

SUSTAINABLE EXTRACTION AND PROCESSING OF RAW MATERIALS



Edited by Prof. Dr. Marinela Panayotova

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Dear readers and authors,

It is a great honour for me to present to your attention the seventh volume of the "Sustainable Extraction and Processing of Raw Materials" Journal (SEPRM) published by the University of Mining and Geology "St. Ivan Rilski", Sofia, Bulgaria.

The "Sustainable Extraction and Processing of Raw Materials" Journal is a specialised scientific publication aimed at presenting original and innovative research papers as well as concise reviews on the environmentally friendly and viable provision of resources from primary and secondary sources in order to contribute to the sustainable development of our society. It publishes also selected papers from the Annual International Scientific Conference of the University of Mining and Geology "St. Ivan Rilski", Sofia, Bulgaria.

The official language of this double-blind, double peer reviewed journal is English. The following fields are covered:

- Geological and geophysical studies related to the assessment of mineral resources and their environmentally friendly extraction;
- Sustainable mining (underground and open pit, geo-technology - chemical, physicochemical, biochemical, and microbiological methods, urban mining, conservation, liquidation and reclamation of mining sites);
- Sustainable processing of primary and secondary raw materials - physical methods (comminution, milling and dewatering), physicochemical separation methods (flotation, bio-, hydro-, and electrometallurgy), mineralogical aspects and analytical techniques to follow the mentioned processes;
- Environmental issues, related to mining and raw materials processing, particularly those related to sustainable development;
- Modelling, control, economics and management of extraction and processing of raw materials.

The journal adheres to the standards of publication ethics recommended by the Committee on Publication Ethics (COPE) Core Practices.

I would like to acknowledge the contribution of all the prominent scientists who agreed to be members of the SEPRM Editorial board!

I am grateful to all authors who have chosen SEPRM Journal to share their research!

I am happy to remind that the previous volumes of the SEPRM are indexed in Google Scholar and included in CrossRef, DOAJ, BASE, OpenAIRE, Academic Resource Index (ResearchBib), ROAD, the Scientific Indexing Services, the Russian Scientific Electronic Library (eLIBRARY) and the National Reference List of Contemporary Bulgarian Scientific Publications with Scientific Review. It is archived in COBISS and in the Bulgarian Portal for Open Science certified according to CoreTrustSeal standards and Bulgarian National Library.

Editor-in-Chief: Prof. Dr. Marinela Panayotova

GRATITUDE TO REVIEWERS

I would like to express my deep thankfulness to all reviewers for their time and dedicated labour to review all papers submitted to the SEPRM Journal in order to choose the soundest works.

This volume of the journal is available due to the efforts of the volunteer reviewers - colleagues listed below:

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Dear Colleagues,

I am very obliged and thankful to you!

With a hope for further cooperation,

Yours Sincerely,

M. Panayotova, Prof. Dr., Editor-in-Chief - SEPRM Journal



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CONTENTS	Page
Brodt, A. FEATURES OF INTERACTION BETWEEN POTASSIUM SALTS MINING AND THE ENVIRONMENT	6
Doneva, B., Panov, Z., Stefanovska, R. K., Popovski, R. GEOPHYSICAL INVESTIGATIONS USING SEISMIC REFLECTION METHOD IN THE AREA WITH THE GEOTHERMAL WATERS	13
Duru, N. U. DEVELOPMENT OF A NON-LINEAR LEAST-SQUARES KINETIC MODEL FOR HEAP LEACH CHEMICAL EXTRACTION USING COLUMN LEACH DATA	20
Georgiev, P., Nicolova, M., EFFICIENCY AND SELECTIVITY OF COPPER PRECIPITATION AS COPPER OXALATE FROM SOLUTIONS FROM THE MINING INDUSTRY	28
Georgiev, P., Nicolova, M., Spasova, I. NON-FERROUS METAL BIOLEACHING FROM COPPER SLAG WITH A SPENT MEDIUM OF SPOROSARCINA UREAE	34
Ivanov, R. INFLUENCE OF THE CONSTRUCTION OF A BIOSENSOR BASED ON SEDIMENT MICROBIAL FUEL CELLS ON ITS SENSITIVITY TO WATERS CONTAMINATED WITH HEAVY METALS	40
Korobiichuk, V., Iskov, S., Mamrai V., Shamrai, V., Bilobrov, D. STUDY OF STRENGTH REDUCTION IN NATURAL STONE UNDER REPEATED NON-DESTRUCTIVE DYNAMIC LOADING	45
Loukanov, A. SUSTAINABLE MATERIALS FOR URANIUM REMOVAL FROM MINE WATER: COMPARATIVE EVALUATION OF ZERO-VALENT IRON NANOPARTICLES, CONVENTIONAL SORBENTS, AND FUNCTIONALISED MAGNETIC NANOMATERIALS	53
Petrov, P., Stefanova, V., Vasilev, Z., Ivanova, S., Stamenova-Yordanova, I., Georgieva, E. REHABILITATION AND RECONVERSION OF COAL MINING SITES: SUSTAINABLE SOLUTIONS FOR ENERGY TRANSITION IN THE PERNIK REGION	62
Polischuk, D., Panasiuk, A., Mamrai, V. INVESTIGATION OF FACTORS AFFECTING UAV-BASED MINE SURVEYING ACCURACY	69
Svietkina, O. Yu., Fedoskina, O. V. INTENSIFICATION OF THE PROCESS OF BENEFICIATION OF MINERALS BY VIBRATION-IMPACT ACTIVATION	75
Instructions for authors	83

GEOPHYSICAL INVESTIGATIONS USING SEISMIC REFLECTION METHOD IN THE AREA WITH THE GEOTHERMAL WATERS

Blagica Doneva, Zoran Panov, Radmila Karanalkova Stefanovska, Risto Popovski

Faculty of Natural and Technical Sciences, Goce Delcev University, Stip, North Macedonia, blagica.doneva@ugd.edu.mk

Corresponding author: blagica.doneva@ugd.edu.mk

ABSTRACT. Reflection seismic investigations in the „Podlog-Banja“ geothermal field are the first investigations of this kind planned to perform „pilot“ doublet-system for using of geothermal energy in the Republic of Macedonia. The selection of the „Podlog-Banja“ geothermal field for the installation of a pilot doublet system was based on its favourable geothermal characteristics and the availability of an established team of qualified experts who could manage, monitor and operate the system effectively. Reflection seismic surveys were conducted within a metamorphic rock complex overlain by sedimentary and volcano-sedimentary formations with a thickness of approximately 300–500 m. Under such geological conditions, the quality of the seismic reflection data is expected to be lower than that typically achieved in geological environments characterised by horizontal layers. The effectiveness of the studies is further limited by the inclined spatial orientation of the geological structures and the low seismic velocity contrasts among the lithological units in the investigated metamorphic complex. These factors reduce the resolution and interpretability of the acquired seismic data. Due to the inclined spatial orientation of the geological units, the litho-spaces identified through reflection seismic investigations have not been adequately documented by previous drilling activities within the „Podlog-Banja“ geothermal field. As a result, the litho-physical interpretation of the reflection seismic results should therefore be regarded as „forecasting“.

Key words: Podlog - Banja, seismic, reflection, geothermal.

Introduction

Reflection seismic investigations are actual phase of the investigations for performing the pilot-industrial doublet system in geological environment of the „Podlog-Banja“ geothermal field.

The feasibility of the proposed location for the doublet wells is evaluated primarily on the basis of the presence of karstified carbonate rocks. With that goal, reflection seismic investigations were realised on 4 profiles at a depth of 1500 m. On the base of the results from the reflection seismic investigations final decisions for micro locations and projecting of the performance of the planned investigational and doublet - system wells was made (Babaei, 2019; Mahbaz, 2021).

Kocani geothermal field is situated within a complex geologic region, structured by the following 3 tectonic units: Vardarian zone, East-Macedonian zone and Kratovo-Zletovo volcanic area between them. The main directions of the tectonic distortions of this geologic region are north-west and north-east. The block of Kocani geothermal field is a lifted structural-tectonic block with an approximate area of 2.5 x 4.0 km, which is bended to the north-east. The depth of bedding in this block varies from 400 m to south-west to 750 m to the north-east.

According to the geological data, the terrain of the Kocani geothermal field is structured from the following litho-stratigraphic units (Rakicevic et al., 1965 – 1968):

- Q - Quaternary (alluvial) sediments – of dust, clay, sand, gravel;
- Ol - Oligocene sediments – predominantly of alevrolites;
- (aw) - Oligocene upflowing magmatism - andesites, andesitic tuffs and breccia;
- E₃ – Upper Eocene sediments - erosion backwards of marble, sandstone limestone;
- Pz₁ - Palaeozoic (and Proterozoic age rocks) - metamorphic basement of the terrain, built from schist and carbonate rock (limestone and dolomites) which are of

great importance for the „Podlog-Banja“ hydrothermal system.

The metamorphic basement of the terrain is related to the Hercinic orogenesis. The general structural and tectonic framework of the geothermal field can be interpreted as a tectonic, pre-existing anticlinal structure. The strongest tectonic processes are related to the Tertiary, more particularly the Neogen till the beginning of the Quaternary.

Hydrogeothermal conditions of the Kocani geothermal field have been studied based on analysis of the drilling results and testing of 19 (nineteen) investigating and operational wells and data on the industrial operation of 4 (four) exploitation and 1 (one) reinjection well. The depth of these wells varies from 86.5 m to 1096 m. As general characteristics of the Kocani geothermal field, we should note the following:

- The distribution of temperature in the area of the geothermal aquifer is unequal. In the central part of the field the temperature is 70 °C – 78 °C, while in the peripheral part it decreases to 50 °C. During the operational period (about 25 years) no changes of temperature have been observed both in the area and in the exploitation well head.
- The circulation of thermal waters within the field is not limited by a particular lithological type of rocks but it relates to porous and cracked permeable zones within the geological environment of the geothermal aquifer. In general, the distribution of these zones is typical for 450-550 m depth.
- The thermal waters are characterised as bicarbonate–sulphate–chloride–sodium type waters, with pH = 7 and water mineralisation of ≈1.0 g/L.

Static heat measurements in the wells show that within the field there is a natural flow of ground water, which flows to the northern direction, i.e., the flow is directed from the central part of the Kocani valley to its peripheral parts.

Although the seismic data were originally acquired during investigations conducted in 2008 for the „Podlog-Banja“ geothermal field, the present paper does not represent a simple reproduction of the original technical report. The current study

provides a revised geological and hydrogeological interpretation focused specifically on the suitability of the area for modern geothermal doublet - system applications. In contrast to the original report, this paper integrates the seismic interpretation with contemporary concepts of geothermal reinjection systems, well-doublet spacing optimisation, and sustainable geothermal reservoir management. The study additionally discusses the limitations of seismic reflection investigations in metamorphic environments characterised by inclined structures and low seismic-velocity contrasts, which were not elaborated in detail in the original documentation. The results from 2008 have not been published previously.

Well locations of the doublet system

The selection of the doublet-wells locations was based on the following considerations (Wu, 2021; Wang, 2022):

1. The distance between the reinjection and production wells should ensure the time needed for the temperature front to reach the reinjected cooled down waters, i.e., operation of the production well with constant temperature of the heat carrier at the head for a period of about 30 years.
2. The production well should be located as close to the geothermal heat exchangers as possible to decrease the capital costs for laying down the heat insulated thermal water pipeline.
3. The geological structure, the geothermal and hydrogeological conditions of the section, where the doublet system well will be placed, should comply with the following requirements:
 - a. The productive collector should be maintained in horizontal and vertical perspective;
 - b. The filtration parameters of the productive collector within the area of developed section should be relatively the same;
 - c. The stratum temperature within the whole developed section should be approximately the same;
 - d. There should be no hydrodynamic interaction of the productive collector with the upper and lower aquifers;
 - e. The capacity of the productive collector should ensure a high injectivity of the reinjection well;
 - f. The natural stream of thermal waters, if any in the productive aquifer, should impact the reinjected cooled down thermal waters in a way preventing their movement to the side of operation, within the geothermal field wells.

The spacing between the production and reinjection wells of the doublet system is determined through heat mass transfer calculations within the permeable reservoir formation in which both wells operate. The temperature of the stratum fluid is set to 80°C. The temperature of the cooled down geothermal water is set to 30°C.

Depending on the heat load in a heating season, the reinjection flow varies between max 40 l/s and min 12.5 l/s.

Within the heating season there is a constant production and reinjection flow in the doublet system equal to 22 l/s. In the summer period the doublet system is closed, i.e., the production and reinjection volumes equal to zero (Torres, 2019; Gascuel, 2024).

Using the above assumptions and the thermal physical and filtration parameters of the stratum fluid and rock structure, the set period of 30 years of the doublet system operation is ensured by a production and reinjection volume of 22 l/s. This proves that

the distance between the production and reinjection wells ensuring the production of geothermal water with constant temperature at the well head should be at least 800 m. This is the distance between the wells' bottoms but not the distance between drill sites (Satman, 2011; Xia, 2017).

Two drilling sites were selected for the reinjection and production wells in the Kocani valley - two recommended options for dislocation of the production and reinjection wells of the doublet system to be established on the Kocani geothermal field (Figure 1).

The final decision on the location of the production well must be taken during the drilling project design upon completion of additional geophysical works.

The reinjection well is in the northern outskirts of the village D. Podlog close to the thermal water main pipeline (Vardon, 2020; Vižintin, 2024).

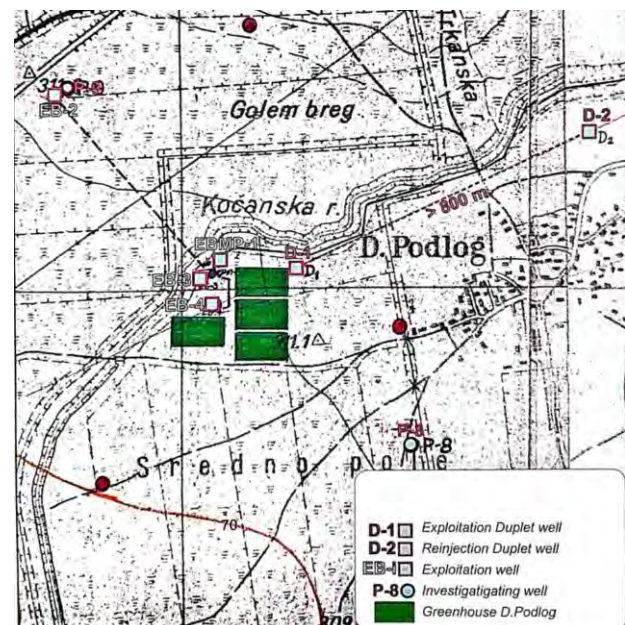


Fig. 1. Topographic map with wells locations
EBMP-1 – exploitational well

The main arguments justifying the selection of drilling sites are given below:

- The doublet system wells should be located close to the designed geothermal heating substation, where geothermal heat exchanges are installed.

- The doublet wells should be located perpendicular to the natural stream of thermal waters in the productive aquifer which ensures drift to the zone of thermal water pumping due to this stream. This zone is in the opposite direction from the production wells EB-1; EB-2; EB-3 and EB-4 (Figure 1). This one is an additional factor ensuring safety of the heat mass transfer calculations.

- Doublet wells are located within the tectonically insulated block of well heated rocks with relatively homogeneous filtration properties and roughly similar, on the block area, stratum temperature.

- Wells have to be located on the flat relief area having nearly horizontal surface which allows elimination of the hydraulic resistance in the pipeline that could happen due to

overcoming difference in the geodesic marks in some sections of the pipeline.

Re-injection and production wells level has shown the following:

- The water level in reinjection well D-2 during operation is expected to remain below ground surface elevation. Consequently, the well is expected to operate in a "pouring-in" reinjection mode.

- Regardless of the water re-injection into well D-2 in the amount of 340 000 m³/year, the depth of the level in both D-1 and D-2 wells shall continue to decline in time indicating strata energy recharge deficiency by re-injection into D-2.

- The intensity (rate) of the level drop in the doublet wells is different and depends on the total volumes of geothermal water production in Kocani.

- The anticipated depth of geothermal water in the production and the re-injection wells within 30 years of operation: re-injection well about 70 - 90 m, production well - about 80 – 100 m.

Reflection seismic investigation

The reflective seismic investigations were conducted on the following four investigated profiles: Ko-0701, Ko-0702, Ko-0703 and Ko-0704. The investigated profiles were realised with effective length of 1.250 m to 2.600 m, and with a total effective length of 7.815 m (Mirakovski, 2008).

The profile Ko-0701 was carried out with a length of 2.5 km, in parallel with the structural-tectonic direction "Podlog - Banja" (close to the North-South direction). The other investigated profiles were carried out approximately in normal direction of Ko-0701 (East-West), with lengths of 1250 - 2300 m, and their eastern sides were intersected with profile Ko-0701.

Parallel to profile Ko-0702, two shorter parallel profiles, Ko-0702a and Ko-0702b, were surveyed on either side of the facility. Each profile had a length of approximately 320 m and provided an investigation depth of 700–1000 m. These profiles were conducted to improve the understanding of the local hydrogeological conditions in the vicinity of production well D-1 and to support the selection of its optimal microlocation.

Seismic wave generation was achieved using explosive charges placed in boreholes with a depth of 2.5 m, ensuring detonation below the groundwater table. Seismic data acquisition was carried out using 30 Hz geophones and a 24-channel Terraloc Mark-6 seismograph (by ABEM, Sweden). Linear disposition was used for the excitement and geophone positions, with excitement step of 20 m and geophone distance of 10 m.

Investigations were carried out with two excitements for each position, and with two geophone dispositions with 24 channels.

Profile Ko-702 was realised with minimal offset of 40 m. To register better reflections from the metamorphic complex, the minimal offset of the other profiles was enlarged to 160 m.

Results of the reflection seismic explorations

Using 2D - processing, the results of the investigations were finalised in the following reflexive seismic sections:

- Definitive (non-migrated) time section;
- Migrated time section;
- Definitive (non-migrated) depth section;
- Migrated depth section.

To convert the Time-section to Depth-section a "Smoothed RMS- velocity" was used within "time-velocity models" per each of the investigated profiles.

For a series of parallel layers of velocity V_i , where the travel time of the seismic energy perpendicularly through each layer is t_i , the RMS (root-mean square) - velocity is defined using the following expression:

$$V_{RMS} = [\sum V_i^2 t_i / \sum t_i]^{0.5}.$$

where is:

V_{RMS} - root mean square seismic velocity

V_i - interval seismic velocity of the i -th layer

t_i - two-way travel time through the i -th layer.

Geological interpretation

The results from the investigation are shown on definitive and migrated (Figures 2 and 4) depth seismic sections of the exploration profiles, in variants with "presented" and "generalised" deposit over metamorphic basement. The following litho-mediums are interpreted in the depth sections:

- ✓ Quaternary sediments (Q) - alluvial deposit present at a depth of $\approx$ 200 m;
- ✓ Oligocene sediments (Ol) - alevrolites present at a depth up to 500 m;
- ✓ Oligocene up flowing magmatism (aw) - andesites and andesitic tuffs, with presence in the "roof" as well in the basement of the Oligocene sediments;
- ✓ Eocene sediments (E_3) - erosion backwards with thickness of up to 50 m;
- ✓ Paleozoic basement (Pz_1 - probable Ordovician age) - presents at depths from 280 m up to over 500 m, built from low water-permeable or non-water - permeable schist rock.

The objective of the investigation was to characterise the lithophysical structure of the metamorphic basement underlying the geothermal field. Particular attention was paid to the occurrence and spatial distribution of karstified limestone units within the basement complex, as these formations represent the most favourable reservoir environment for both geothermal water production and the reinjection of spent geothermal fluids through the doublet-well system.

From the "Time-Velocity" models (Figures 3 and 5) of the investigating profiles the following interpretation of the terrain structure is presented:

According to the first half of profile Ko-702 (Figure 3), the increased amplitudes of the seismic sections indicate karstified limestones, but they are not the only factor for this increase. Similar seismic reflection patterns were not identified elsewhere along the surveyed profiles. However, this observation should not be interpreted as evidence for the absence of additional karstified limestone bodies within the investigated area due to the following considerations:

- The limestone rocks in the investigated terrain are among the oldest rocks in the region, and it is realistic to expect to be intensively cracked;

- Cracking of the carbonate rocks is a precondition for their karstification. Taking into account the geological age of this terrain, it is reasonable to assume that karstification processes have been active over extended periods of time.

- With geothermal water above 40 °C, the karstification processes become more intensive, and dolomites can also be karstified.

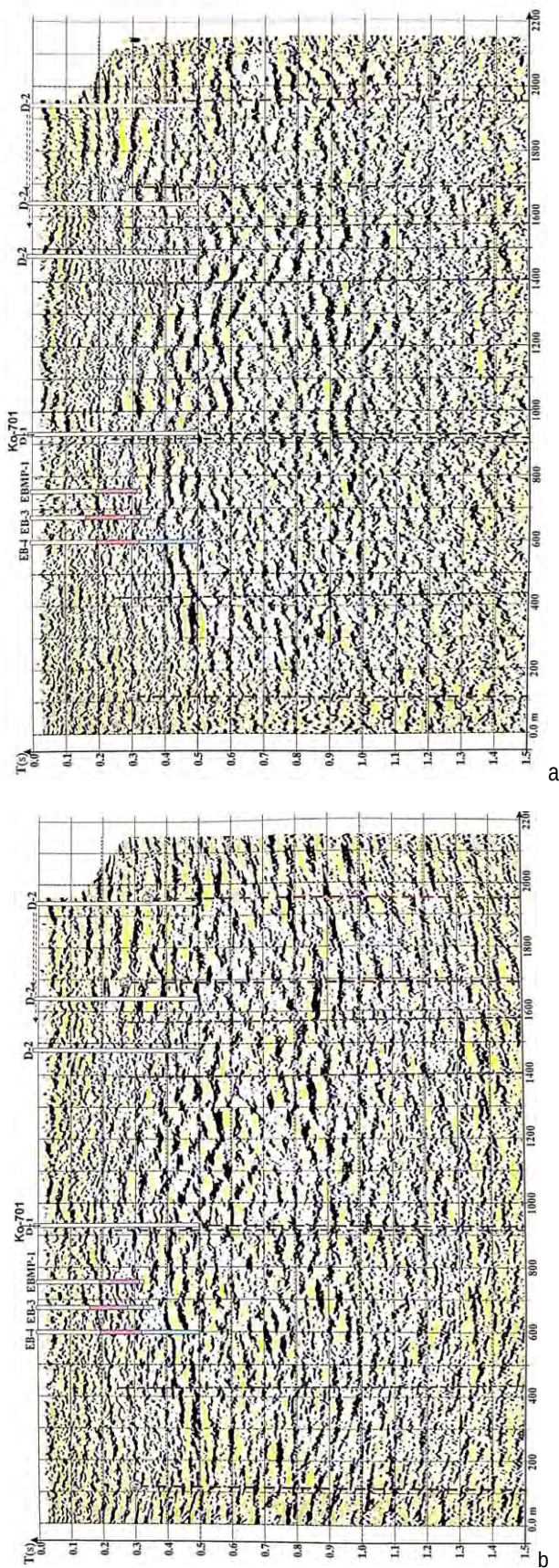


Fig. 2. Profile Ko – 702 Definitive (a) and migrated (b) time section

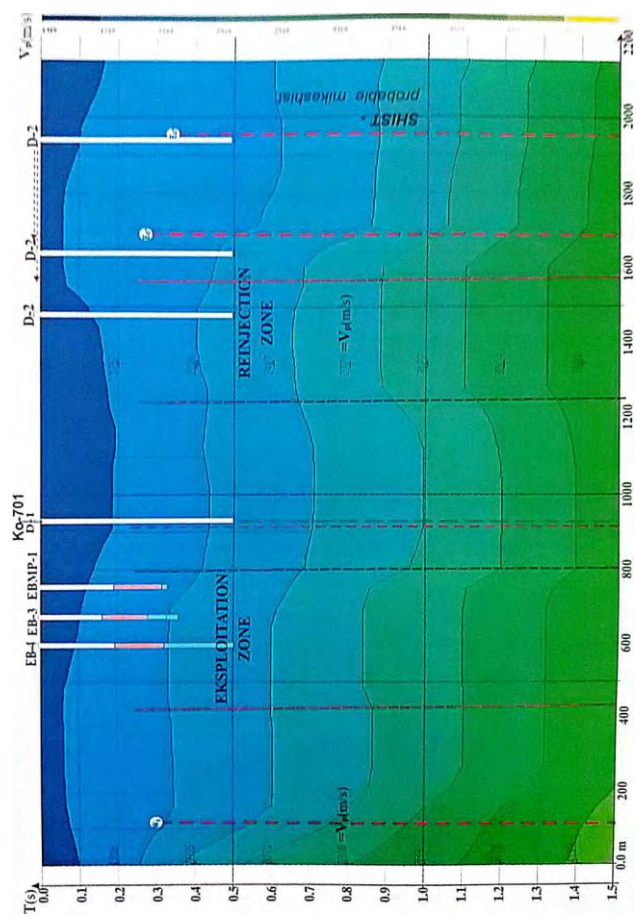


Fig. 3. Profile Ko – 702 – Time – Velocity model

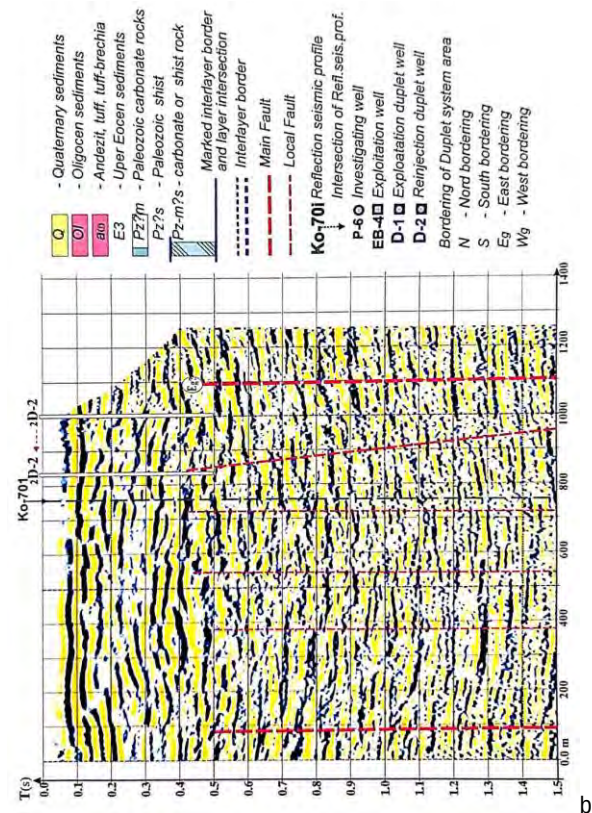
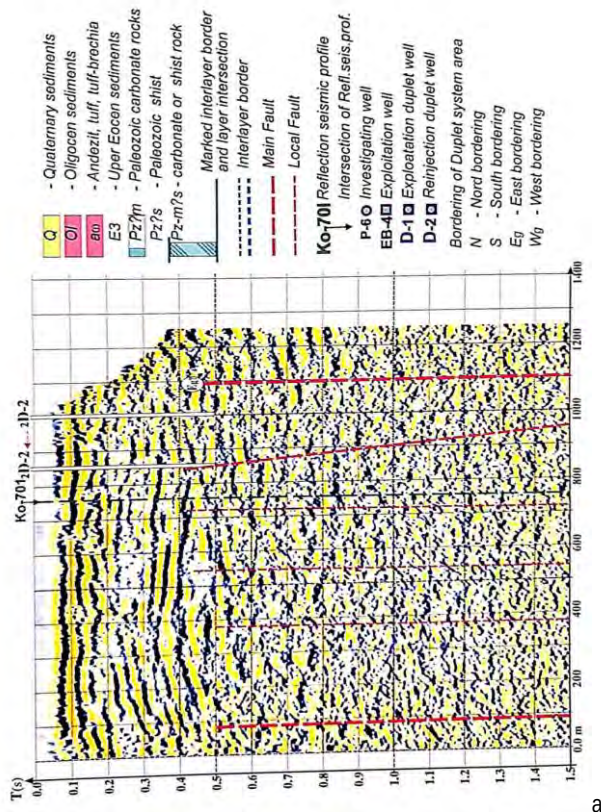


Fig. 4. Profile Ko – 704 – Definitive (a) and migrated (b) time section

With regard to the above considerations, the presence of karstified carbonate rocks within the limestone units of the metamorphic basement is considered highly probable.

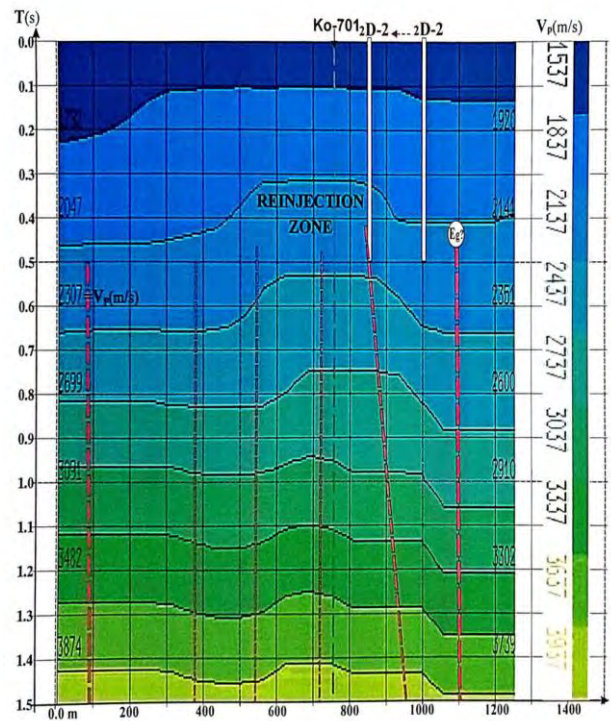


Fig. 5. Profile Ko – 704 – Time – Velocity model

However, it should be taken in consideration the “geological positioning” of the karstification by predestined structures (faults, cracked zones, clear calcite inter-layers, in the lower parts of the carbonate layers when placed over the water non-permeable layers, etc.)

Structure of the investigated terrain

The structure of the investigated terrain was analysed by developing a fault network model of the area (Figure 6).

“Faults net” of the investigated terrain is constructed on the base of interpreted faults in the metamorphic basement of the investigating profiles Ko-0701 to Ko-0704. Seismic investigations were conducted to interpret the faults in a direction normal to the exploration profiles. As a result of that, several mistakes are often made when connection is established between faults indications on different profiles. Also, built-up net of the profiles is not suitable for quality interpretation of fault net (a profiles net for 3D investigation is more appropriate for better quality interpretation of the fault net).

The constructed fault network indicates that the interpreted faults can be grouped into three systems:

- The system with orientation in the direction of the “Podlog-Banja” structure,
- The system with orientation East-West,
- The system with extension North-South, probably formed with horizontal faulting of the terrain.

A fault system with extension North-South is detected as follows:

- Correlation of similar structure at ≈ 250 -500 m length from the Ko-702, at ≈ 200 -450 m length from the Ko-703 and ≈ 1100 m from profile Ko-704, indicates the presence of tectonic zone with a near north-south orientation;



Fig. 6. Map with locations of doublet-system wells and faults net

2. The Basic geological map of the Republic of North Macedonia indicates the presence of several horizontal fault systems with north-south extension within the metamorphic basement of the geothermal field in the Plackovica mountain.

Discussion

The reflection seismic investigations performed in the “Podlog-Banja” geothermal field demonstrated both the potential and the limitations of applying seismic reflection methods in complex metamorphic terrains. Unlike sedimentary basins characterised by nearly horizontal layers and strong seismic impedance contrasts, the investigated area contains inclined lithological contacts, heterogeneous metamorphic rocks, and relatively small differences in seismic velocities between litho-units. These geological conditions significantly reduce the clarity and continuity of seismic reflections.

Despite these limitations, the processed seismic sections enabled identification of several important structural features relevant for geothermal exploitation. The interpreted fault systems and fractured carbonate zones indicate potential pathways for geothermal fluid circulation and represent favourable targets for locating geothermal production and reinjection wells.

The increased amplitudes observed in parts of profile Ko-702 are interpreted as indicators of fractured and potentially karstified carbonate rocks. However, such amplitude anomalies cannot be considered as a definitive proof of karstification because seismic amplitudes may also be influenced by lithological heterogeneity, structural discontinuities, and local velocity variations. Therefore, interpretation uncertainty remains

significant and should be considered during planning of future drilling activities.

An important limitation of the study is the absence of dense borehole control data within all interpreted seismic sections. Because of this, parts of the lithological interpretation remain extrapolative in nature. The integration of future drilling data, well logging, and additional 3D seismic investigations would substantially improve the reliability of structural and hydrogeological interpretations.

The identified fault systems with NW-SE, E-W, and N-S orientations suggest a structurally complex geothermal reservoir controlled by multiple tectonic phases. These structures likely influence permeability distribution and geothermal fluid migration within the reservoir. Such structural interpretation is important for optimising the positioning of geothermal doublet wells and minimising thermal breakthrough during long-term exploitation.

Overall, the study confirms that reflection seismic investigations, despite their limitations in metamorphic environments, can provide valuable structural information for geothermal reservoir assessment when integrated with geological and hydrogeological data.

Conclusions

The conducted reflection seismic investigations provided important structural and geological information regarding the “Podlog-Banja” geothermal field and its suitability for future geothermal doublet-system development.

The interpreted seismic sections enabled identification of major lithological units, including Quaternary sediments, Oligocene deposits, volcanic units, Eocene sediments, and the Paleozoic metamorphic basement. Special attention was focused on fractured and potentially karstified carbonate zones within the metamorphic basement, which represent the most favourable environments for geothermal fluid circulation.

The investigation confirmed that fault systems with different orientations play a significant role in controlling the structural framework and permeability conditions of the geothermal reservoir. These tectonic structures are considered important factors for determining optimal locations of production and reinjection wells.

The study also demonstrated the limitations of applying reflection seismic methods in metamorphic terrains characterised by inclined geological structures and low contrasts in seismic velocities. Because of these unfavourable geological conditions, interpretation uncertainties remain, especially regarding differentiation of lithological units within the metamorphic basement.

Nevertheless, by integrating seismic interpretation with available geological and hydrogeological information, the investigations provide a useful basis for planning future drilling activities and further geothermal development in the “Podlog-Banja” field.

Future work should include integration of borehole logging data, additional geophysical investigations, and preferably 3D seismic surveys in order to reduce interpretation uncertainty and improve characterization of the geothermal reservoir.

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