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Determination of the coal-bearing zones and the alteration zones containing uranium ore by using two dimensional (2D) seismic reflection method in Thrace Basin

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ABSTRACT

It is aimed to reveal the basement topography, the coal-bearing levels, the alteration zones containing uranium ore, and the tectonic structure prevailing by using two dimensional (2D) seismic reflection method in the Thrace Paleogene-Neogene Basin. In this context, seismic data collected on the six profiles were interpreted by correlating with the data of 97 wells. In the seismic lines, respectively, the metamorphic basement-Eocene boundary, the top of the coal-bearing zone and the boundary of the Danişmen-Ergene formations were confirmed by using the borehole data. By evaluating seismic data, the coal propagation is modeled with three dimensional (3D) figures. Moreover, coal accumulation starts from the southwest of the field and continues towards the northeast, and it is supported by the results obtained from the borehole data. The presence of uranium ore in some of the alteration zones and borehole data indicated that all alteration zones determined should be inspected for uranium ore. In addition to normal and reverse faults, positive and negative flower structures formed in the strike-slip fault zones were determined, and lignite deposits were cut in the flank of these structures. Finally, it is recommended to carry out seismic studies before drilling, to investigate potential coal and uranium areas and to plan more seismic lines.

1. Introduction

The Thrace Basin is a Paleogene-Neogene Basin bounded by the metamorphic Rhodope Massif within the borders of Greece and Bulgaria in the west, the Strandja Massif consisting of metamorphic-granitic rocks in the north within the borders of Bulgaria and Türkiye, the Marmara Sea in the south and the İstanbul Zone in the east. The Thrace Basin located within these geographical boundaries lies across Greece to the west, Saros Bay to the southwest and the Aegean Sea. Paleozoic and Mesozoic aged metamorphic and

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magmatic rocks constitute the base of the Thrace Basin. The basement rocks in the basin are seen in the Strandja Mountains in the north, in the Rhodope Massif in the west, in the North Anatolian Fault Zone and Sakarya Continent in the south, and around the Bosphorus in the east (Sezen and Taşkıran, 2020).

Strandja is located in the north of the Thrace Basin, the Rhodope Massif in the west, and the Sakarya continent in the south. The Strandja Massif is represented by gneissic rocks at the bottom and metamorphosed Paleozoic Mesozoic aged sedimentary rocks in greenschist facies above them (Üşümezsoy, 1982; Taner and Çağatay, 1983; Çağlayan and Yurtsever, 1998). Sedimentary rocks were cut by Late Cretaceous granitoid rocks and partly covered by a Late Cretaceous volcano-sedimentary unit (Taner and Çağatay, 1983). Metagranitic rocks are outcropped on the southern slope of the Strandja Massif (Öztunalı and Üşümezsoy, 1979). In the north of the Thrace Basin, lignites are generally located on the southern slopes of the Strandja Massif. The lignites outcropping in the north and south of the basin gradually deepen towards the middle of the basin and are located at depths exceeding 600 meters in a sedimentary sequence that reaches approximately 10 km in the middle parts of the basin. . In the Northern Thrace region, a lobata type delta formation with fluvial dominant characteristics was detected in the Middle Eocene (Sonel and Büyükutku, 1998). With the regression that occurred in the basin, completely deltaic and lacustrine conditions were formed in the Oligocene. Coals of the Thrace Basin are also included in the units deposited in these environments. The high sedimentation rate caused the sediment thickness to be high but made the correlation of coal seams difficult (Şengüler, 2010). However, coal exploration, production, and development activities continue in the region. Kangal et al. (2018) produced high-calorie (5036 Kcal/kg) clean coal from fine coal processing 14.3% amount in a coal preparation plant in the region.

As a result of the drillings carried out by the General Directorate of Mineral Research and Exploration in the Thrace Basin, it was determined that uranium mineralization took place in the Süloğlu formation. As a result of the evaluations made about the mineralization in the study area, igneous rocks with acidic character are thought to be the source rocks of uranium. The uranium ore in these rocks is transported in solution under suitable conditions and stored in sedimentary environments (Sezen and Taşkıran, 2020; Figure 1).

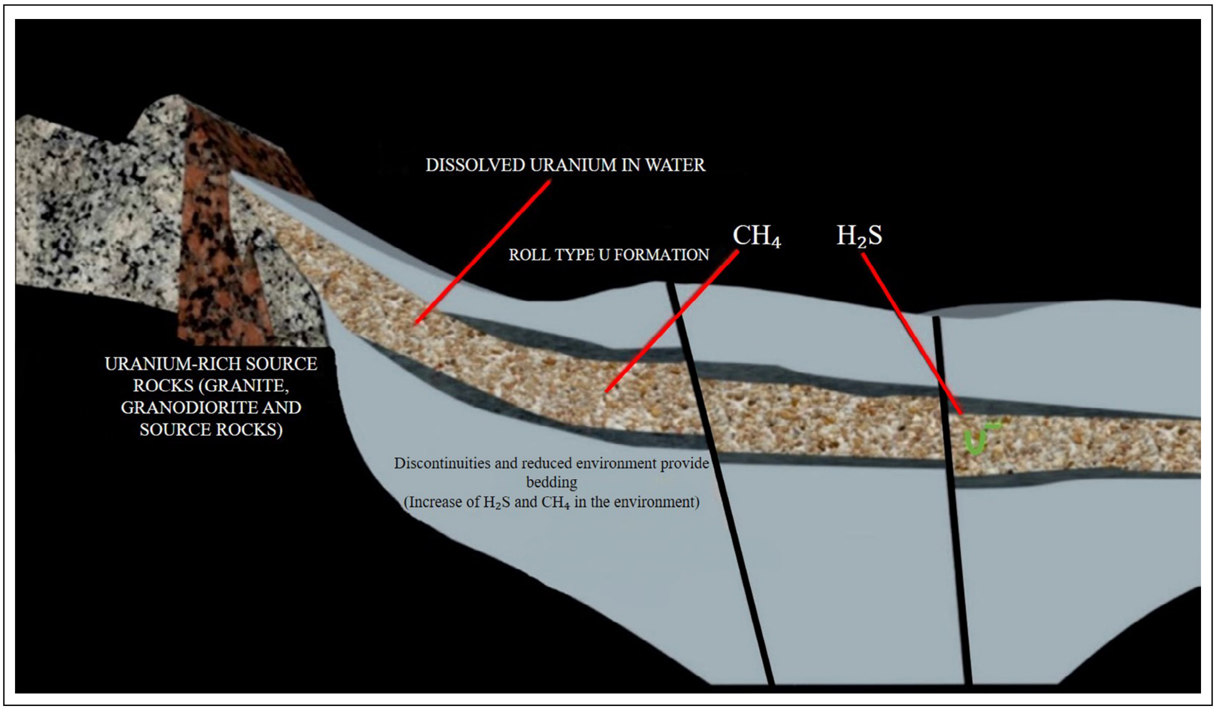

Figure 1- The general conceptual model of uranium mineralization in the study area (Sezen and Taşkıran, 2020).

Considering the study site, the necessary conditions for uranium formation have been shown below:

i) Source rock: There are granitoids and similar depth rocks rich in radioactive elements (uranium, thorium, etc.) in the Strandja Massif.

ii) Transport: Paleo-current channels extending from the Strandja Massif to the Thrace sedimentary basin carry out the transport of radioactive minerals (uranium, thorium, etc.) dissolved in water.

iii) Subsidence: Based on the assumption that alteration zones are formed as a result of tectonic movements affecting the site, oxidation-reduction takes place in these zones, and the organic materials required for chemical reaction are supplied from the lignite layers, it is thought that the uranium in solution in the alteration zone precipitated into the sandstones, which is the reservoir rock in the field.

iv) Cap rock: The lithological required system for the storage of uranium is the alternation of permeable layers (sandstone) with non-permeable (claystone) layers. Sandstone-claystone alternation can be given as an example. Since claystone is not permeable, it acts as a stratigraphic cap rock and directs uranium-containing melts to subside uranium in sandstone.

Except for geophysical radiometric methods, other geophysical methods are indirect methods for uranium exploration. The seismic method, like all geophysical methods, is successful if there are physical differences to be detected in the field. Structural elements, lithological sequence, alteration zones, basement topography, and paleochannels are the most important elements for uranium exploration.

The study area is located in the area between the center of Edirne Province and the center of Kırklareli, the southeast of Süloğlu, and the north of Kocahıdır (Figure 2).

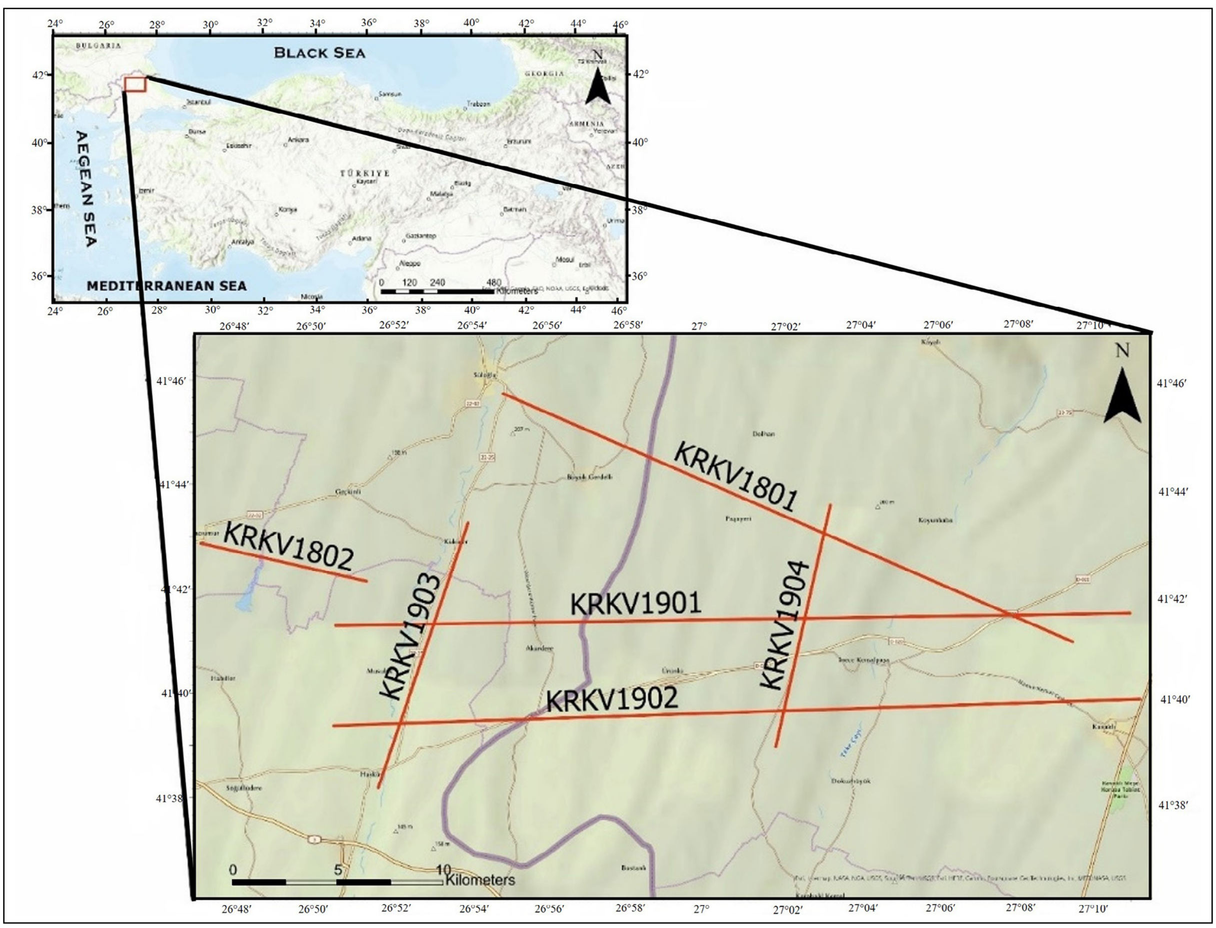

Figure 2- The location of the study area and the seismic reflection lines on the map. The collected seismic reflection lines are indicated by the red line. The KRKV1801 and KRKV1802 lines were collected in 2018, while the other seismic lines were collected in 2019.

In this study, with the application of the seismic reflection method; it is aimed to determine the basic topography of the area, the extent of the spread of the coaly layers, the alteration zones containing uranium ore, and the tectonic movements that contribute to the formation of these structures. In this context, seismic reflection data were collected and 6 profiles were interpreted; 2 east-west (E-W) (KRKV1901, KRKV1902), 2 northeast-southwest (NE-SW) (KRKV1903, KRKV1904), 2 NW-SE (KRKV1801, KRKV1802) in the study area.

The seismic method is based on the reflection of acoustic waves emitted from active (earthquake) or passive sources (dynamite, vibroseis, etc.) between two layers in accordance with the laws of physics as they move through the subsurface. These waves are recorded by receivers (geophones) laid along a certain profile (2D or 3D space) on the surface. From these recorded waves, a seismic image of the subsurface is obtained by using various seismic data processing techniques. With the obtained seismic images, the layer/formation boundaries, faults, slopes, and angles of the layers are determined and the geological model of the seismic cross-sections is revealed (Güreli, 2021).

2. Geological Settings

The Tekedere Group (Çağlayan and Yurtsever, 1998), which consists of various Paleozoic gneisses and schists, and the Şeytandere Metagranite (Çağlayan and Yurtsever, 1998), which consists of meta granites containing pink, white-colored, large feldspar crystals, are located at the base of the study area (Okay et al., 2001). Şeytandere metagranite shows a distinctive steep slope morphology. Isotopic dating using the single zircon Pb-Pb evaporation method shows two magmatic events: One occurred in a short time interval between 312 ± 2 and 315 ± 5 Ma, and the other was dated as 257 ± 6 Ma (Sunal et al., 2008).

İslambeyli formation (Keskin,1966) which consists of Middle Eocene aged, beige, white, yellow, gray colored, volcanic clastic at the base, sandy, clayey limestone, sandstone, and marl overlies the basement units with an angular unconformity. Moreover, Kırklareli limestone (Keskin, 1966) consisting of late Eocene aged white, grayish white, gray, cream, yellow-colored, abundantly fossiliferous, sandy-clay, reef limestone overlies the basement units with an angular unconformity (Şengüler, 2010).

The Eocene units are also the reservoirs of the geothermal system. Pınarhisar Formation consists of white-colored oolitic limestone and beige-colored, thick-bedded, abundant Congeria tuffite, sand, clay, and marl interlayer limestone on Kırklareli limestone in an angular unconformity and yellow, gray, light brown colored, locally coal banded, sand, Süloğlu formation, which consists of alternating silt and clay (Şengüler, 2010). Overlying these units with angular unconformity, the Sinanlı Member (Boer, 1954) is composed of late Miocene-aged white, yellowish gray colored muddy sandstone and carbonate claystone intermediate level, lacustrine limestones. In addition, the Ergene Formation also consists of yellowish-white, white-colored, cross-bedded sandstone, clayey sandstone, and reddish, greenish, laminated claystone and slightly attached conglomerate lenses, cropping out in a small area in the study area. This unit is unconformably overlain by the Pliocene-aged Thrace formation, which is red, brown, light brown, yellow, locally white and cross-bedded, poorly sorted, reddish clay-mil matrix, unconsolidated conglomerate, pebble, sandstone and claystone (Kirk, 1936; Gürsoy et al., 1996; Günaydın and Çolak, 2010, 2011). Quaternary-aged alluviums cover all these units with angular unconformity, especially in stream beds (Figures 3 and 4; Sezer and Taşkıran, 2020).

2.1. Tectonics

The tectonic evolution of the Thrace Basin began as a result of the movements between the macro plates in the region. The tectonic development took place as a consequence of the interaction of the African, Anatolian, and Eurasian plates during the Late Cretaceous and Miocene (Şengör and Yılmaz, 1981). With the compression in Eastern Anatolia and the opening event expressed by grabens in Western Anatolia, the Thrace Basin was uplifted and eroded in this period, and as a result, the Late Miocene aged Ergene Formation (Umut et al., 1983; Umut et al., 1984) covering the entire Oligocene succession was formed. The Intra-Pontide Suture Belt was also affected by these movements and became the North Anatolian Fault (NAF) (Şengör, 1979). The Thrace

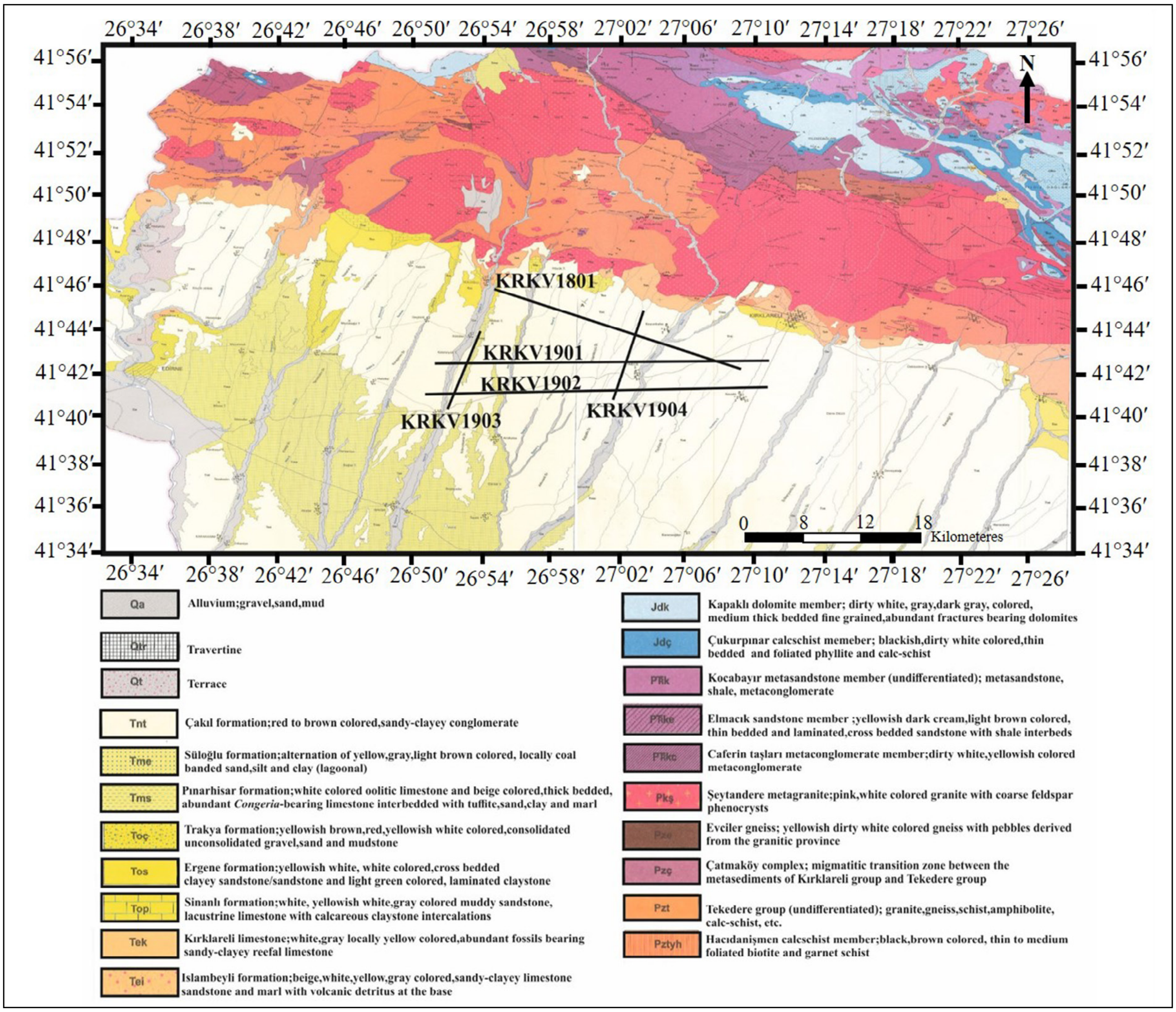

Figure 3- Geological map of the study area covering the Edirne-e17 and Kırklareli-e18 sheets with a scale of 1/100.000 (Çağlayan and Yurtsever, 1998).

Basin was intersected by the young NAF in the south, within the Marmara Sea. The NAF is a strike-slip fault located between the Anatolian and Eurasian plates (Şengör, 1979). As a result of the activity of the fault, porosity, permeability, and dolomitization developments were observed in the structural trap types and reservoir units in the basin (Perinçek, 1987; Coşkun, 1998). As a result of the NAF and ongoing plate movements, abundant clastic material from the Strandja and Rhodope Massifs comes to the Thrace Basin as a result of erosion and transport (Erten and Çubukçu, 1998).

The general tectonic regime of the region is shown by NW-SE trending normal faults as seen in Figure 5 (Turgut et al., 1991). The North Osmancık Fault Zone is an important fault zone that provides facies distribution in the region. Strike-slip faults appear during the middle Miocene (Perinçek, 1991). In the middle of the basin, the greatest displacement occurred in the Terzili Fault Zone. This fault zone reflects the characteristics of strike-slip faults defined by positive and negative flower structures in seismic data. This fault zone extends from the south of the Hamitabat area towards the Turkish-Greek border.

As a result of the studies carried out using seismic cross-sections and subsurface data, strike-slip fault zones were determined through the basin. These are Kırklareli Fault Zone (KFZ), Lüleburgaz Fault Zone (LFZ) and Babaeski Fault Zone (BFZ). These faults, which developed in the Thrace Basin,

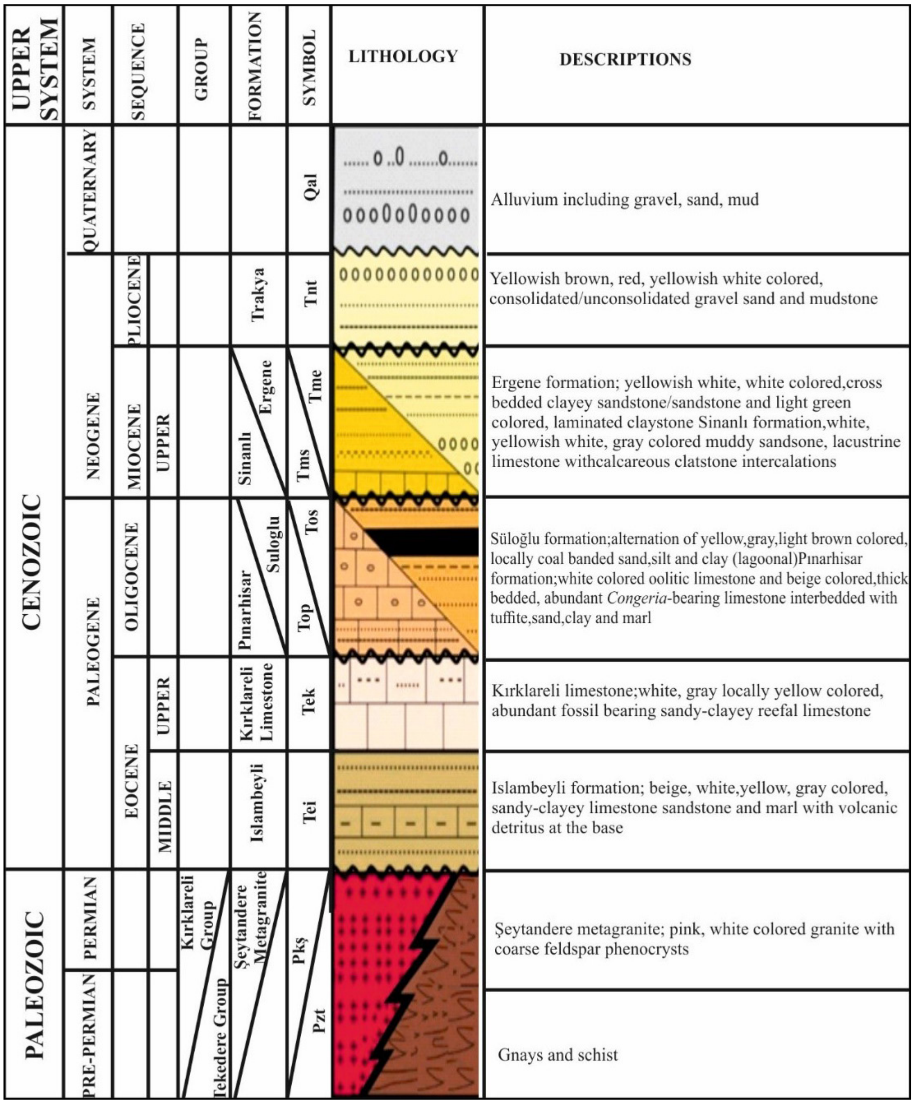

Figure 4- Generalized stratigraphy of the study area (modified from Sezen and Taşkıran, 2020).

caused improvements in the reservoir properties of the reservoir Osmancık sandstone (Ünal, 1967) and Kırklareli limestones in the basin. Flower structures and fault traps formed due to these faults are important geological structures that allow hydrocarbon accumulation in the basin.

3. Two-Dimensional (2D) Seismic Reflection Method

Elastic waves produced from any energy source propagate in the subsurface and reach the surface again by reflecting from the interfaces of units with different acoustic impedances. The seismic waves reaching the surface are recorded by receivers called geophones on land with the help of a seismic recording unit. The important point of the method is to record the amplitudes against the time of elastic waves emitted from an energy source. The main physical parameters that are effective in the seismic reflection method are velocity and density.

The seismic method is based on the reflection of acoustic waves emitted from active (earthquake) or passive sources (dynamite, vibroseis, etc.) between two layers in accordance with the laws of physics as they move through the subsurface. These waves are recorded by receivers (geophones) laid along a certain profile (2D or 3D space) on the surface. From these recorded waves, a seismic image of the subsurface

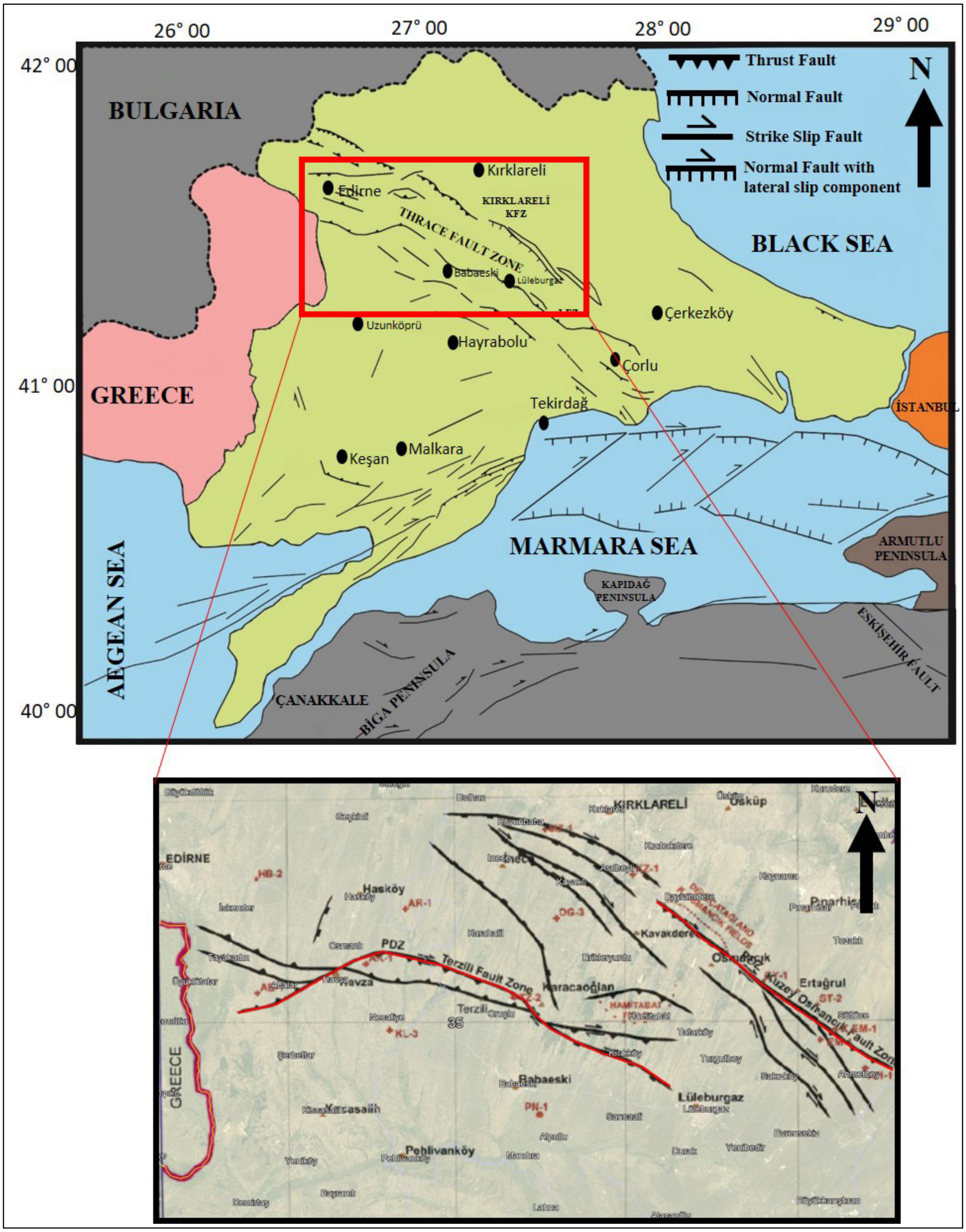

Figure 5- Structural map of the Thrace region and its surroundings (modified from Sakınç et al., 1999).

is obtained by using various seismic data processing techniques. With the obtained seismic images, the layer/formation boundaries, faults, slopes, and angles of the layers are determined and the geological model of the seismic cross-sections is revealed (Güreli, 2021).

3.1. Seismic Reflection Data Acquisition and Methodology

The seismic reflection profiles designed within the scope of this study were obtained using Sercel 428 XL data acquisition equipment and 2 vibroseis seismic energy sources (Mini Vib II). The recording parameters used in the seismic reflection profiles in Table 1 were determined as a result of the parameter test studies carried out in the study field according to the target depth to be obtained from the subsurface. While the seismic data of the KRKV1801 and KRKV1802 lines were collected in 2018, the seismic data of the KRKV1901, KRKV1902, KRKV1903, and KRKV1904 lines were collected in 2019. The number of shots and profile lengths in meters of each of these seismic lines are shown in Table 2. Thus, a total of 89165 m of seismic reflection data was collected.

Table 1- Data acquisition parameters.

Parameters	Value
Near Offset (m)	17,5
Initial Frequency (Hz)	24
End Frequency (Hz)	180
Number of Vibroseis	2
Number of Sweep	3
Sweep Length (s)	8
Sweep Type	Logarithmic 2 dB
Taper (ms)	350
Group Interval (m)	5 (2 String-12 geophones)
Shot Interval (m)	10
Spread Length (m)	662.5
Spread Type	130+130 (Symmetric)
Record Length (s)	2
Sampling Interval (ms)	1

Table 2- Number of shots and lengths of seismic lines.

Name	Number of Shots	Line Length (m)
KRKV1801	1137	11975
KRKV1802	319	1670
KRKV1901	2592	27240
KRKV1902	2596	27280
KRKV1903	863	9950
KRKV1904	973	11050
Total	8480	89165

3.2. Processing of Seismic Reflection Data

Seismic data processing is making the collected data meaningful and interpretable with various processes. At the data processing stage, the aim is to process the data in the best way and make it ready for the interpretation stage. Within the scope of the project, the most ideal seismic cross-section and geological model were tried to be obtained by processing the data collected in the field.

The data recorded in the field were collected in SEGD format, and the Disco Focus 5.4 seismic reflection data processing software was used for the purpose of analysis and processing of the data. Transforming the data collected in the field into meaningful and interpretable seismic cross-sections depends on determining the correct data processing parameters by performing signal analysis. With the determined parameters, the data processing steps in Table 3 were applied and the seismic cross-sections were prepared for interpretation.

Table 3- Main seismic data processing steps.

Data Loading
Geometry Definition
Trace Edit (Kill-Mute)
Gain (500 ms)
Deconvolution [Prediction Lag:12 ms; Operation length:200 ms]
Filter [25-100 Hz]
Static Correction
Ground Roll Attenuation
CDP Sort
Velocity Analysis1
NMO and Stack (Brute1) (Vel1&NMO&Stack)
Residuel Statics1 (Brute2) Res1 and NMO and Stack
Velocity Analysis2 (Brute3) Vel2 and NMO and Stack
Residuel Statics2(Brute4) Res2 and NMO and Stack
Final Stack (Final Datum)
Migration

In order to increase the seismic resolution (S/N ratio), several different data-processing steps can be applied to the seismic data. The data processors applied a series of parameter tests to the input data for each step to determine the suitable parameters.

In this context, the gain was applied to remove the absorption in the seismic data. Afterward, deconvolution was applied to compress the wavelet and increase the resolution. Then, the low-velocity layer and variations in elevation were eliminated by applying a static correction process. The Ground

Roll Attenuation process was applied to weaken the surface wave. With the first velocity analysis, the brut stack section was created and NMO data were produced, and residual statics were calculated and applied to the data. Now, velocity analysis can be done more effectively for the second time after the residual static process. With the velocity information obtained from the second velocity analysis, the residual static correction process was applied again. After these processes, the final stack section was prepared and the migration process was applied.

3.3. Interpretation of Seismic Reflection Data

Seismic interpretation is the process of revealing the detailed geological model from the seismic cross-sections obtained as a result of data processing. Although the interpretation studies are carried out on the seismic cross-section, the studies that will be the basis for the interpretation are started while the seismic cross-sections are being planned. For this, first of all, the geology of the study area, the general geological structure, and the structural elements of the region are investigated. All kinds of geological information belonging to the geological units spreading in the field are compiled and the structural positions of these formations in the surrounding areas are revealed.

Professional seismic interpretation applications are used for the interpretation of seismic cross-sections. The boundary of the geological formations on the seismic cross-sections is defined by transferring well information to the interpretation software. Simultaneously, all structural elements (fold, fault, thrust, etc.) that can be identified in seismic cross-sections are marked. Finally, by correlating the seismic cross-section with the information obtained from the well logs, the geological model of the subsurface, the surface maps of each level, and the isometric maps are revealed. Within the scope of the study, seismic reflection cross-sections were interpreted using the Schlumberger Petrel 2019.2 interpretation software.

4. Findings

With the seismic reflection study conducted around Kırklareli and Edirne-Süloğlu districts in the Thrace Region, 4 seismic reflection profiles (KRKV1901, KRKV1902, KRKV1903, and KRKV1904) were fulfilled in 2019 in order to determine the uranium formation areas and coal-bearing zones in the region and to reveal the uranium ores. In addition, two seismic reflection profiles (KRKV1801, KRKV1802), which are thought to contribute to the interpretation and intersect with the study area from the lines collected in the Thrace Basin in 2018, were included in the data set. Sections 4.1, 4.2, 4.3, and 4.4 contain the findings of the seismic cross-sections that modeled the study area in the best way. The seismic horizons determined on the evaluated seismic cross-sections were interpreted by using borehole lithology. The correlation of seismic horizons with the borehole data was made using the stack velocities obtained from the seismic data processing. While evaluating the seismic cross-sections, data from a total of 97 wells located near and/or on top of the lines were utilized.

4.1. KRKV1801 Seismic Reflection Cross-Section

In this seismic line, which starts near Edirne–Süloğlu and continues in the northwest-southeast direction, the level observed around 400 ms at the northwest and goes 1200 ms at the southeast of the seismic cross-section has been determined as the Metamorphic Basement-Eocene boundary. The seismic horizon observed between the 20125 and 28120 CDP numbers above the basement is called the Eocene-Oligocene boundary. The Danişmen-Ergene formations boundary, which was marked by utilizing the lithology levels of the borehole logs, and the reflection surfaces drawn between the CDP numbers approximately 21353 - 21962 were also determined as the surface of the coal zone (the top of the coal). While the seismic cross-section was examined, it was determined that the reasons why the boreholes drilled in the northwest of the seismic cross-section did not intersect the coal were the thinning of the coal-bearing zone, ending towards the Ergene formation and the rising of the basement throughout the northwest. It is thought that the discontinuities observed on the interfaces correspond to the fractures (yellow faults) intersecting the basement. The basin shows a stepped structure and deepens from northwest to southeast due to fracture lines (Figure 6). Boreholes were drilled mainly around Süloğlu, near CDP numbers 20123 and 22170 and in the north and south of the seismic cross-section. Uranium ore with low ppm values was observed in the borehole approximately 550 m

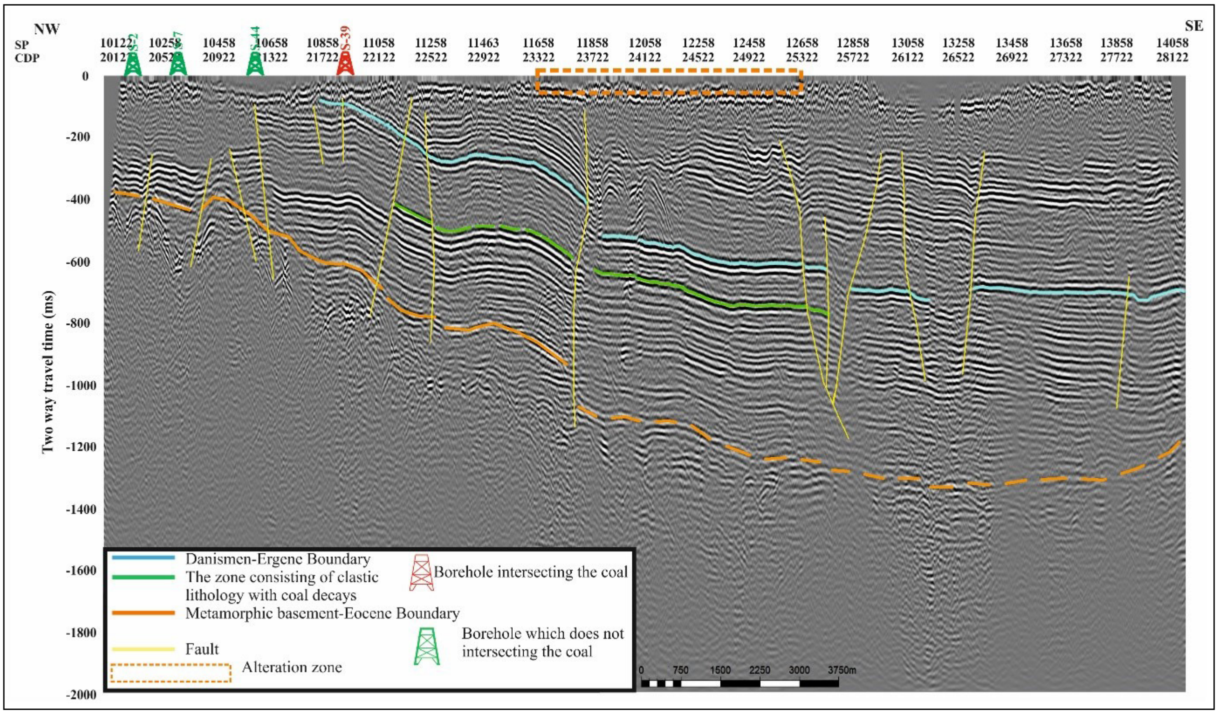

Figure 6- Interpreted KRKV1801 seismic cross-section. The small and large-scale faults that are not named and dominate throughout the region are shown in yellow. The location of the borehole intersecting the coal (S-39) is shown with a red symbol in the figure. The location of the boreholes which does not intersect the coal (S-2, S-7, and S-44) is shown with a green symbol in the figure. The boundary of the alteration zone is shown with the orange dashed line.

southwest of CDP number 20688 and in the borehole approximately 850 m northeast of CDP number 20424.

4.2. KRKV1901 Seismic Reflection Cross-Section

The basin deepens in the east direction towards the CDP number 24132 due to the fractured structures that intersect the basement and cap layer in a stepped way and continues horizontally between CDP numbers 24132-28132. Then, after CDP number 28132, it rises again and continues towards the east (Figure 7). Faults interpreted with yellow lines are unnamed in Figure 7 since normal faults are common throughout the seismic cross-section. With the effect of these normal faults, the seismic horizons deepen in the middle of the seismic line.

One of the drilled boreholes is approximately 14 m away from the 21364 CDP number in the seismic cross-section. The Danişmen-Ergene formation boundary and coal-bearing zone were seen at 77.3 m (~260 ms) and 194.6 m (~380 ms) respectively while 302.3 ppm uranium was observed at 131.3 m (~320 ms) in the well. Considering its proximity to the seismic line, the well data and the seismic cross-section were correlated, and the interpretation was started from this seismic cross-section.

It was observed that a coal-bearing unit was not found in some boreholes close to the KRKV1901 seismic line. Depth conversion was made using data processing velocities (± 5% margin of error) and it was seen that the coal-bearing unit could not be observed due to the suspension of the borehole.

According to the geological interpretation of seismic cross-section; the metamorphic basement-Eocene boundary, which can be followed throughout the seismic line, the uppermost layer of the coal-bearing zone and Danişmen-Ergene formations have been identified from oldest to youngest with the help of borehole logs.

Areas indicated by orange dashed rectangles on the seismic cross-section were determined as alteration zones. The first alteration zone was observed at the intersection of KRKV1901 and KRKV1903 lines, approximately between CDP numbers 20640-21720,

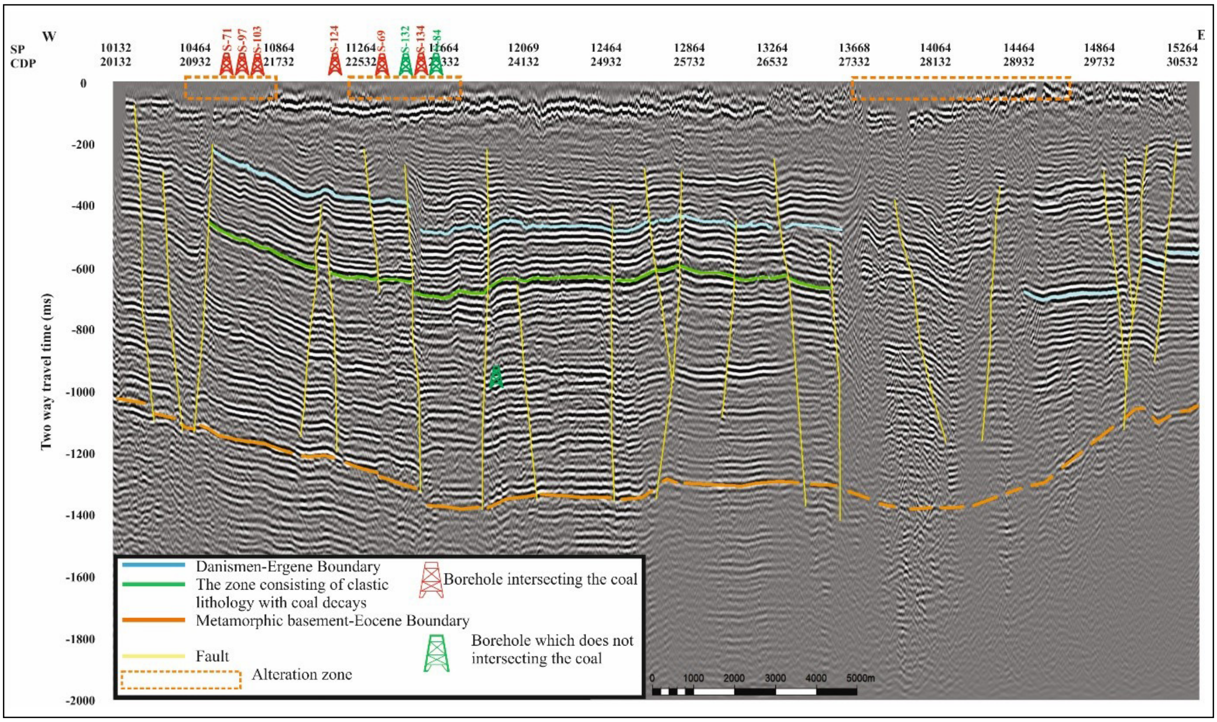

Figure 7- Interpreted KRKV1901 seismic cross-section. The small and large-scale faults that are unnamed and dominate throughout the region are shown in yellow. The location of the borehole intersecting the coal (S-71, S-97, S-103, S-124, S-69, S-134) is shown with a red symbol in the figure. The location of the boreholes which does not intersect the coal is shown with a green symbol (S-132 and S-84). The boundary of the alteration zone is labeled with the orange dashed line. It is seen that the seismic levels, which are colored blue, green, and orange, are followed approximately along the line.

the second alteration zone is between CDP numbers 22245 - 23520 and the third alteration zone is also at the intersection of KRKV1901, KRKV1904 and KRKV1801 lines, approximately between CDP numbers 26732-29232. It is seen that the interpreted alteration zones are compatible with the topography seen on the seismic cross-section (Figure 7).

4.3. KRKV1903 Seismic Reflection Cross-Section

KRKV1903 seismic line is one of the lines collected in the NE-SW direction. The horizon shown between approximately 1460 ms in the south and 960 ms in the north of the seismic cross-section has been interpreted as the Metamorphic Basement-Eocene boundary. This boundary and the upper layer of the coal-bearing zone (determined by the information of borehole and intersections of seismic cross-sections) interpreted on the KRKV1903 seismic cross-section can be followed to the end of this section, while the Danişmen-Ergene formations boundary can be followed up to CDP number 62810. In this section, it is observed that the geological structures, especially the interface of the Danişmen-Ergene formations, are inclined towards the south (Figure 8). The discontinuity surfaces that intersect the reflection surfaces and the basement were interpreted as fracture lines (normal and strike-slip fault systems).

Two different flower structures formed by the strike-slip fault were defined on the seismic cross-section. The first of these is the positive flower structure observed in the CDP range of 60810 to 61710. It has been observed that the folding causes reverse fault uplift with the effect of the compression formed in this strike-slip fault zone, resulting in a positive flower structure. While the probability of lignite layers in the center of positive flower structures based on folding is very low, the coal-bearing units are much more likely to be seen on the flanks of the structure. In this context, the observation of coal-bearing horizons with an average thickness of 30-150 m in the boreholes was carried out on the flanks of the positive flower structure. This structure can be clearly seen on the KRKV1903 seismic line.

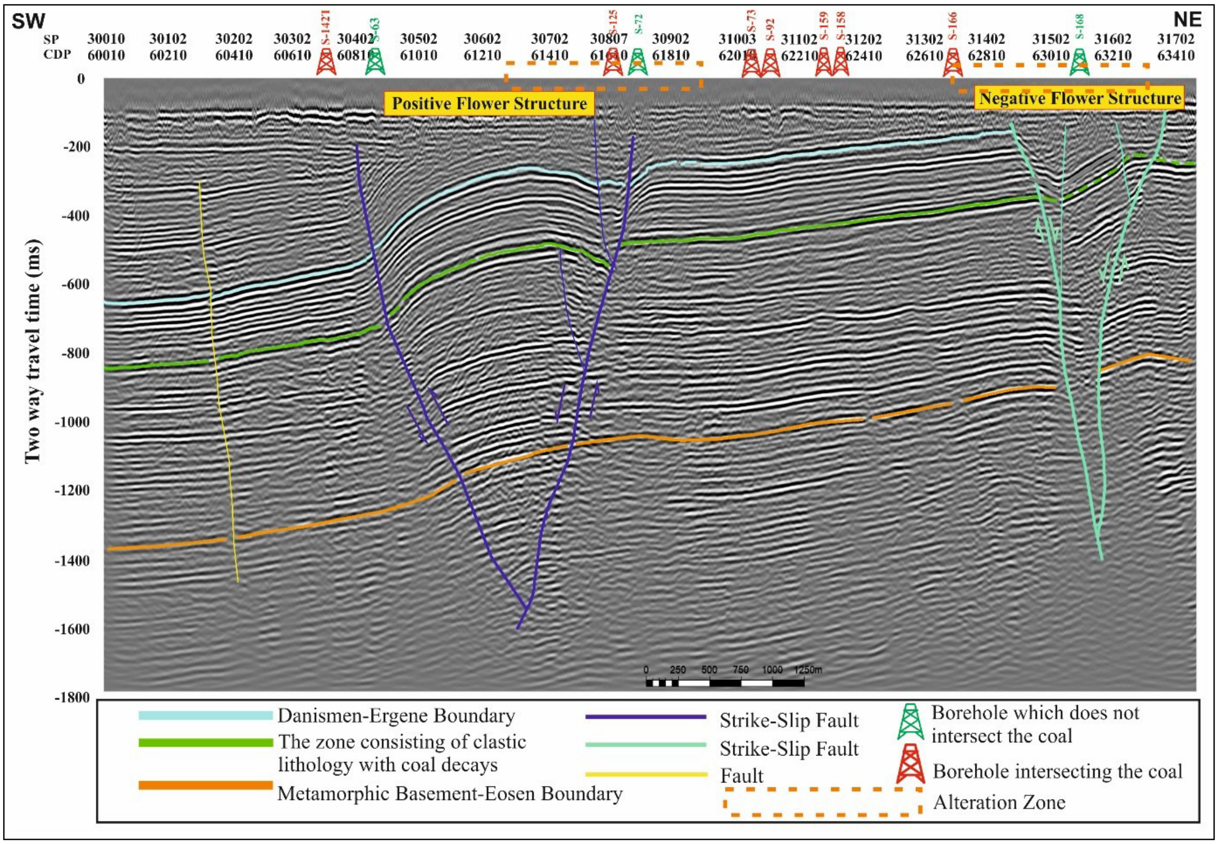

Figure 8- Interpreted KRKV1903 seismic line. One of the strike-slip faults is represented by a blue color, and the other is represented by a green color. The fault that is not named and dominate throughout the region are shown in yellow. The alteration zones observed above the positive and negative flower structures are shown with orange dashed lines. The location of the borehole intersecting the coal (S-142T, S-125, S-73, S-92, S-159, S-158, S-166) is shown with a red symbol in the figure. The location of the boreholes which does not intersect the coal (S-63, S-72, and S-168) is shown with a green symbol in the figure. It is seen that the seismic horizons, which are colored blue, green, and orange, are followed along the line.

A negative flower structure interpreted with green color is another structure that is located in the CDP range of 62810 and 63400 in the northeast of the seismic line. The negative flower structure was formed by the effect of normal faults developing in the strike-slip fault zone. Lignite and uranium ores were not discovered since the boreholes on this structure could not reach sufficient depth. In addition, it was observed that some boreholes drilled before the seismic study did not intersect the coal-bearing sequences because they coincided with the fault zones seen in the seismic cross-section. For this reason, the determination and consistent interpretation of strike-slip fault systems in hydrocarbon exploration are important for future borehole studies.

The areas indicated by the orange rectangular box on the seismic cross-section were determined as the alteration zones. The first alteration zone is approximately between 61260 - 61910 CDP numbers, and the second alteration zone is between 62710-63314 CDP numbers. It was thought that these alteration zones should be investigated, indicating the presence of uranium ore, and a borehole was suggested in this area (Figure 8). In light of all the findings obtained with these suggestions, uranium ore was observed in the boreholes at the intersection of the KRKV1901 and KRKV1903 seismic lines. The presence of alteration zones in this area indicates that alteration zones in other seismic lines should also be discovered and may indicate the presence of uranium ore.

4.4. KRKV1904 Seismic Reflection Cross-Section

The KRKV1904 seismic profile is designed in the NE-SW direction and it intersects the KRKV1901 line at the receiver point 40845 (CDP 81690) and the KRKV1801 line at the receiver point 41425 (CDP 82850). The level labelled at approximately 1580 ms in the south and approximately 820 ms in the north of the seismic cross-section has been interpreted as the Eocene-Metamorphic basement boundary. The Metamorphic Basement-Eocene boundary interpreted on the seismic cross-section and the upper layer of the coal-bearing zone (determined by the information of borehole data and intersections of seismic lines) and the Danişmen-Ergene formations boundary are continuously observed up to the CDP number 82100 (Block A) (Figure 9). Up to this CDP number the quality of the seismic cross-section is quite good. Beginning from the CDP number 82700, only Danişmen-Ergene boundary and the Metamorphic Basement-Eocene boundary have been approximately marked (A[1] Block). When the KRKV1904 seismic cross-section is investigated, it is seen that the geological structures, especially the Danişmen-Ergene formations boundary, are inclined towards the southwest.

The discontinuity surfaces intersecting the reflections observed in the seismic cross-section were interpreted as fracture lines (yellow and pink faults). The region where there are reflective surfaces that can be observed horizontally is interpreted as Block A and A[1], and the region where the levels cannot be observed clearly is interpreted as Block B. Considering the seismic reflection packages, the discontinuity and deterioration of the reflections in the B block can be explained by the presence of a strike-slip fault. However, due to the few number of seismic lines in the region, the existence of this fault could not be clearly demonstrated.

In the seismic cross-section, two areas thought to be alteration zones were identified. The first alteration zone is approximately between 80200–80620 and the second alteration zone is between CDP numbers 82140 – 82860. It is known that in the second alteration zone, which coincides with the intersection of KRKV1901, KRKV1904, and KRKV1801 lines, a subsidence area was formed due to tectonism and provides a suitable environment for uranium ore. For this reason, it is thought that alteration zones should be investigated in detail and these zones may have very high-grade ppm uranium (Figure 9).

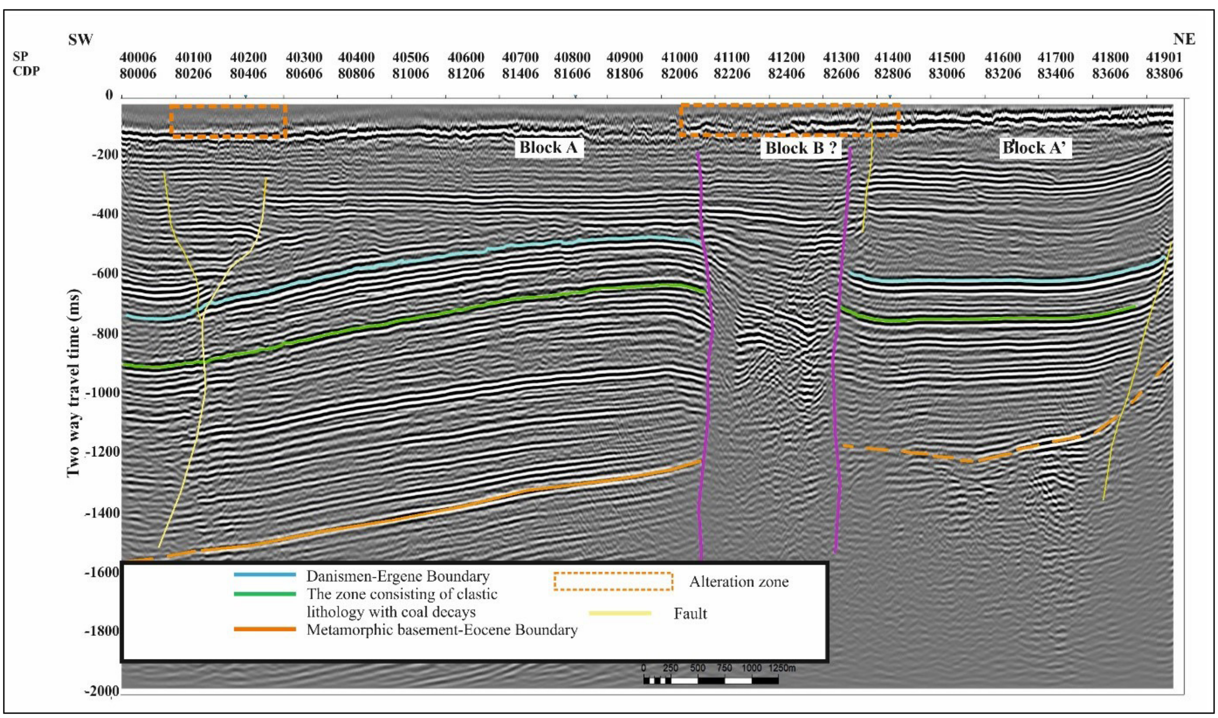

Figure 9- Interpreted KRKV1904 seismic cross-section. A possible strike-slip fault is shown in pink and the fault that is not named is shown in yellow. The boundary of the alteration zone is shown with the orange dashed line. It is seen that the seismic levels, which are colored blue, green, and orange, are followed along the line in blocks A and A' but in block B these seismic levels are deteriorating.

5. Discussion

Coal formations in the Thrace Cenozoic Basin are located within the Oligocene-aged Danişmen Formation (Şengüler, 2013). Lignite outcropping in the north and south of the basin gradually deepens towards the middle of the basin and is observed at depths exceeding 600 m in a sedimentary succession reaching 10.000 m in the middle parts of the basin (Şengüler, 2013). The coal reserve of the Thrace-Ergene Basin has exceeded 1 billion tons with the studies initiated by the General Directorate of Mineral Research and Exploration (MTA) in 2005 and still continues (Şengüler, 2013). According to the 2011 coal reserve preliminary study report of the General Directorate of Energy Affairs, the possible coal reserve in the Süloğlu field located within the study area was determined as 14.5 million tons. This result was obtained according to the results of the boreholes drilled in the region. The boundary of the coal spread, which was determined by evaluating the lines obtained as a result of the seismic study conducted in 2019, was modelled in a 3D environment and it was determined that the boundary of the coal spread started from the southwest of the study area and continued towards the northeast (Figure 10). It was observed that some boreholes were suspended as a result of the determined coal-bearing layers transported deeper with tectonic movements (Figure 8). This supports the argument that the calculated coal reserve ratio may be higher for the Süloğlu field.

Perinçek (1987, 1991) argues that the faults in the Thrace fault system were formed before the deposition of the Ergene formation and were right-lateral strike-slip (Figure 11a). Perinçek (1991) in his study stated that the NAF was active before the late Miocene in the Thrace Basin and named the aforementioned fault zone as Kırklareli, Babaeski, and LFZ extending from southeast to northwest. In the previous seismic studies carried out in the Thrace Basin, the positive flower structure formed by the effect of the LFZ, one of the fault zones mapped as a continuation of the NAF, was determined on the seismic cross-sections (Figure 11b).

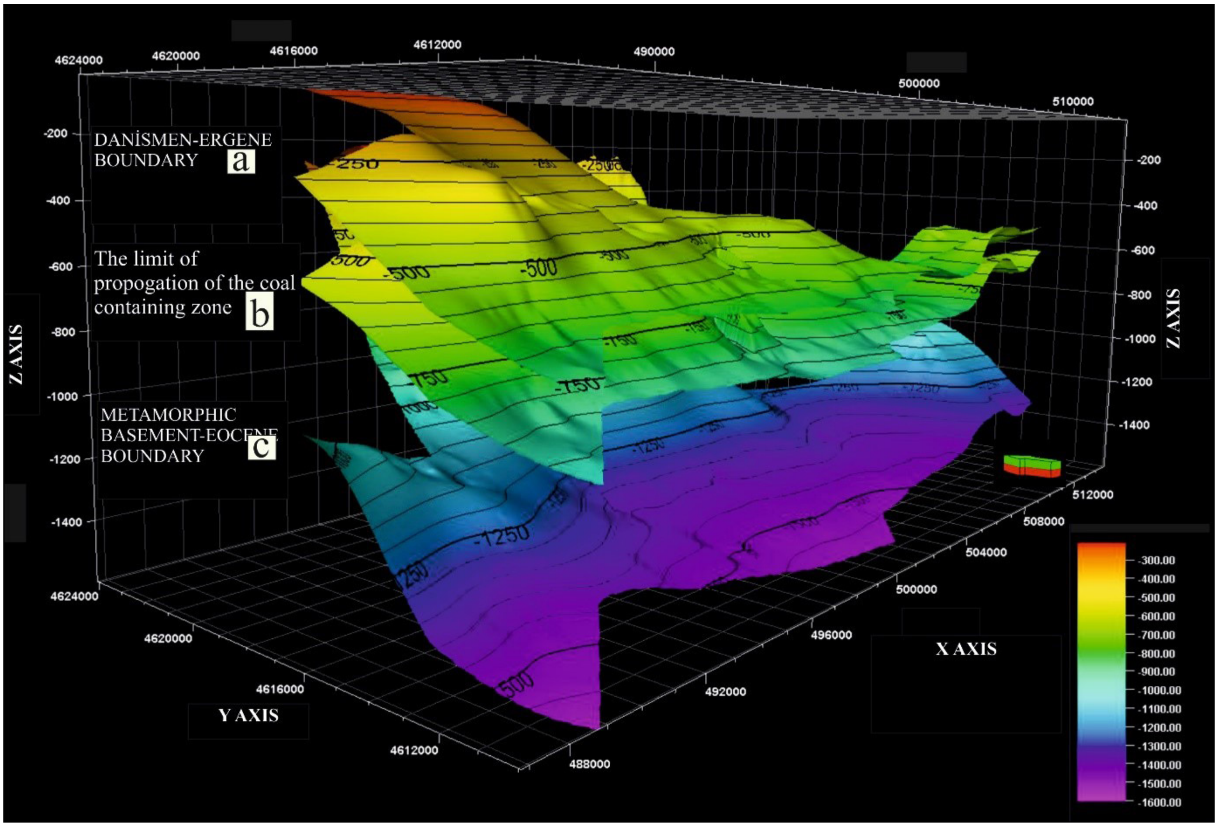

Figure 10- 3D view of; a) Danişmen-Ergene boundary, b) extensions of the coal-containing zone and c) metamorphic Basement-Eocene boundary. All boundaries are plotted on a millisecond (ms) scale.

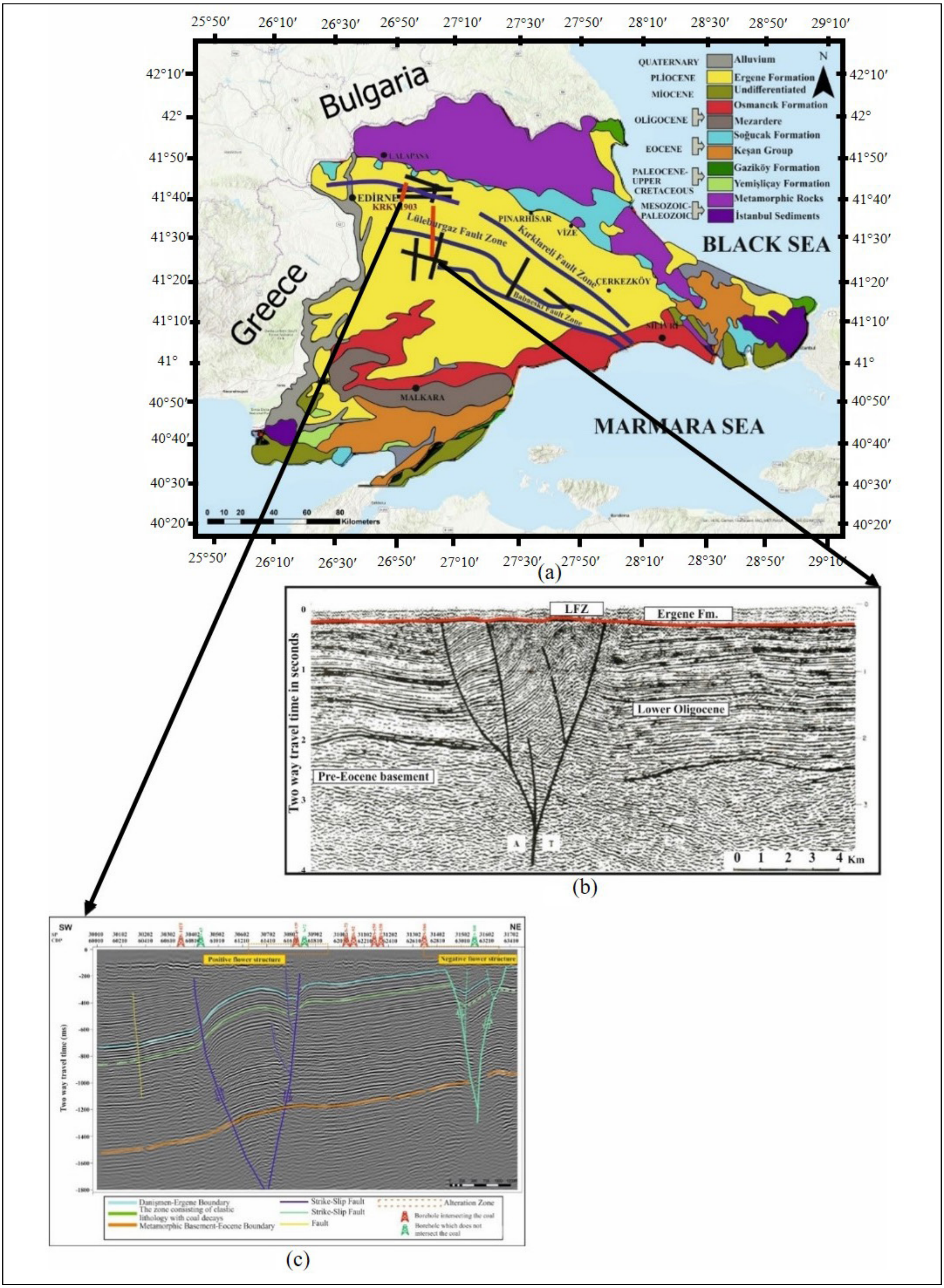

Figure 11- a) Geological map of Thrace Basin and Thrace fault zones (geological map; Kasar et al., 1983; modified from Perinçek, 1991; Perinçek et al., 2015), b) positive flower structure near the western part of the Lüleburgaz Fault Zone (LFZ) (Perinçek, 1991; Perinçek et al., 2015) and c) fault systems observed on the KRKV1903 seismic cross-section.

When the seismic lines studied by MTA in 2018-2019 are placed on the map drawn from Perinçek (1991), it is thought that the positive flower structure determined on the KRKV1903 seismic cross-section was formed by the effect of the northern branch of the KFZ (Figure 11c).

By using a high-resolution seismic reflection method, it is possible to detect small-size ores and alteration zones with low acoustic impedance in terms of mining (Hajnal et al., 1997). In light of this information, the existence of zones was tried to be determined in all seismic lines carried out in the field. The tectonic structure in which the presence of uranium ore observed in the determined alteration zone is similar to the structure observed in the east of the line suggests that it may indicate the presence of uranium ore in this region as well (Figure 8). For this reason, it is important to give priority to this area in the drilling plans to be carried out in the future.

6. Results

As a result of the study, the basic topography of the area, the alteration zones assumed to be important for uranium deposition, the extension of the coal-bearing zones, and the tectonic structures affecting the area were determined, and 3D surface maps were created.

After the evaluation made by showing the 2D seismic cross-sections in a 3D block diagram, it was determined that the thin Ergene formation was deposited in the uplift areas developed due to faulting in the basin, and the formation was thicker in the synclines in the trough areas. In addition, it has been observed that the geological formations, especially the Danişmen-Ergene formations boundary, are inclined in the NW-SE direction. In some areas in the east of the basin, the unconformity surface at the base of the Ergene formation was folded due to the compression created by the fault activity. The probability of seeing lignite layers in the center of areas with positive flower structures is rare due to folding. It is recommended to drill on the flanks of these structures so as to detect the lignite layer.

The extension coal-bearing zone determined by evaluating the seismic lines collected in the study area was modeled with a 3D image. In light of these obtained data, it has been determined that the extension of coal continues from the southwest of the basin to the northeast, and the borehole information have also supported this model.

This study was carried out for radioactive purposes, as an example, it is recommended to conduct seismic reflection studies before coal-targeted drilling for level monitoring and determination of target zones in coal exploration areas.

The uranium ore in the alteration zones determined at the intersection of the seismic cross-sections KRKV1901 and KRKV1903 indicates that the alteration zones in the other seismic cross-sections should also be explored in this respect. The seismic reflection method contributes to the identification of geological structures that are not outcropped, the determination of the inclination angles of the formations, and detailed site characterization with new boreholes. In order to obtain more detailed information about the study area, the seismic reflection method should be performed before drilling activities and more frequent seismic lines should be planned. In addition, with the data obtained as a result of the study, it is recommended to drill new boreholes in areas with coal and uranium potential.

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