SEISMIC EXPLORATIONS IN THE AREA OF THE STRUMICA FIELD, THE REPUBLIC OF NORTH MACEDONIA

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ABSTRACT. The main goal of these researches is, based on the previous and newly performed geophysical measurements, more precise definition of the potential micro-localities for construction of future geothermal boreholes or artesian boreholes for water supply of the population and irrigation of the Strumica Field. Or, based on the analysis and possibilities of individual geophysical methods, to provide guidelines for the application of the most appropriate methods in future research.
These surveys are performed as basic surface and in-depth surveys on one or two profiles with a total length of 1 km. Refractive surveys are performed in order to obtain data for the subsurface layers to a depth of 30 - 50 m, as necessary for performing the interpretation of in-depth reflective surveys and for defining the structural and physical-mechanical condition of the subsurface layers. Reflective surveys are performed as basic for defining the deeper structural-geological structure of the terrain with full coverage of tertiary sediments and the surface part of the basic rocks, granites or other rocks. The research was performed with continuous measurements of two profiles located in the areas of the villages Petralinci and Borievo.

Key words: Strumica, seismic, reflection, refraction.

СЕИЗМИЧНИ ПРОУЧВАНИЯ В РАЙОНА НА СТРУМИШКОТО ПОЛЕ, РЕПУБЛИКА СЕВЕРНА МАКЕДОНИЯ

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РЕЗЮМЕ. Основната цел на настоящото изследване е въз основа на предишни и настоящи геофизични измервания да се направи по-точно определяне на потенциалните микроместоположения за изграждане на бъдещи геотермални сондажи или артезиански сондажи за водоснабдяване на населението и за напояване на Струмишкото поле; или въз основа на анализа и възможностите на отделните геофизични методи да се дадат насоки за прилагане на най-подходящите методи при бъдещи изследвания. Тези проучвания се извършват като основни повърхностни и дълбочинни заснемания на един или два профила с обща дължина от 1 km. Рефракционните проучвания се извършват с цел получаване на данни за подповърхностните слоеве до дълбочина 30 - 50 m, които са необходими за интерпретация на дълбочинни отразяващи снимки и за определяне на структурното и физико-механичното състояние на подповърхностните слоеве. Отразяващите проучвания се извършват като основни при определяне на по-дълбокия структурен и геоложки строеж на терена с пълно покритие на терциерните седименти и повърхностната част на основните скали, гранитите или други скали. Изследването е извършено с непрекъснати измервания на два профила, разположени в районите на селата Петралинци и Бориево.

Ключови думи: Струмица, сеизмичен, отражение, рефракция.

Introduction

Reflections and refractions of seismic waves at geologic interfaces within the Earth were first observed on recordings of earthquake-generated seismic waves. The basic model of the Earth's deep interior is based on observations of earthquake-generated seismic waves transmitted through the Earth's interior (e.g. Mohorovičić, 1910).

The refractive seismic method studies the propagation of elastic waves that are refracted at boundary surfaces. The refractive method is performed by placing geophones from the source of the elastic waves along the measuring profile line at a certain distance. Geophones are connected by cables to the seismic apparatus. At the moment when the seismic waves hit a boundary area that separates two different elastic media, they are refracted and, as such, the feedback signals are registered. The geophones placed on the surface of the ground convert the mechanical oscillations into electrical pulses that are transmitted to the seismic apparatus. The seismograms record the time of arrival of the elastic wave as well as the moment of excitation of the ground. Based on the seismograms, diagrams are constructed that determine the dependence between the distance of the geophone from the point of excitation as well as the time of arrival of the seismic oscillations to each geophone placed. Such diagrams are also called hodochrones.

The refractive seismic method successfully determines horizontal, vertical, and steep boundary surfaces, provided that in each deeper layer the propagation velocity of the elastic waves is higher than the velocity in the previous one. However, when this condition is not met or in cases where the differences in the elastic properties of the media are not sufficiently pronounced and when the boundary surfaces are located at great depths, the application of the refractive method is ineffective. Due to the fact that the length of the refractive seismic profiles should be 3 to 5 times longer than the depth at which the boundary surface is located, seismic examinations are significantly more difficult for several reasons:

- When the length of the test profile is large, more explosives must be used to excite the ground;
- When using more explosives, the hole in which an explosive is placed should have a greater depth, which significantly complicates the operation procedure;
- Using more explosives significantly increases the possibility of damage to the surrounding buildings.

For these reasons, since 1929, the reflective method has been used instead of the refractive one in certain seismic examinations.

Seismic reflection provides information about the subsurface stratigraphy and allows geoscientists to makes inferences regarding the geologic structure. Seismic reflection works off of the basic principle of impedance contrasts between two different geologic units, where either the density, velocity, or both, is different between the two structures. This lesson introduces the concepts of frequency, period, and wavelength, and their relationships to velocity and density structure.

Seismic Explorations

The investigated terrain is located in the southeastern part of the Republic of North Macedonia, in the area of the Strumica field. In tectonic sense, the research site belongs to the Serbian - Macedonian massif and is located near the western border with the Vardar zone.

Investigations were aimed to determine the existence, quantity, and quality of underground water.

The geological structure of the research area is represented by rocks from the Precambrian, the Paleozoic, the Mesozoic, and the Quaternary. The Precambrian rocks are presented with biotite gneisses, the Paleozoic rocks are represented by two-mica granite-gneiss, the Mesozoic is represented by rhyolites and porphyries, and the Quaternary is represented by diluvial and proluvial deposits, organic-marsh sediments, and upper terrace sediments (Fig. 1).

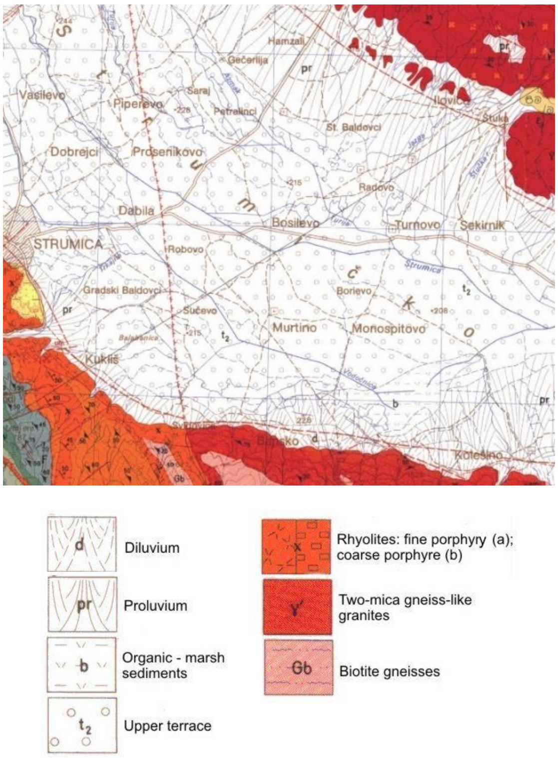


Fig. 1. Geological map of the investigated terrain

According the hydrogeological characteristics of the Strumica field, the following types of well are present (Fig. 2):

- Boundary spring,
- Fissure type of well,
- Karst water body,
- Waterless areas.

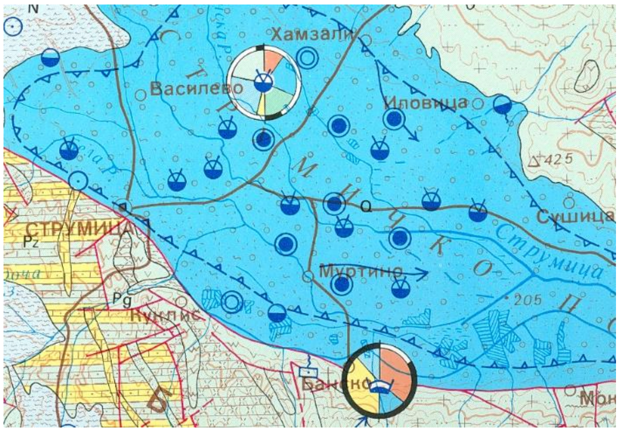


Fig. 2. Hydrogeological map of the investigated terrain

According the hydrodynamic features of the water level in the well, the following are issued:

- with free water level;
- with pressure level.

Boundary springs are most prevalent in alluvial, proluvial, Quaternary, and Pliocene sediments, and in granite gravel. The alluviums of the Strumica, the Turija, the Trkanja, the Shtuka, and the Javga rivers are rich in water with a filtration coefficient of $k \approx 1 \cdot 10^{-2}$ cm/s and thickness of up to 5 m.

The fissure type of well has a large distribution along the edge of the Strumica valley, but without much economic importance for water supply. It is formed in the crack porosity of the base rocks, and its movement and accumulation depends on the connection of the cracks.

Karst water bodies are present in the carbonate terrains.

Waterless areas are found in terrains built of granite and gneiss-like granite, the cracks of which are filled with clay or other cement binder.

Refractive surveys were performed in order to obtain data on the subsurface layers to a depth of 30 - 50 m, as necessary for performing the interpretation of in-depth reflective surveys and to define the structural and physico-mechanical condition of the subsurface layers.

Reflective surveys were performed as basic for defining the deeper structural and geological structure of the terrain with full coverage of Tertiary sediments and the surface part of the basic rocks, granites, or other rocks.

The research was performed with continuous measurements of two profiles located in the areas of the villages of Petralinci and Borievo. They were made with the "TERALOG" MK - III computerised refractive-reflective system produced by ABEM-ATLAS Copco from Sweden.

Refractive measurements were performed on individual profiles with a length of 120 m. The seismic waves were excited by hammer blows against a metal plate, and received by vertical geophones of 28 Hz. From the first encounters of P and S waves, their hodochrones were constructed and the apparent values of V_p and V_s velocities were calculated. Then, with the analytical processing of the hodochrons (Ti-method), a physicogeometric and geological interpretation of the subsurface structure of the terrain was performed according to the research profiles and the true values of the seismic velocities V_p and V_s were determined. Using the knowledge of the engineering and geological structure, the interpretation is transformed into physico-geological with lithological separation of the environments according to the values of the seismic V_p and V_s velocities (Fig. 3).

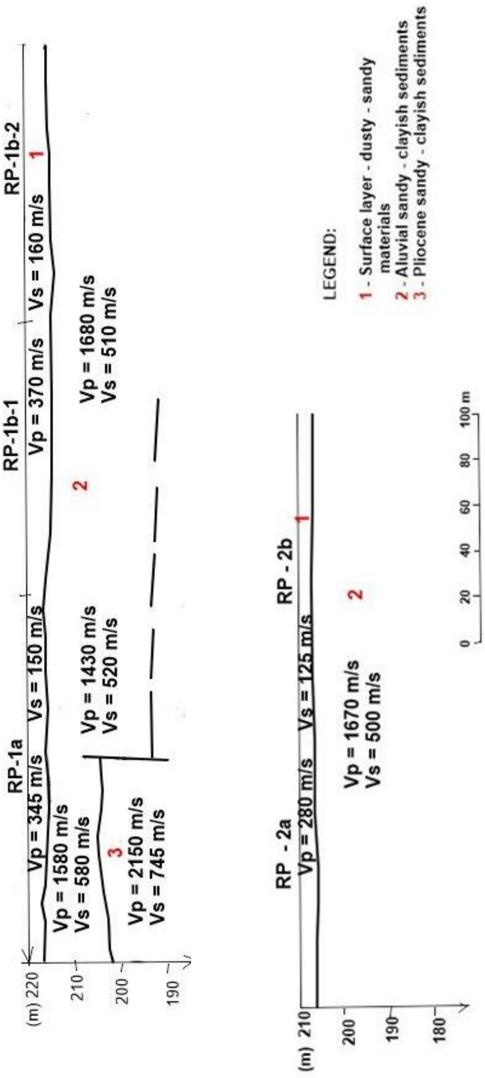


Fig. 3. Interpretation of refractive profiles in the region of the village of Petralinci RP-1 and the village of Borievo (RP - 2)

Reflective seismic surveys are performed with two procedures:

- Using individual profiles, identical to the refractive ones, with excitation of seismic waves with shocks against a metal plate;
- Using deep seismic profiling of reflective research, by excitation of seismic waves with the explosive (Q = 250 - 400 g) put in boreholes drilled for this purpose at a depth of 1.5 m.

In both procedures, seismic waves are received with 28 Hz vertical geophones.

The first procedure covers a depth of 400 - 500 m, and the interpretation of the subsurface structures is performed using the technique of shallow reflection, based on the hondrochron of the reflected waves and the mean values of the seismic velocities V_p and V_s from the surface to the depth of individual reflective lithogeological boundaries.

The following equations are used to calculate the individual parameters for:

- the mean V_p or V_s velocities (V_{sr})

$$V_{sr} = \left[\frac{x^2 - x_0^2}{t_{x(i)}^2 - t_{0(i)}^2}\right]^{0.5}$$

- the values of the interval V_p and V_s velocities (V_i) -

$$V_{i(1)} = V_1 = \frac{2h_1}{t_{0(1)}}$$

$$V_{i(2)} = \frac{\left[V_{sr(2)}\, h_2 - V_1 Z_1\right]}{Z_2}$$

$$V_{i(n)} = \frac{\left[V_{sr(n)}\, h_{i(n)} - \sum_{i=1}^{n-1} V_i Z_i\right]}{Z_i}$$

- values of depths (h) and thickness of interval layers (Z) -

$$h_1 = Z_1 = \frac{t_{0(1)}\, V_1}{2}$$

$$h_2 = \frac{t_{0(2)}\, V_{i(2)}}{2} + h_1 - V_2 \left(\frac{Z_1}{V_1}\right)$$

$$h_n = \frac{t_{0(n)}\, V_{i(n)}}{2} + h_{n-1} - V_{i(n)} \sum_{i=1}^{n-1} \left(\frac{Z_i}{V_i}\right)$$

$$Z_1 = h_1$$

$$Z_2 = h_2 - h_1$$

$$Z_n = h_n - \sum_{i=1}^{n-1} Z_i$$

where:

t_0 is the time of arrival of the reflective waves near the point of excitation of the waves, at x = 0;

x is the distance between the point of excitation and the geophones;

i = 1, 2, 3, ... n is the number of elastic (layer) boundaries.

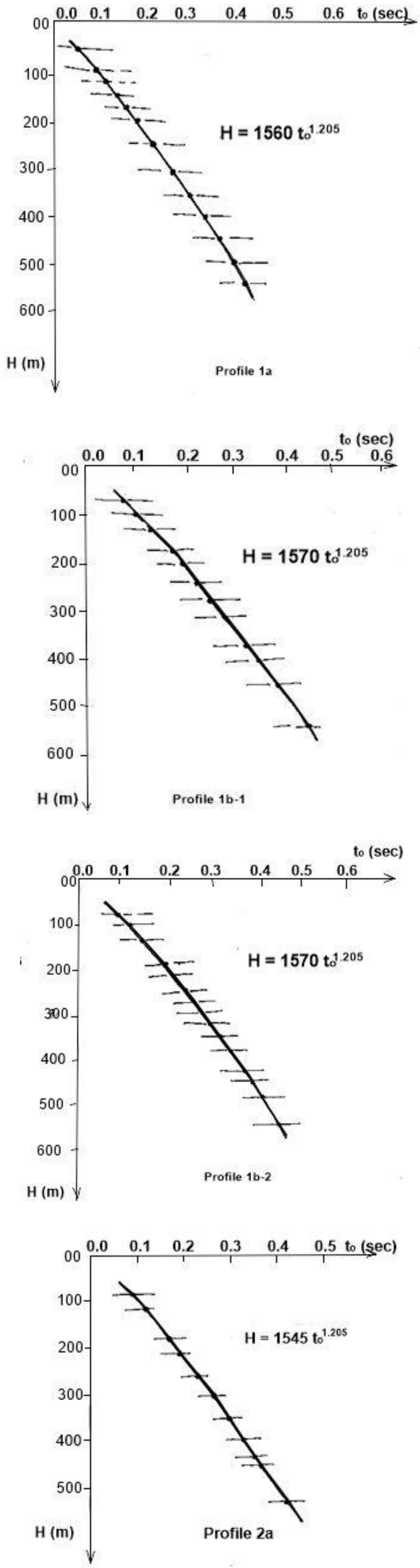
The arrival time of the reflective signals $t_{x(i)}$ along the profile x was controlled by the following equation for the case of environments with horizontal boundaries:

$$t_{x(i)} = \left[\frac{4h_i^2 + x^2}{V_{sr}^2}\right]^{0.5}$$

The control of the interval V_p or V_s velocities (V_i) is carried out with the following equation:

$$V_i^2 = \frac{V_{sr(i)}^2\, t_i - V_{sr(i-1)}^2\, t_{i-1}}{Z_i - Z_{i-1}}$$

The subsurface elastic boundaries and environments interpreted in this way are given in Fig. 4.



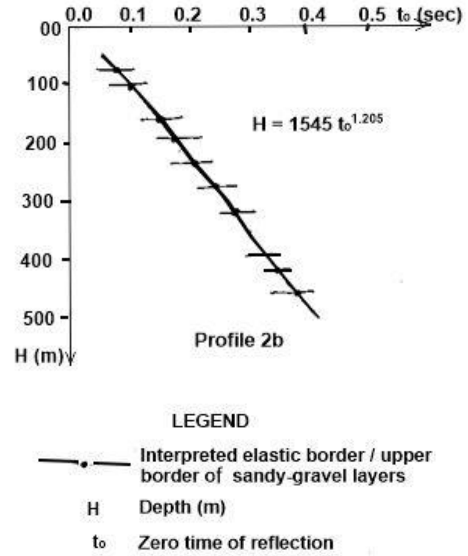


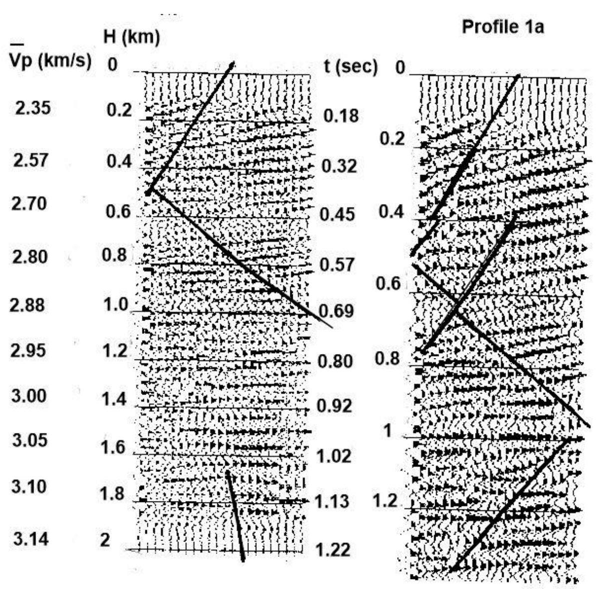
Fig. 4. Interpretation of shallow refrlective explorations in the area of the villages of Petralinci (Profile 1a, 1b-1, 1b-2) and Borievo (Profile 2a, 2b)

The second procedure is performed with the common point method, i.e. the CDP technique (or: common depth point technique). The procedure of continuous seismic profiling was performed by moving the points of the springs (explosions) and the profile layout of the geophones (12 x 10 m) by 30 m, which achieved fourfold coverage of the reflections.

These reflective surveys were performed as experimental, in order to determine the possibilities of the reflective method in the study of the Strumica Valley, in terms of determining the depth of the Tertiary basin, the statification, and composition of the basin and the present tectonic structures.

According to previous knowledge about the possible depth of the basin (1200 - 1250 m), and in order to perform more accurate measurements, they were performed with a time interval of registration of reflections of 1000 and 2000 milliseconds. By registering the reflections of 2000 milliseconds, only the first part of the RRP-1 profile was covered in the area of the village of Petralinci.

The data obtained from the temporal and deep sections of the reflections are shown in fig. 5.



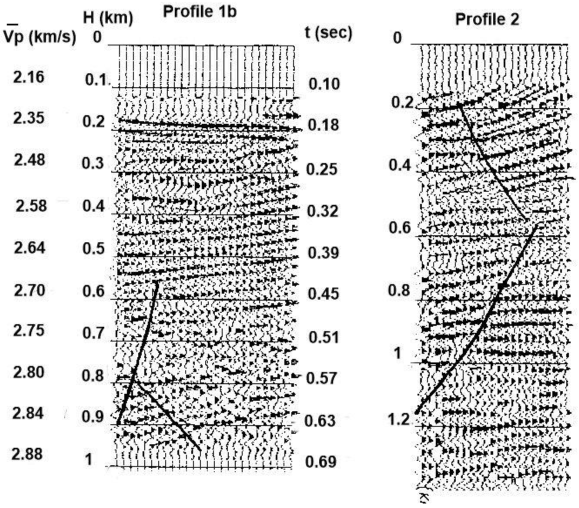


Fig. 5. In-depth view of reflected horizons

Analysis of the seismic velocities and interpretation of the results

The interpretation of the data from the refractive and reflective research is shown in figures 3, 4 and 5.

Figure 3 shows the interpretation of refractive surveys. These surveys cover the surface Quaternary layers and they are defined by the values of seismic V_p and V_s velocities and their thickness. There are two main Quaternary areas:

- Surface loose layer of dusty-sandy materials with a thickness of 2.5 - 5 m. and seismic velocities V_p = 270 - 370 m/sec and V_s = 125 - 165 m/sec;
- Medium of sand and clay with a thickness of 10 - 30 m and seismic velocities V_p = 1430 - 1680 m/sec and V_s = 480 - 580 m/sec.

On the RRP-1 profile with this research, the surface part of the Pliocene sandy-clayey sediments is affected, at a depth greater than 15 and 28 m, with seismic velocity Vp = 2150 m/sec and Vs = 745 m/sec. This profile also registers environments with lower seismic velocities in the Quaternary layers, which indicate either a fault zone or the appearance of inclined layers with a steep slope.

On the RRP-2 profile, due to the short length of the profiles, the Pliocene layers are not affected, but according to the other investigations, they are expected at a depth of about 30 m.

Figure 4 shows the interpretation of shallow-reflective research, performed in parallel with the refractory ones. These studies have interpreted the depths of the recorded reflections, but as informative values. Due to the positive reflection coefficients that are conditioned by the presence of groundwater, the designated depths should correspond to the boundaries between clayey and water-saturated sand-gravel layers. The maximum depths determined by these surveys are about 500 m. Based on this research, the following mean dependence is determined between the depths H_i (m) and the zero times of the reflections $t_{0(i)}$ (sec) from the individual i-th elastic limits, for:

t_0 - times of distances x = 5 to 50 m,

$$H_i = 1480\, t_{0(i)}^{1.125}$$

$$H_i = 1560\, t_0^{1.205}$$

According to these correlation dependencies, the following average dependencies for estimating the means (sr) and the interval (i) V_p - velocities are determined:

1. $V_{P(sr)} \approx 3035\, t_0^{0.146}$ m/s
2. $V_{P(i)} \approx 3360\, t_0^{0.146}$ m/s
3. $V_{P(sr)} \approx 1215\, H^{0.125}$ m/s
4. $V_{P(i)} \approx 1345\, H^{0.125}$ m/s

The determination of these dependencies is also the basis for estimating other parameters that are related to the values of seismic Vp-velocities, such as the interpretation of reflections from greater depths, the average porosity of the rock areas, and others. (Fig. 5).

With the interpretation of the data from the reflective research with the CDP technique (fig. 6), which is performed based on the reflective sections, and with the reflective signals (in figure 5), the values of the reflection time t (sec), the depth of the reflective limits H (km), and the mean values of $\overline{V_r}$ velocities (km/sec) are defined

According to this interpretation, stratification and parquet tectonics of tertiary geological environments are indicated. From the aspect of geological affiliation, tertiary environments can not be determined with certainty. However, according to the characteristics of the reflections, the following environments can be distinguished:

- Medium of sediments with Pliocene age from a depth of 800 to 1000 m and more, in which more than 20 sand-gravel layers (blackened reflections) are expected between the depths of 150 to 1000 m in this environment;
- Medium of deeper and older Tertiary sediments; older Pliocene or Eocene sediments.

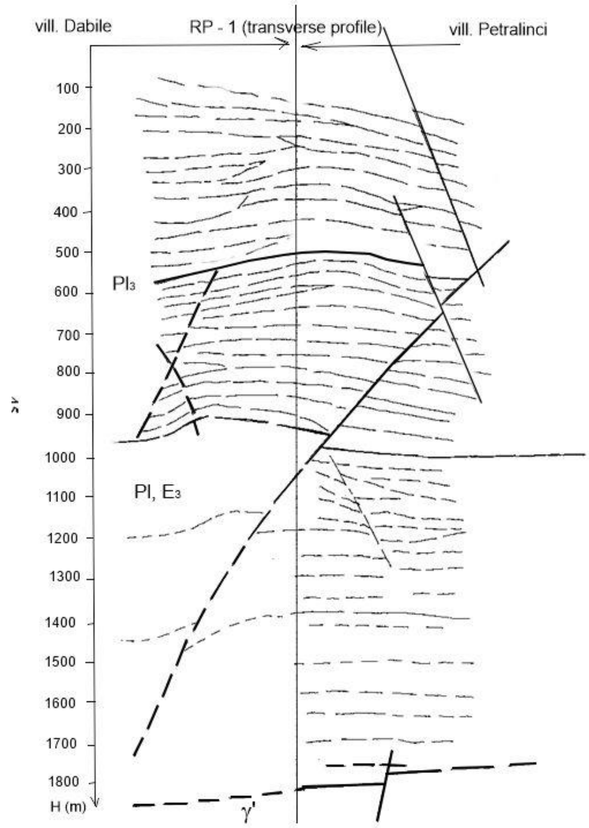


Fig. 6. Interpretation of the data from the reflective research with CDP technique

According to the reflections of profile 1a (RRP-1) on which the reflections up to 2000 milliseconds are registered, the lower limit of these sediments can be at a depth of 1800 m. This is an unexpected fact because the previous geophysical surveys in this area have obtained maximum depths of tertiary sediments around 800 m.

If the thickness of the Tertiary sediments in this part of the terrain is 1800 m, then the regional fault predicted by regional gravimetric surveys should cross near the village of Petralinci.

The interpretation of the reflective research emphasises the way of locating the faults and of defining their mechanism. This finding is of particular importance for directing and planning future geophysical surveys.

Conclusion

For the needs of this investigation, the seismic reflective surveys were performed as experimental, in order to determine their possibilities in detecting the bearers of artesian and thermal waters in the Strumica valley. It was proved that they are necessary accompanying methods, regional or detailed. They are regional due to the discovery and tracking of individual geological structures at greater depths, and detailed - due to the more precise location and design of exploration or exploitation boreholes.

Seismic reflective surveys provide the same data, but with greater reliability in tracking and spatially locating geological strata and fault structures. From this point of view, compared to other geophysical methods, this seismic method is irreplaceable and, as such, necessary for the correct location of exploration or exploitation boreholes.

Experimental seismic reflective surveys are designed and performed according to the known thickness of the Tertiary depression (1200 m), except for the first part of the profile of the village of Petralinci, where they are performed by capturing greater depths. Thereby, in this part of the terrain, a possible depth of a Tertiary depression of about 1800 meters is interpreted.

By continuing the reflective research towards the village of Petralinci, will find out if it is a deep fault established by regional gravimetric surveys (based on gravimetric anomalies associated with tertiary volcanic eruptions), or if it is the occurrence of hydrothermal altered zones in the granites, volcanic outcrops. In the case of a fault structure, it can jump up to 1000 meters, because in the immediate vicinity of the village of Saraj, granites are drilled at a depth of 713 m.

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