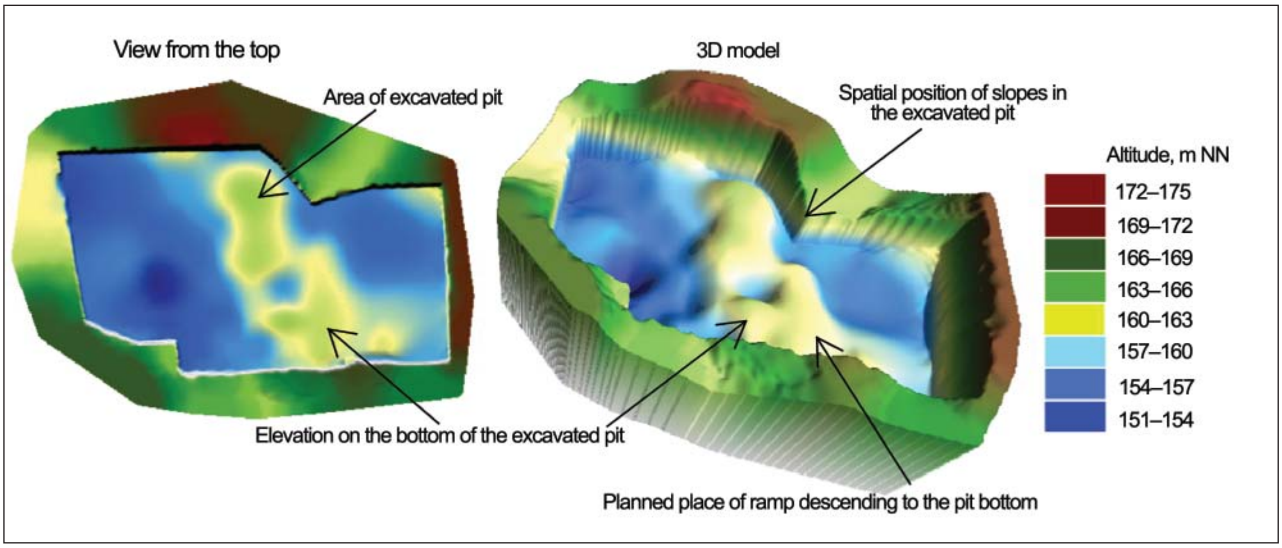

Fig. 7. Model of excavated Rūsteikiai quarry

7 pav. Iškasto Rūsteikių karjero modelis

and for a plot explored in detail and to be used as a pit. The calculation was performed by the GRID method (Patašova, Jurgaitis, 2008).

Furthermore, a 3D model of the excavated pit was compiled (Fig. 7) for the area of 20.36 ha explored in detail. 3D visualization makes it easier to determine the direction of excavation, to select the site for entrance into the pit, to design the final excavator's working ground and to choose the recultivation type. The model of an excavated open pit in case of Rūsteikiai shows that after a proved volume of minerals is exploited, a waist elevation will be formed in the central part extending NW–SE, indicating this site to be best for the minerals to be taken out in order to minimize the losses of minerals.

Based on the 3D model of the excavated pit, the recoverable reserves were calculated and losses were planned (Fig. 8). The losses in the design area were defined as those within the massif (in the untouchable strip, on the slopes and under them, on the bottom) and beyond the massif (deposit top, transportation) (Rzhevskiy, 1985; Trubetskoy et al., 1994). All losses of useful minerals make 170 000 m^3 (Tables 2 and 3).

Table 2. **Total losses of useful minerals**

2 lentelė. **Bendri naudingųjų iškasenų nuostoliai**

Position	Lost volume, m^3
Losses inside the deposit massif	
Under the intact margin of deposit	96 693
On the mining slopes	23 073
At the bottom of the pit	22 219
Total inside massif losses	**141 986**
Losses outside the deposit massif	
At the top of the deposit	18 763
Transportation	9 558
Total outside massif losses	28 321
Total	170 307

Accordingly, the recoverable reserves in the area within the contour of the area explored in detail comprise 956 000 m^3.

The final stage comprises the automated drafting of the mining timetable according to a given mining rate, mining trends, and the position of the initial trench. The Rūsteikiai area explored in detail is designed for the Stage-1 mining with the demand of 40 000 m^3, or 40 400 m^3 with transportation losses. The area (20.36 ha) designed according to the given parameters is to be mined for 24 years (Fig. 9, Table 4).

Table 3. **Losses of useful minerals on mining slopes**

3 lentelė. **Naudingųjų iškasenų nuostoliai karjero šlaituose**

Position (batter)	Lost volume, m^3
A	7 537
B	4 552
C	5 518
D	5 466
Total	23 073

Table 4. **Timetable of mining works**

4 lentelė. **Kalendorinis kasybos darbų planas**

Year	Area by a slope middle, m^2	Average thickness, m	Volume, m^3
1	8 080	5.0	40 400
2	8 978	4.5	40 400
3	8 978	4.5	40 400
4	8 080	5	40 400
5	6 733	6	40 400
6–10	33 667	6	202 000
11–15	40 400	5	202 000
16–20	36 727	5.5	202 000
21	8 080	5	40 400
22	8 080	5	40 400
23	9 506	4.25	40 400
24	6 659	4	26 635
Total	177 309		955 835

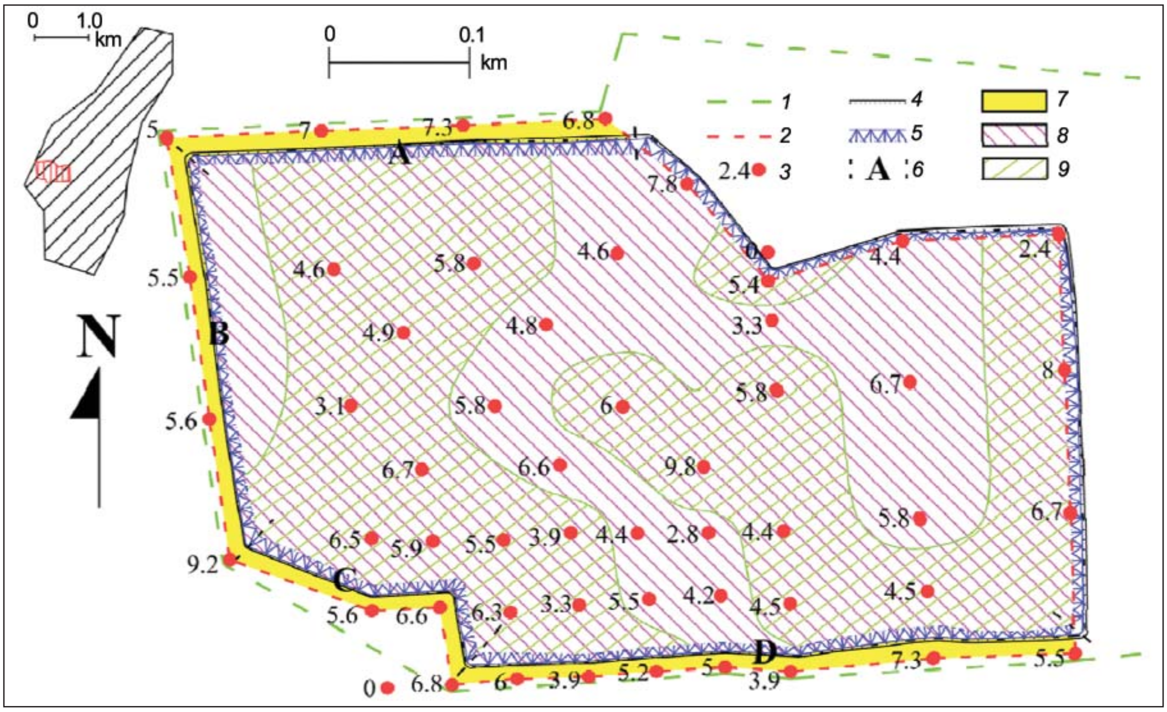

Fig. 8. Scheme of calculated losses in the Rūsteikiai quarry explored in detail and designed for mining and its location:
1 – land plot boundary, *2* – mining plot boundary, *3* – borehole (left – thickness of mineral deposit to be mined, m), *4* – non-mined slope of the cover (overburden) bench, *5* – non-mined slope of the mining bench, *6* – batters and their No. for calculation of losses on slopes of the mining benches, *7* – losses under the untouchable strip of the deposit margin, *8* – losses at the top of the mineral bed, *9* – losses at the pit bottom

8 pav. Nuodugniai išžvalgyto ir projektuojamo kasti Rūsteikių karjero apskaičiuotų nuostolių schema ir jo padėtis tyrimų plote:
1 – žemės sklypo riba, *2* – kasybos sklypo riba, *3* – gręžinys (kairėje – iškasamo naudingojo klodo storis m), *4* – dangos pakopos nedarbo šlaitas, *5* – gavybos pakopos nedarbo šlaitas, *6* – nuostolių gavybos pakopos šlaituose skaičiavimo bortai ir jų Nr., *7* – nuostoliai po nejudinama telkinio pakraščio juosta, *8* – nuostoliai naudingojo klodo kraige, *9* – nuostoliai karjero dugne

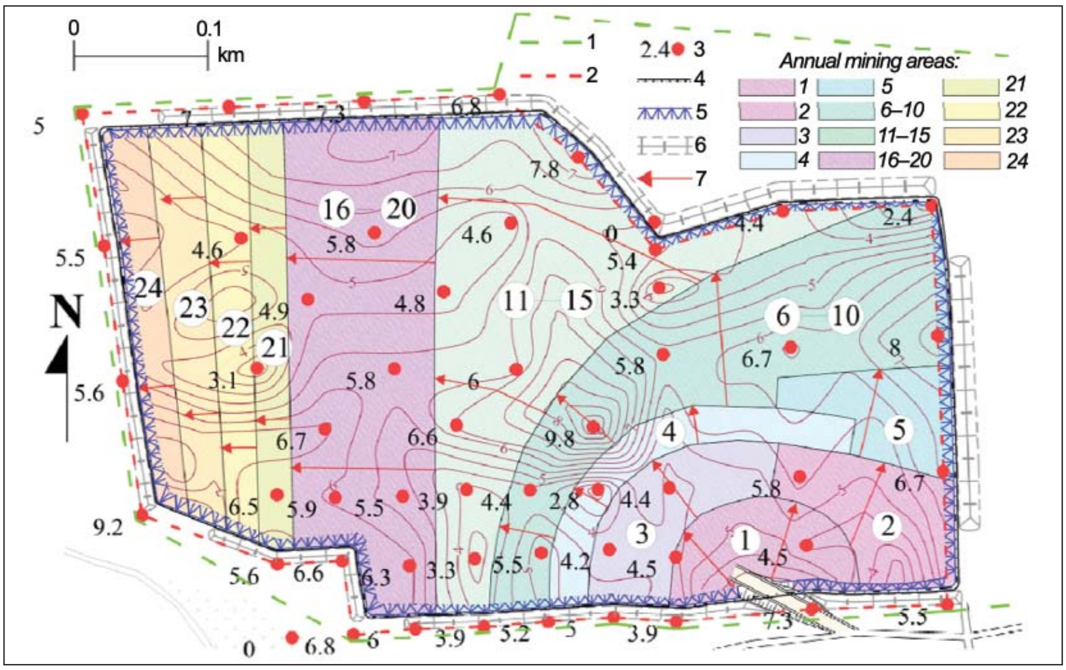

Fig. 9. Mining timetable of Rūsteikiai mineral deposit:
1 – land plot boundary, *2* – mining plot boundary, *3* – borehole (left – thickness of mined useful bed, m), *4* – non-mined slope of the cover (overburden) bench, *5* – non-mined slope of the mining bench, *6* – soil dams, *7* – direction of mining front

9 pav. Rūsteikių telkinio gavybos darbų kalendorinis planas:
1 – žemės sklypo riba, *2* – kasybos sklypo riba, *3* – gręžinys (kairėje – iškasamo naudingojo klodo storis m), *4* – dangos pakopos nedarbo šlaitas, *5* – gavybos pakopos nedarbo šlaitas, *6* – dirvožemio pylimai, *7* – kasybos darbų kryptis

CONCLUSIONS AND PROSPECTS

Applying the 3D methods, geological mapping is performed in a volumetric manner. A 3D deposit model can be viewed from different directions, cross-cut in any required direction, used to compile geological-cross-sections and block-diagrams. The final goal of the modelling is to depict all parameters of a geological body in the most accurate way.

The obtained results show a complex polygenetic course of the formation of Rūsteikiai marginal deposits, starting from glaciolacustrine conditions, followed by glaciofluvial sedimentation of various intensity at the glacier's margin zone and, finally, by formation of a marginal glacial deposit cover of unwashed till matter that had slipped down from the glacier's surface. After the retreat of the glacier, the buried ice blocks began melting and the overlying deposits laid earlier were deformed. The stratification caused by faulting indicates that the bottom and the bank of the sedimentation basin are of glacial origin.

Based on the 3D mathematical cartographical model, the calculation of recoverable reserves was performed, a 3D model was built for the excavated pit, and losses were calculation and mining timetable plans drafted in an automated way.

After the development of the deposit had started, the 3D model can be used for recording the mining processes by the production enterprises and related state institutions as well as for controlling the surveyor services and planning the mining scope.

Moreover, the models introduced into the register can be widely applied in the field of territorial planning.

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MATEMATINIO KARTOGRAFINIO MODELIO KŪRIMAS IR PRITAIKYMAS SMĖLIO-ŽVYRO TELKINIAMS IR PERSPEKTYVIEMS PLOTAMS

Santrauka

Naudingųjų iškasenų telkinių modeliavimas yra sudėtingas procesas, todėl šia kryptimi dirba daug įvairių sričių specialistų. UAB „GJ Magma" kartu su UAB „Infoera" nuo 2006 m. kuria automatizuotą 3D geologinio modeliavimo sistemą. Programinės įrangos kūrimui 2009 m. buvo gauta Europos Sąjungos struktūrinė parama.

Šiame darbe yra pristatomas matematinio kartografinio modelio kūrimas ir jo taikymo galimybės Zarasų rajono Rūsteikių zonos kraštiniams fliuvioglacialiniams dariniams.

Parengiamajame 3D modelio kūrimo etape buvo peržiūrėti nagrinėjamoje teritorijoje ankstesnių žvyro bei smėlio telkinių paieškų ir geologinės žvalgybos bei stambaus mastelio geologinio kartografavimo darbų rezultatai. Papildomais lauko ir laboratoriniais tyrimais siekta patvirtinti prielaidas dėl tiriamo telkinio sandaros ir formavimosi sąlygų. Gauti rezultatai rodo sudėtingą poligenetinę Rūsteikių kraštinių darinių formavimosi evoliuciją: pradedant limnoglacialinėmis sąlygomis, vėliau ledyno pakraščio zonoje vykstančia įvairaus intensyvumo fliuvioglacialinių nuogulų sedimentacija ir baigiant kraštinių glacigeninių nuogulų dangos atsiradimu nuo ledyno nušliaužus moreninei neišrūšiuotai medžiagai. Galutinius gūbrio sandaros ir reljefo bruožus suformavo glaciokarstiniai procesai. Ledynui atsitraukus, palaidoti ledo luitai pradėjo tirpti ir anksčiau sukloti sluoksniai deformavosi. Sprūdžiais sujauktas sluoksniuotumas patvirtina, kad sedimentacinio baseino dugnas bei krantai buvo ledyninės kilmės.

Išanalizavus tiriamojo ploto sandarą ir formavimosi sąlygas, sukurtas 3D modelis buvo panaudotas apskaičiuoti geologinius išteklius ir priimti tiriamojo ploto projektinius sprendimus: sukurti iškasto karjero modelį, įvertinti naudingųjų iškasenų nuostolius, apskaičiuoti nuostolius ir išgaunamus išteklius, suprojektuoti kasybos darbus ir sudaryti kalendorinius planus.

Raktažodžiai: fliuvioglacialiniai dariniai, 3D geologinis modeliavimas, geologiniai ištekliai