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The Approach to 3D Numerical Modelling in Order to Evaluate an Environmental Constraints and Assessment of Shallow Geothermal Resources in Urban Areas on the Example of Krakow, Poland

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ABSTRACT

The paper address issues related to the use of Petrel software package to 3D numerical modelling and other applications of the software to shallow geothermal, including evaluation of parameters needed for resource assessment and environmental constraints - encountered in densely populated areas on the example of the Krakow city. The approaches and presented solutions have been tested in Krakow pilot area, within the framework of INTERREG-CE project entitled: Shallow Geothermal Energy Planning, Assessment and Mapping Strategies in Central Europe – GeoPLASMA-CE, carried out in 2016–2019. In addition, issues related to integration and various data management rules for the purpose of 3D model preparation, aiming at assessment of geothermal potential of closed loop (CLS), as well as preparation of a geometric matrix for further hydrogeological modelling and assessment of geothermal potential of open loop systems (OLS) are presented.

1. INTRODUCTION

The paper presents a partial results of the work carried out within the framework of the project entitled “Shallow Geothermal Energy Planning, Assessment and Mapping Strategies in Central Europe – GeoPLASMA-CE” carried out in 2016–2019, by 11 partners from 6 countries, within the framework of the INTERREG Central Europe 2014–2020 international cooperation programme. The project concerns various aspects of the use of shallow geothermal both for heating and cooling purposes in urban and non-urban areas in 6 selected pilot areas: Vogtland-Western Bohemia (borderland D-CZ), Wałbrzych-Broumov (borderland PL-CZ), and the following cities: Kraków, Vienna, Bratislava and Ljubljana.

As the results of the cooperation of geological surveys, universities, NGOs, local governments administration units and private companies, maps of geothermal potential, as well as new sustainable management strategies of shallow geothermal resources are being developed. One of the elements of the pilot activities is the risk assessment related to the use of geothermal/ground source heat pumps, both for open and closed loop systems, specific environmental conditions, including: geogenic, hydrogeological and anthropogenic issues. These conditions are of a diverse nature, that occur on the one hand, in densely populated urban areas, as Kraków, with well developed underground infrastructure, and on the other, in rural areas, where environmental constraints are related to, for example, extensive mining areas, degraded as a result of the former hard coal mining, as is the case in the Wałbrzych /Poland and Vogland /Germany pilot areas.

Identification of the above hazards, preliminary assessment of their significance and visualization in the form of a "traffic light map" allow obtaining information about the possibility of installing geothermal heat pumps in a given location (by category: installation allowed, with restrictions, not allowed) for selected open and/or closed loop systems. Moreover, the thematic layers drawn up will indicate the existence and allow for the specification of other threats/conflicts related to, for example, the specificity of land development (resulting from the Local Spatial Development Plans), the location of protected areas (ground waters), underground infrastructure, landslides, etc. Identification of the above elements and gathering information in one place (on the internet platform) will facilitate both the individual and the expert’s future planning of investments in the field of geothermal heat pump installations.

2. GEOLOGICAL SETTINGS

Kraków is situated in the southern part of Poland, in the Vistula valley – at a distance of about 100 km from the Tatra Mountains. Research area is located in very complex geological settings as it embraces from the south outermost tectonic units of Carpathians, Miocene deposits Carpathian Foredeep, Jurassic and Cretaceous deposits belonging to south-western outskirts of Kraków-Silesian Monocline, and Carboniferous to Cambrian deposits belonging to Palaeozoic tectonic units, of the Małopolska Block and Upper Silesia Block separated in the eastern part of Kraków by Kraków–Lubliniec regional fault zone (Żelaźniewicz et al., 2011).

Tectonic evolution of the area include several tectonic phases e.g. Golonka et al. (2006), Jawor and Baran (2004), Buła and Habryn (2008), but, in respect to shallow geothermal targets, the most important episodes of tectonic reorganization tectonic related to the Carpthians emplacement. A very important component of processes creating sedimentary architecture were very extended in time periods of erosion active in Permian – Triassic, early Cretaceous and pre-Miocene periods (Golonka et al., 2006; Oszczypko 1996, 1997; 1998). Folding, faulting and erosion processes created accommodation space for the potential geothermal aquifers.

In the Kraków region two large rock complexes, so called tectonic structural stages can be distinguished. The older stage includes Devonian, Carboniferous as well as older deposits tectonically deformed during Variscan orogenesis (Żaba, 1999). The younger complex built from Permian, Triassic, Jurassic and Cretaceous deposits is the so called Mesozoic–Permian stage. The rocks of both the complexes became inclined towards north east – during the Laramide phase – between the Cretaceous and the Tertiary – what caused the forming of a monoclinal structure.

Tectonic modelling of the Silesia–Kraków Monocline was taking place by stages (mainly in the Neogene) and caused emerging of horsts and depressions.

The geological structure of Kraków is dominated by horsts creating distinct elevations are visible in the land morphology. In historical times some of them were exploited to situate various edifices. Neogene tectonics in the Kraków region is connected mainly with phases of rocks forming movements in the nearby Carpathians. Here the faults belong to several generations, and their detailed dating is not always possible (Rutkowski, 1993; Felisiak, 1992).Within the faults mainly the Upper Jurassic limestone rocks, sometimes also Upper Cretaceous ones appear. Whereas the depressions are filled with Miocene clay deposits among which, locally, evaporates (clays with gypsum, gypsum rocks) appear. These formations belong to the Carpathian Foredeep, of the smallest (ca. 10 – 15 km) width in Poland in this area, and its north border shows an erosive character (Ney, 1968).

The youngest formations in the geological profile of Kraków region are represented by the Quaternary ones (Pleistocene and Holocene) – mainly filling up the paleovalleys of the Vistula and its tributaries as well as other morphological depressions. Pleistocene formations connected with glaciations are represented by glacial tills, fluvioglacial and alluvial sands and gravels and loesses. Whereas younger Holocene formations create a series of terraces, mainly in the Vistula and Rudawa valleys and are represented by sands, gravels and alluvial soils (Duda et al., 1997). The youngest Quaternary, so called Anthropocene formations appear mainly as banks connected with human settlements, and – in the Kraków centre – with the town's historical layers (Duda et al., 1997; Wardas, 2007).

From the hydrogeological point of view Kraków has been located in the upper course of the Vistula river (the Baltic Sea reception basin). In the city of Kraków groundwater occur within the water-bearing aquifers: Paleozoic and Jurassic (cracked and karstified limestones), Cretaceous (cracked marls and limestones), Miocene and Eocene (fine-grained sandstones and sands) and Quaternary (sand and gravel). The dominant role played in terms of aquifer levels are: Jurassic, Neogene (Bogucice sand) and Quaternary (Pleistocene) (Duda et al., 1997; Wardas, 2007).

A fresh groundwaters occurs within hydrostratigraphic units creating usable groundwater levels. Area characterized with the most abundant reserves constitute the main groundwater reservoirs. Groundwaters are generally of good quality and can complement the needs of the City. Groundwaters are also a source of emergency supply system of Kraków. The system consists of wells that draw water from the Quaternary aquifer and a few intakes of Neogene and Jurassic. In addition, the groundwater are a source of supply for residents on the outskirts of town, with no water supply system. Drinking water for water supply in Wieliczka also comes from area of Neogene – Bogucice reservoir located is south of Kraków. Groundwaters in the area of the City of Kraków are poorly insulated from the ground, and therefore very non-resistant to the passage of contaminants from the surface. Quality and effective protection of groundwater resources is one of the most important tasks and problems taken into account in the preparation of local development plans.

In Kraków area quite a large number of wells and springs with high quality, even mineral water, also suitable for drinking are present. Furthermore two health resorts (SPA) uses mineralized waters are located: a statutory one in Swoszowice (south Kraków) and another in the Mateczny region (central–west Kraków) where valuable sulfide waters are exploited.

In this respect, the conflict maps show limitations in the application of GSHPs, especially in relation to water protection areas, which is of importance in the case of OLS installations.

3. GENERAL METHODOLOGY

Mapping tasks during the GeoPLASMA-CE project were completed in the form of the 2D grids and 3D models elaborated with the use Schlumberger's Petrel™ Software Platform. In this specific case it allowed for integration overall geological, hydrogeological, engineering cartographic, petrophysical data within model project. In this philosophy of geological modelling the centre of all performed analyses is the digital geomodel (Petrel Project). First of all it plays the role of the Spatial Database. Collected data are then converted into spatial form of 2D and 3D structural and parametric grids. Interactive data integration enables analyses in various scales – from basin to field scale (Wygrala, 2014; Papiernik & Michna, 2019).

A 3D modelling used for shallow geothermal is a process strongly similar to procedures used in petroleum geology processing methods, from data acquisition, structural and tectonic interpretations, through structural and thickness mapping, sedimentological analyses, to modelling the variability of lithology and petrophysical parameters, ending at resources / reserves assessments and uncertainty analysis by Deutsch and Journel (1992), Dubrule (1998, 2003), Coburn et al. (2006), Cosentino (2001), Mallet (2008), Zakrevsky (2011), Papiernik et al. (2015), Vernik (2016), Papiernik in: Górecki (ed.), Hajto et al. (2011, 2013), Papiernik (2017a, b), Papiernik and Michna (2019) op cit). Considerable difference is strongly confined a use of seismic data in shallow geothermal surveys.

A Corner Point Grid was created by pillar gridding thus the faults network defined the shape of a 3D grid. General lateral resolution was set up in pillar gridding process. During the modelling process independent geological horizons were built. The space between the horizons is represented by a hexahedral structure which was divided into a smaller cells using the layering Petrel process. Finally a complete structural model have been created.

4. 3D MODEL OF KRAKÓW

Modelling performed in the course of the research comprise two generation of models, the regional one – covering drainage areas of rivers flowing through the Kraców area, and the local one confined to Kraków City administrative borders.

4.1 Input Data

Core data for geological modelling came from the boreholes. Borehole profiles were available in tree databases: CBDG (stratigraphic and geophysical data), BDGI (engineering database) and CBDH (hydrogeological database).

Most of these databases provides first of all stratigraphic and lithological information. Well databases have been merged manually, in order to generate a harmonized well marker and lithology profiles database for previously defined modelling units at the Kraków pilot area. Complete data set used for modelling was composed of 25,302 borehole profiles, including: 23,012 ones from BDGI, 1,618 from CBDH and finally 672 wells from CBDG. The location of boreholes in Kraków area is shown in Figure 1.

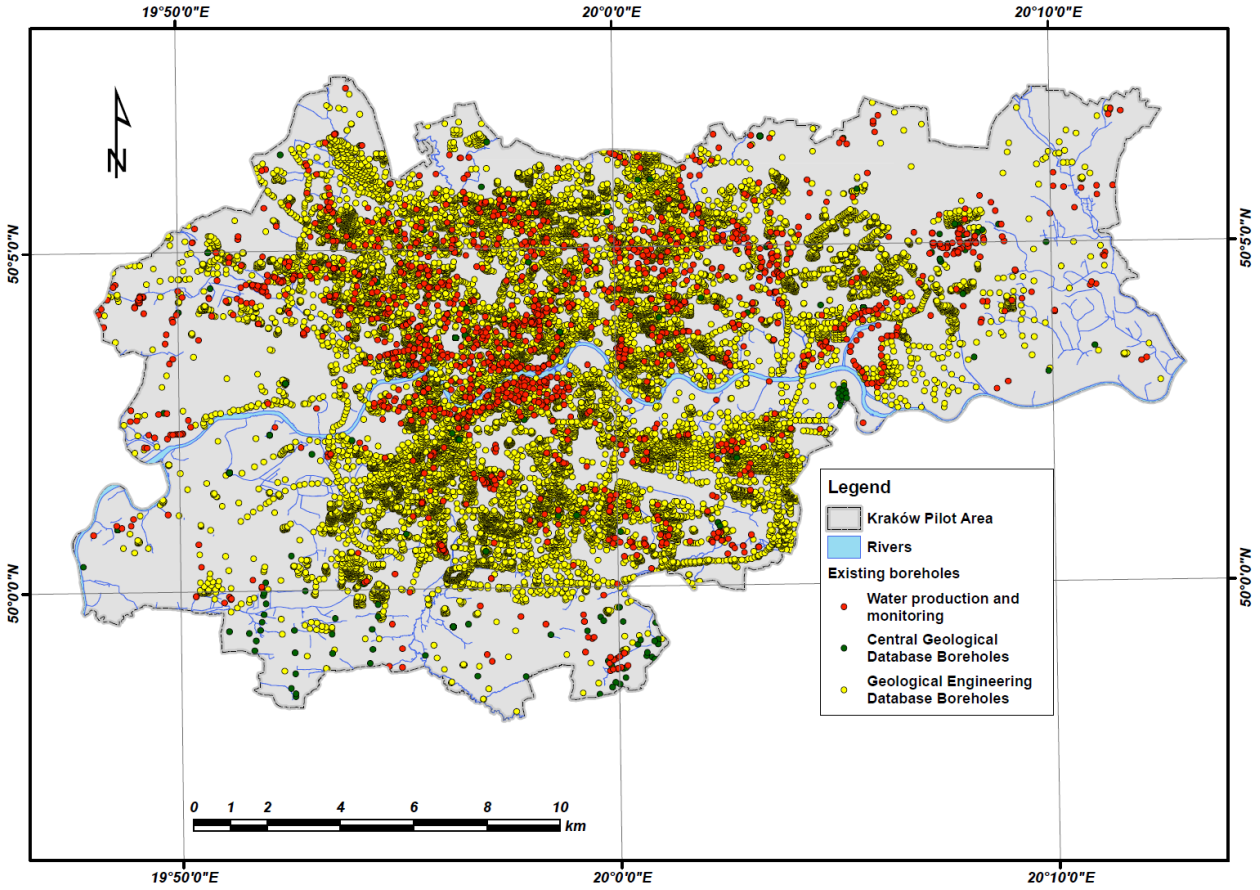

Figure 1: Location of boreholes (mainly shallow) in Kraków based on various databases

The other crucial data for structural modelling where archive maps – mostly available in analog form, very rarely in digital formats. Among such source a "Detailed Geological Map of Poland", scale 1:50,000 (4 map sheets) was of the paramount importance.

The Krakow area of research is covered with four map sheets, namely: Kraków (Rutkowski, 1989, *in GIS format* Niepołomice (Gradziński, 1955, *also in GIS format*), Myślenice (Pawlak and Zając, 1978) and Wieliczka (Burtan 1954). Among the most important input, the maps from Geological–Engineering Atlas of Krakow (the whole Krakow area by PGI–NRI 2005) were included in the study.

A regional models input data sets was extended by additional four sheets of a "Detailed Geological Map of Poland", located to the N and W of Kraków were used as input for regional scale model. In this case also some regional maps were used as preliminary trend data, including: Geological map of Poland – horizontal sub crops maps (Kotański, 1997), Geological map of Poland without Cenozoic deposits, scale 1:1,000 000 (Dadlez, Marek and Pokorski, 2000), Geological and structural Atlas of the Palaeozoic Basin of the Outer Carpathians and the Carpathian Foredeep (Buła and Habryn, 2008), Geothermal Atlas of the Western Carpathians (Górecki (ed.) and Hajto et al., 2011), Map of the tectonic outline of the Western Carpathians (Żytko et al., 1989), Map of the basement of the tertiary of the Western Carpathians (Oszczypko et al., 1989).

Structural interpretation was also supported with spatially calibrated cross-sections and maps, including Cyran (2008), Duliński et al. (2002), Habryn et al. (2007), Haładus et al. (1990), Szklarczyk and Kaczmarczyk (2015), Szklarczyk (2015) and Szklarczyk (2016). Most of above cartographic sources were characterized with very low resolution, not enough to be directly used during preparation the structural model of Krakow.

5. MODELLING RESULTS

Modelling performed in the course of the research comprise two generation of models, the regional one - covering drainage areas of rivers flowing through the Kraków area, and the local one confined to Kraków City administrative borders.

5.1 Fault Framework

Presented in the project tectonic and structural solutions are the novel one. Tectonic interpretation is based on analysis of DEM variability, fault lines published in legacy data and analysis of geological complexes extent. Two main fault directions can be distinguished within the modelled area. First set of faults has N-E direction, while the second set is not so consistent, but may be described by general N-S direction. Fault network is built of 303 individual faults, including approximately 100 within Kraków pilot

area (Figure 2). These faults were used during the process of structural maps preparation, and afterwards adapted to aimed structural–parametric 3D models. Additionally they were helpful during the reinterpretation work on determination of extent lines of individual stratigraphic units in Pilot area. A complex tectonic system in Kraków and adjacent areas is shown on Figure 2.

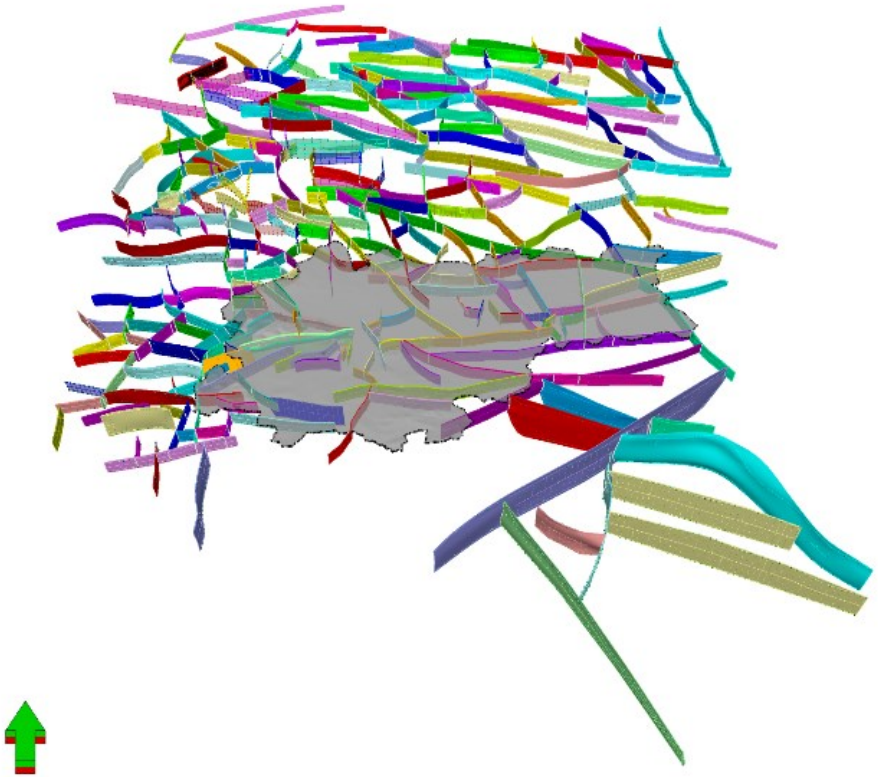

Figure 2: Fault network of regional model in Kraków (grey shaded area express administrative extent of Kraków city)

5.2 Structural Framework

Structural variability spatial reconstructions are based on legacy data, especially borehole data. With the increase of depth uncertainty of the presented result rises considerably. At depths up to 500 m below ground surface six main stratigraphic complexes can be observed comprising: Quaternary, Carpathian Flysch in the southern part of research area, Miocene filling erosional valleys, Mesozoic strata, carbonates of Upper Cretaceous and Upper Jurassic, mostly clastic, strata of Middle Jurassic, Upper Triassic far to the north from Krakow, Early Palaeozoic carbonate complex of Lower Carboniferous – Upper Devonian, Late Palaeozoic – clastic complex of Silurian–Cambrian (Precambrian ?).

The approach of structural framework analysis undertaken during the project seems to be a milestone in the recognition of Krakow's tectonics. Structural variability spatial reconstructions are based on legacy data, especially borehole data. With the increase of depth uncertainty of the presented result rises considerably.

Construction of the listed above complexes was starting point of the structural model building. To satisfy demands of hydrogeological modelling additional complexes had to be interpreted. The goal of construction that structural model was to prepare horizons and grids for further static and dynamic hydrogeological modelling. Main modelling units were defined in coordination with regional geological maps and hydrogeological condition. As a result stratigraphic complexes were subdivided into permeable (aquifer) and poorly permeable due to combination of lithology and hydrogeological conditions in Krakow Pilot Area. Finally 18 structural maps (Petrel 2D grids) were created (Table.1).

Table 1: Stratigraphic units modelled in Kraków area

Layer number	Stratigraphy	Type of layer
I	Quaternary	semipermeable
II	Quaternary	aquifer
III	Tr+K (Carpathian Flysch)	aquifer
IV	Tr+K (Carpathian Flysch)	poorly permeable
V	Neogene (Miocene)	poorly permeable
VI	Neogene (Miocene)	aquifer
VII	Neogene (Miocene)	poorly permeable
VIII	Neogene (Miocene)	aquifer
IX	Neogene (Miocene)	poorly permeable

X	Neogene (Miocene)	aquifer
XI	Neogene (Miocene)	poorly permeable
XII	Cretaceous (Upper)	aquifer
XIII	Cretaceous (Upper)	poorly permeable
XIV	Jurassic (Upper)	aquifer
XV	Jurassic (Upper)	poorly permeable
XVI	Jurassic (Middle)	aquifer / poorly permeable
XVII	Carboniferous+ Devonian+ Cambrian	aquifer
		poorly permeable

Within the area of the Krakow city the topmost Quaternary sediments comprises anthropogenic and clayey deposits and, especially on the topographic heights, loess sheets – these sediments are thought to be semipermeable. Permeable Quaternary deposits fill the ancient valley of the Wisła River (Figure 2, Table 1), creating a series of terraces and alluvial cones of Pradnik and Rudawa rivers (Duda et al., 1997).

These sediments are mainly sand and gravel of fluvial and fluvioglacial origin. In the southern part of research area thrusted, Carpathian Flysch complex occurs. This complex is composed of sandstones and shales. Underlying Neogene sediments are composed of alternating water bearing porous sands and poorly permeable clays, mudstones and sometimes limestone marls and gypsum. These sediments filled erosional valleys. Below Miocene, Mesozoic strata, comprising carbonates of Upper Cretaceous and Upper Jurassic, as well as, mostly clastic, strata of Middle Jurassic (also Upper Triassic far to the north from Kraków) are present. Underlying Early Palaeozoic carbonate complex of Lower Carboniferous – Upper Devonian is present in the modelled area. The last, lowest complex represented by Late Palaeozoic - clastic complex of Silurian – Cambrian (Precambrian?) rocks (Figure 2).

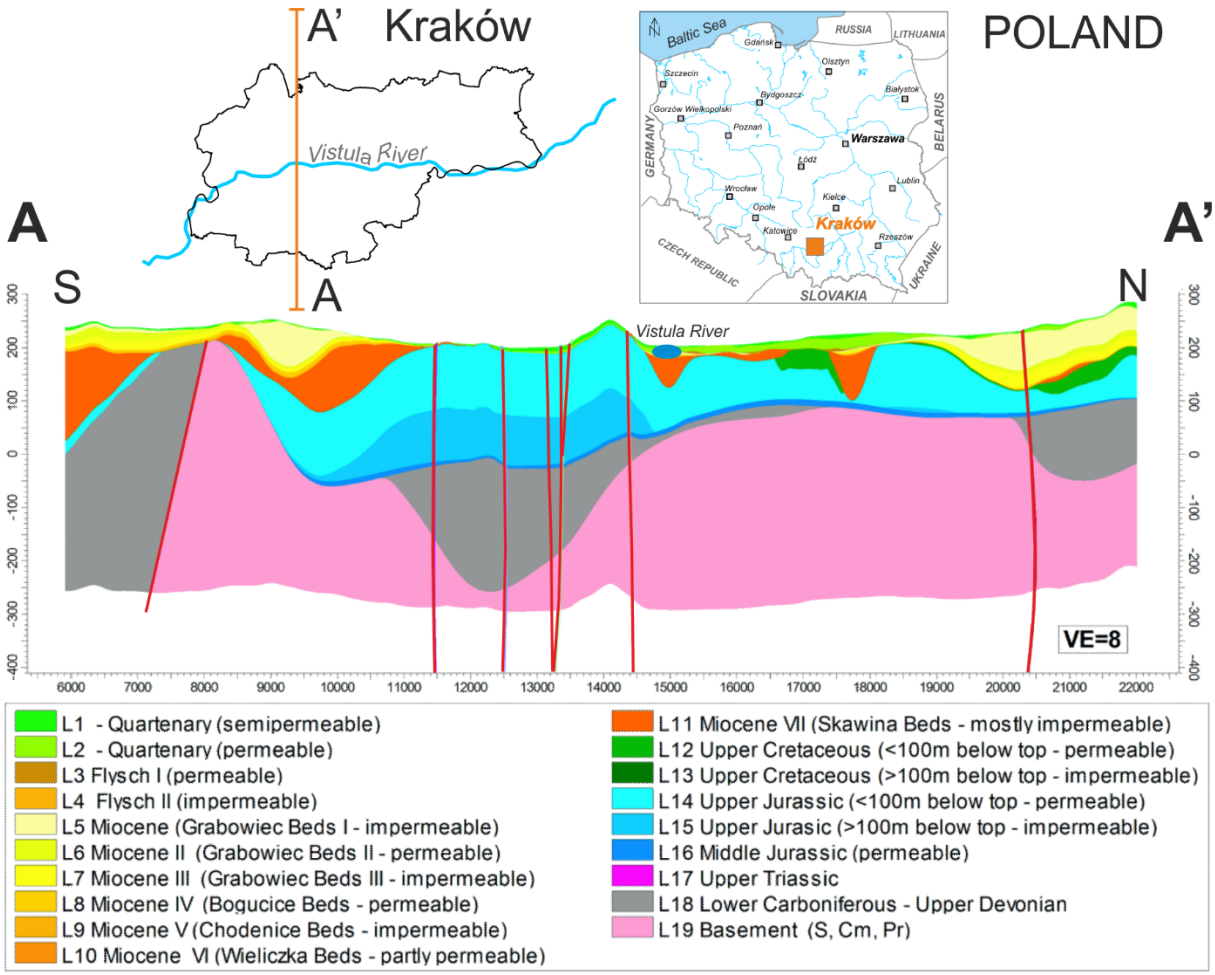

Figure 2: Arbitrary selected cross-section A – A' up to 300 m b.g.l.

5.3 Parametric Models

Using structural models and petrographic information generalised lithological (discrete model) model was created, fitted to the needs of the thermal modelling. The most advanced parametric 3D model within the project was temperature model which integrates TRT temperature measurements in Kraków area, thermograms from deep boreholes in Krakow and surroundings, temperature trends from geothermal atlases (Górecki (ed.) and Hajto, et al. 2011) and average annual temperatures on the surface.

As it was agreed within the GeoPLASMA-CE project all partners used a uniform approach to estimate the mean annual surface temperature based on satellite data, thus these data were derived from daily MODIS-LST database (http://www.geodati.fmach.it/eurolst.html), for period 2000 – 2013. The spatial resolution was 250 m, with temperature sensitivity 0.1 deg C. Possible inaccuracies in urban areas (heat reflected from roofs) and influences were evaluated with regards to existing, local measurements, available through borehole temperature profiles - included in the error analyses and incorporated to the final surface temperature model for Kraków. An example of 2D surface temperature distribution map that constitute a boundary conditions for 3D model in Kraków is shown in Figure 3. The final 3D subsurface temperature distribution up to 500 m depth is presented in Figure 3.

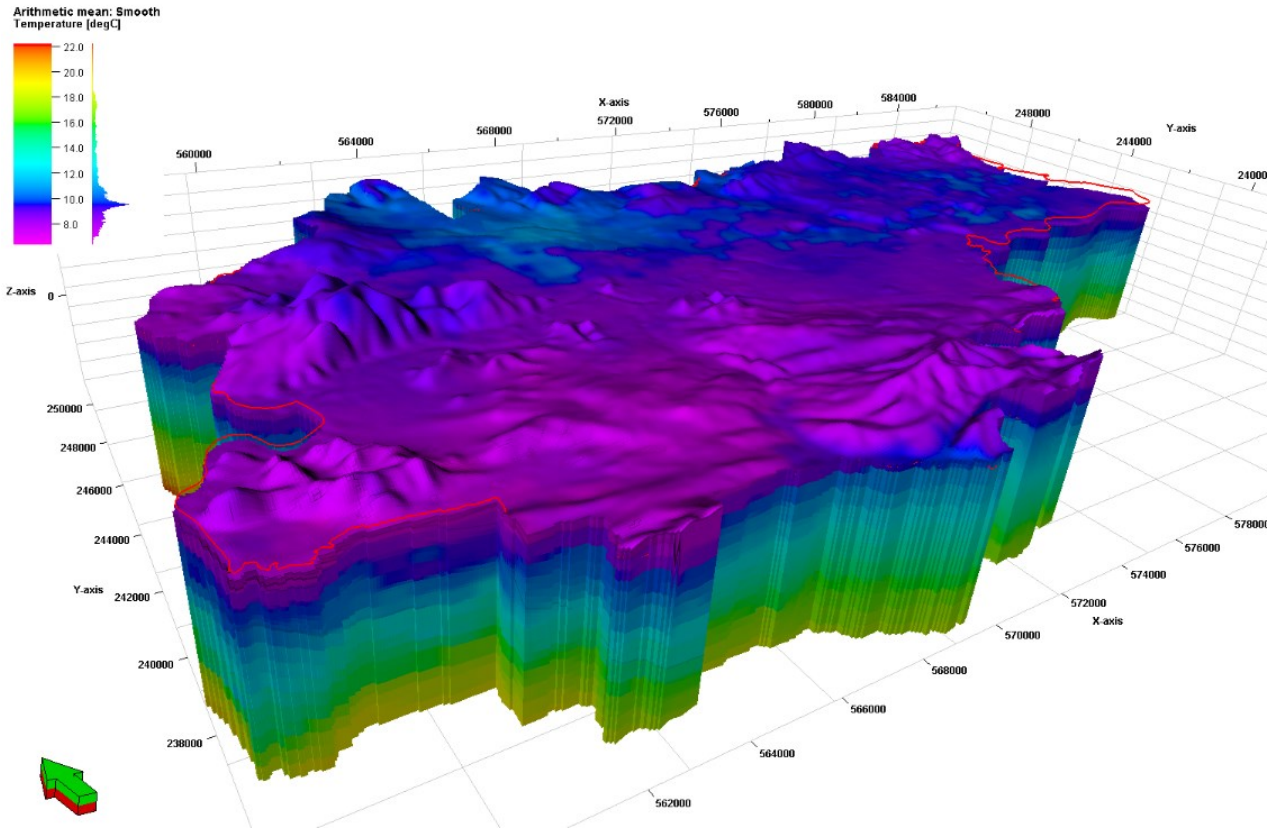

Figure 3: 3D temperature distribution model up to 500 m b.g.l. in the area of Krakow

5.4 Modelling uncertainties and errors

3D model was constructed without geostatistical uncertainty analysis. Nevertheless, several uncertainty elements, mainly associated with input data were distinguished. Firstly archival cross-sections which were georeferenced and implemented into geodatabase seems to be mostly conceptual in many places. Also, archival tectonic maps were inconsistent.

Digitalized fault framework form the archive publications differed among themselves regarding rotation angle but not in pattern and general trend. 3D fault framework was generally constructed as vertical faults. Lack of accurate fault surface mapping led to a generalisation which may differ regarding the dip angle. Furthermore, geological descriptions of borehole profiles mostly related to lithology qualification of geological engineering boreholes proved to be defective. This was due to various interpreters sometimes caused by inexperienced field personnel performing drilling. With the increase of depth of prepared model, uncertainty of the presented result rises considerably.

6. APPLICATION OF MODELLING RESULTS

Knowledge on spatial distribution of available resources and possible limitations related to the use of geothermal/ground source heat pumps, both for open and closed loop systems, specific environmental constrains, including: geogenic, hydrogeological and anthropogenic issues are a major parameters conditioning the use of shallow geothermal energy (Hajto et al., 2018). All of the above can only be properly implemented using 3D structural and parametric modelling approaches.

Resource assessment, supplemented with identification of the overall hazards and initial assessment of their significance through e.g. visualization in the form of a “traffic light map” (by categories: generally possible, with restrictions, not possible) allows information

on the possibility of installing a geothermal heat pumps (open and/or closed loop systems) in a given location. This has been achieved by setting up an interactive web GIS portal (https://portal.geoplasma-ce.eu). A joint web portal for supporting the knowledge transfer on shallow geothermal between the research sector and actors as well as users of shallow geothermal energy offers state-of the-art spatial information systems for the 6 regions addressed in the GeoPLASMA-CE project, including Kraków.

In addition, the thematic layers drawn up will indicate the existence and allow for the specification of other threats/conflicts related to, for example, the specificity of land development, the location of protected areas (ground waters), underground infrastructure, landslides, etc. Identification of the above elements and gathering information in one place will facilitate both the individual and the expert's future planning of investments in the field of geothermal heat pump installations (Hajto (ed.) et al., 2019b).

Distribution of resource potential for closed loop systems (CLS) has been accomplished through construction the maps of thermal conductivities (W/m K) for certain depth intervals expressing depth of designed BHE (50, 100, 150, 200 m) - (Hajto (ed.) et al., 2019b). For open loop systems (OLS) estimation of resources may be finally achieved through the construction of specific productivity maps, expressed in (m^3/h/1m of drawdown) – resulted from separate hydrogeological modelling performed with use of Visual MODFLOW™. The parameters obtained, together with a certain assumptions made, including: the properties of the BHE (radius, thermal resistance), properties of rocks (thermal capacity), the lifetime of the system, the length of the heating season, can be used for the preliminary assessment of shallow geothermal potential expressed in kWh/a – taking into account different resources use (heating, cooling, balanced use).

The advantage of created 3D geological-parametric model comprise also a possibility to display the results of advanced interpretation in a form of virtual borehole profiles, which may constitute an invaluable source of information, especially where a lack of borehole data is observed. The resulting thematic layers are available for free at https://portal.geoplasma-ce.eu. A sample -print screen of the thematic layer illustrating the "suitability for groundwater heat pumps" for Kraków pilot area is shown in Figure 5.

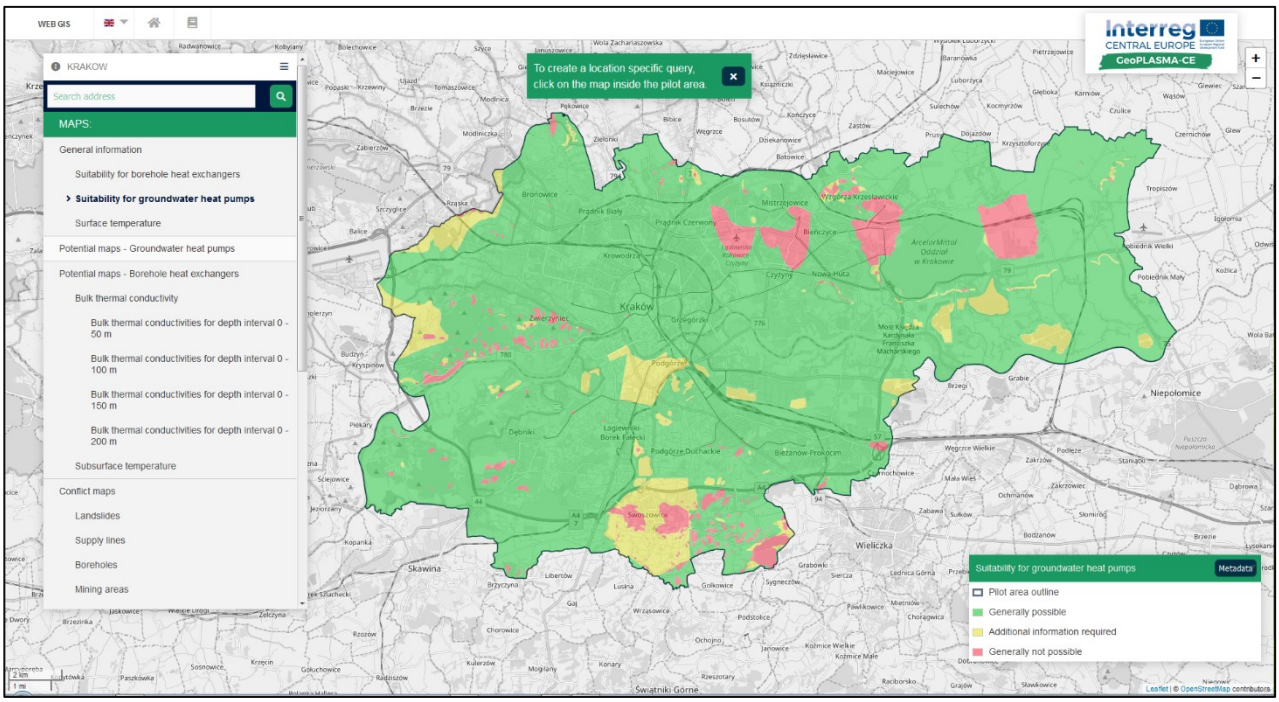

Figure 5: A sample of thematic layer "suitability for groundwater heat pumps" for Kraków, based on 3D geological-parametric modelling (https://portal.geoplasma-ce.eu/webgis/krakow)

7. CONCLUSIONS

Combination of geothermal structural, facies and reservoir variabilities performed with numerical modelling with use of Petrel software may strongly support and intensify the research of geothermal systems including the shallow geothermal. The huge advantage of such approaches allows finding an easy solution to research problems where finding a solution with analytical methods, field studies would take much more time. Mathematical modelling is a good tool not only for preparation a nice graphic presentation, but primarily to provide much likely information on geometry and distribution of various parameters of the geothermal systems, conditioning proper assessment of the resources and determination of overall potential environmental constrains for both open and closed loop system. It seems to be very important, especially in urban areas, when a lack of overall geological and geophysical data is being observed. Use of the Petrel systems allows, for the first time ever, creating a coherent 3D geological/tectonic model of Krakow, what should be considered as a milestone in the field of geological exploration in the Krakow area. Unfortunately, due to lack of time, the accuracy of the obtained 3D model, considering the principles of numerical modelling was not performed during the analysis. From this point of view it may be a starting point for the future work on the quality improvement of the model by means of better structural, lithological and parametric control.

The resulting 3D models will be used (among the others) to calculate the shallow geothermal potential and served on the web-platform, where they can be queried about the conditions for the construction of new shallow geothermal systems. Gathering

information in one place (on the internet platform) will facilitate both the individuals and the experts future planning of investments in that field and hopefully increase the use of these environmental-friendly technologies – to improve the living conditions of Kraków's inhabitants.

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