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# An Approach to Determine of the Formation Stages of Volcanism Using Natural Gamma-Ray Spectrometer from Geophysical Methods (Example of Gölcük Volcanism)

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**Abstract**
Gölcük Caldera is in the Isparta Angle, which is an interesting tectonic structure in Southwest Anatolia. This caldera is formed as a result of back-arc volcanism associated with the northward subduction zone of the African plate under the Eurasian Plate during the Tertiary. It attracts the attention of many researchers with its tectonic and volcanic structure. In this article, the results of in situ natural gamma radiation measurements made in the caldera are evaluated. In the study, radioactive element (Potassium (%K), Uranium (eU), and Thorium (eTh)) contents of volcanic were measured in situ with the portable gamma-ray spectrometer, which is effectively used in Geophysical Engineering. The changes in natural gamma radiation of alkaline volcanic are presented with maps. When these maps are examined, it is understood that K%, U-ppm and Th-ppm concentrations of Gölcük volcanic are higher than the world average values. The high potassium concentration draws even more attention. The high potassium content indicates that the local volcanic are ultrapotassic and contain lithospheric materials. In addition, since the radioactive element concentration will reflect the magmatic development, the volcanic stages in the region have been tried to be determined. The number of these stages was determined from the curves of the radioactive data from a purely geophysical engineering (numerical) point of view, and the study area was interpreted as consisting of three different phases. This finding is supported by the results of the articles on the aging studies of the samples taken as a result of observations. In addition to these, the ranges of radioactive elements belonging to these stages were determined.

## 1. Introduction

Portable gamma-ray spectrometers are widely used in field studies for different purposes. As it is known, the most intense radioactive elements in nature are $^{40}K$, $^{238}U$ and $^{232}Th$. In situ gamma-ray spectrometry studies allow numerically in-situ and instant evaluation of these radioactive elements, which are more or less present in rocks. With these numerical values obtained, environmental radioactivity can be also determined quickly and accurately. The geological environment formed as a result of the ejection and precipitation of ash and rocks, especially during volcanic activities, consists of volcanic products. People living in these volcanic regions are exposed to radiation due to the geological environment. Therefore, it is important to determine the levels of natural radioactivity that will affect human health and to make comparisons according to [1]. For that purpose, many researchers have identified areas with radiological risk in their studies [2]-[17]. Serious health problems may occur in people living in areas with this radiological risk, and it is stated in [18] that people living in environments where radioactive elements are concentrated have serious cancer disorders. Accordingly, many researchers have conducted studies on the effect of cancer (for example: Kırklareli-Türkiye [19]; Isparta-Türkiye [8]; Penang-Malaysia [20]; Afyon-Türkiye [21]). In addition to studies in terms of human health, gamma-ray spectrometry studies geological unit separation [8], [12], precious metal and radioactive element exploration [12], [22], [23], geothermal studies [11], agricultural areas [24], archaeological sites [25] and it are used for many such purposes. In addition, the radioactive element concentration in the field gives also additional information about the geodynamics and tectonics of that region. Generally, $^{40}K$, $^{238}U$ and $^{232}Th$ are found in high concentrations in acidic intrusive rocks. As

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the higher the silica contents of a rock, the higher the uranium content. Ultramafic rocks, on the other hand, have lower radioelement concentrations. Radioelement concentrations of sedimentary and igneous rocks vary depending on their composition and location [26]. The average concentrations of $^{40}K$, $^{238}U$ and $^{232}Th$ elements in the continental crust are in the range of 2-2.5%, 2-3ppm and 8-12ppm, respectively [27]. Many studies show that the radioactive element concentrations in rocks formed as a result of volcanic activity are higher than the crustal averages [8], [11], [12], [28]-[31]. Similarly, it is stated that magmatic stages are also reflected by $^{40}K$, $^{238}U$ and $^{232}Th$ radioelement concentrations [32]-[34].

The study area is mostly composed of volcanic units as a result of Gölcük volcanism. The volcanic products in the field are named as the Isparta volcanic series [35] and it is understood from the in situ gamma-ray spectrometer measurement results that they are quite rich in potassium. As a result of the dating studies carried out in Gölcük volcanism, it is stated that it consists of three different stages [36]-[38]. Gölcük volcanics have a medium-basic composition and are stated to be shoshonitic-ultrapotassic in character [38]. Field measurements include Plio-Quaternary trachytes, tefrifonolites, pyroclastics and Quaternary alluviums. In general, the concentration values of radioactive elements increase from the old to the young volcanic phase. This study presents the results of in situ gamma ray spectrometry on the Gölcük volcanic units and an approach for estimating the stages of volcanism based on these results.

## 2. Formation Stages of Tectonics and Volcanism

The existence of an extensional tectonic setting in Southwest Anatolia has been revealed as a result of analyzes based on earthquake waves [39], [40]. Similarly, tectonic structure can be determined using many Geophysical methods (Gravity [41]-[46], electric-electromagnetic [47], seismic reflection [46], [48] etc.). Gölcük volcanism is associated with dextral strike-slip faults that developed depending on the tension regime as a result of the clockwise rotation of the Pliocene tectonics. This tectonic regime in the Late Pliocene period created normal faulting and, accordingly, the depression areas such as the Kovada graben [49]. The volcanism that took place around Gönen in the north of Isparta, around Bucak in the south of Isparta and in Gölcük was emplaced on these faults approximately in the North-South direction [50]. [51] and [52] emphasize that this hyper-alkaline volcanism around Isparta may be associated with the intra-continental strike-slip regime. Gölcük volcanism is located in the volcanic sequence starting from Antalya and extending to Isparta-Afyon-Kırka within the tectonic structure defined as Isparta Bend [53 or Isparta Angle [54]-[56] by different researchers (Figure 1).

Located in the south of Kırka-Afyon-Isparta volcanic province and common in the southern region of Isparta, pyroclastics and volcanic rock components are the products of Gölcük volcanism. Gölcük volcanism is a maar-type (slightly swollen, wide, water-filled and shallow crater lake formed by magma and lava as a result of eruption or eruption) volcanism [57], [58]. In many studies, the age determination of Gölcük volcanics has been made and the volcanics in question have been aged in the range of 4.7-4.0my [36], [37], [52], [59]. Gölcük volcano continued its explosion and eruption activity during the Pliocene [36], [60], [61]. [36] divided the volcanic activity in the region into two phases; (i) Lamprophyry, basaltic trachyandesitic, trachyandesitic and trachytic lava outcrops represented by Pliocene volcanic activity, and (ii) Pleistocene eruption that started with a big eruption forming the caldera. According to [62], the evolution and dating of the Isparta volcanism: (i) formation of lamprophyric dykes (6.21±0.3my), (ii) trachyandesitic-trachytic (4.6 ± 0.23-4.25 ± 0.21my), (iii) development of basaltic trachyandesitic-trachybasaltic volcanism (4.07±0.2-3.68±0.5my), formation of pyroclastics (1.5±0.18-0.39±0.2my) and phonolitic ring dykes (0.35±0.1my) due to volcanic eruption. In addition to these, [38] states that this volcanism developed in three different phases and these are (i) extrusive volcanism consisting of trachyte, trachyandesite, basaltic trachyandesite, phonolite, tefrite and lamprophyres; (ii) explosive volcanism consisting of ignimbrite, unconsolidated tuff, agglomerate and pumice; (iii) extrusive volcanism consisting of trachyte and trachyandesite.

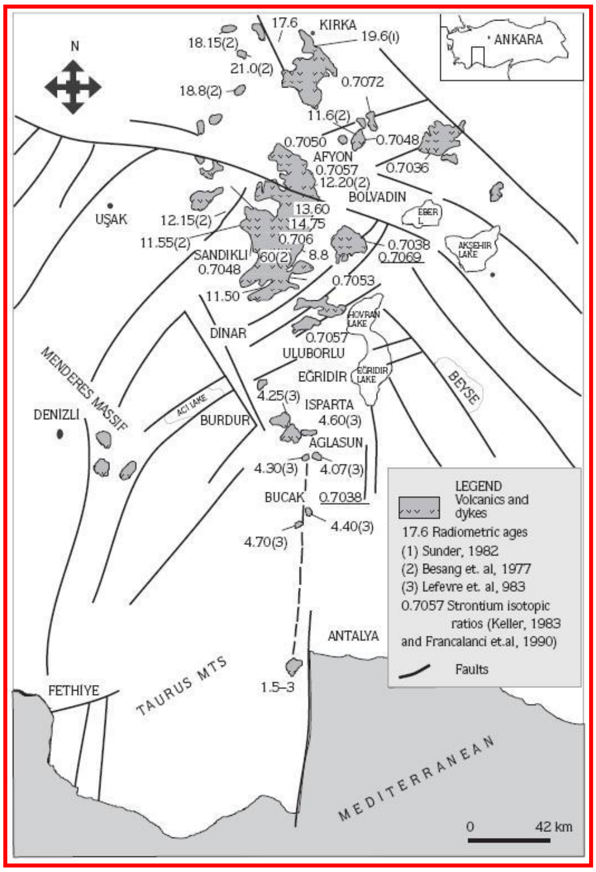


**Figure 1.** Distribution of Kırka-Afyon-Isparta alkaline volcanic rocks in relation to fault systems, Sr isotope and radiometric dating [52]

## 3. Applied Method and Study Area

### 3.1. Gamma-Ray Spectrometer Method

Although there are at least twenty elements known as natural and radioactive, Potassium ($^{40}$K), Uranium ($^{238}$U), and Thorium ($^{232}$Th) isotopes come to the fore in geophysical researches because they are more than other elements. In geophysical studies, gamma ray spectrometers are used to determine the amount of these three elements in soil and rock quickly and in situ. Gamma-ray spectrometers have the same working principle as scintillometers. However, the spectrometer is an electronically more advanced form of the scintillometer, which distinguishes characteristic gamma rays from $^{40}$K, $^{238}$U and $^{232}$Th according to their energies (Figure 2).

Spectrometers with quad-window are standard, and a 512-channel gamma-ray spectrometer in which gamma rays are divided into 512 equal intervals in the 0-3MeV energy band was used in this study. Each channel of the spectrometer has an energy interval of about 6KeV. These types of spectrometers have been successfully used for the detection of artificial and natural radioactive elements [64]. The gamma-ray spectrometer device used in the study is suitable for point, profile and continuous measurements using external GPS. The spectrometer used is a 512-channel, 6.3-inch$^3$-volume thallium-activated sodium iodide [NaI (TI)] crystal, Cs$^{137}$ external reference source, and an efficient and highly discrimination instrument with zero dead time. The purpose of gamma-ray spectrometry is to determine only the numbers of radioactive radiation emitted from the earth's crust. For this purpose, the potassium, uranium and thorium concentrations in the rock or soil are obtained using the equation below.

$$C_w = N_w * S_w \tag{1}$$

Here; Cw, w (K, U, Th) element concentration,
Nw, The net radiation number in the channel belonging to the w (K, U, Th) elements,
Sw represents the sensitivity of the channels belonging to the w (K, U, Th) elements of the spectrometer.

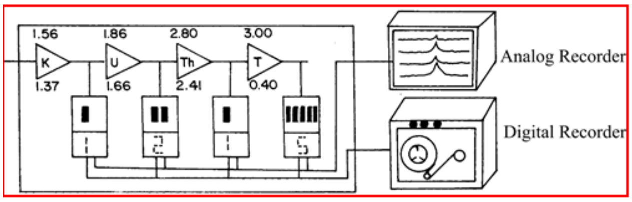


**Figure 2.** Schematic representation of a four-channel spectrometer and recorders [62]

### 3.2. Study Area and Simplified Geology

The units around Gölcük caldera are named as Gölcük volcanics by [35] and Pürenova formation by [65]. The lithological units of the Gölcük Caldera and its surroundings are trachyte, trachyandesite, andesite, volcanic tuff, and pumice series. Plio-Quaternary lithological units of Gölcük volcanism are limited by Middle Eocene aged flysch deposits in the north; Triassic-Cretaceous aged Akdağ limestones in the south, and Isparta plain alluviums in the west, including Gölcük volcanics. The Gölcük formation is intercalated with Plio-Quaternary lake sediments and its thickness is around 1000m [65]. The caldera and its surrounding rock assemblage are defined as an asymmetrical eruption structure with a diameter of 3-4km, located on the south-southwest edge of the Isparta graben at an altitude of 1378m above sea level [66]. In the study area, discontinuous circular tefriphonolitic lava flows on the caldera margins and dykes of the same composition cutting them and trachytic domes of different sizes are observed in the caldera (Figure 3).

In-situ measurements were made at 305 points with gamma-ray spectrometry in the Gölcük Caldera (Figure 3). Measurements include volcano-sediments consisting of alluvium, small and medium-sized trachytes (Trachytic domes in Pilav-Hill and its Southeast), pyroclastics and tefrifonolites within the caldera.

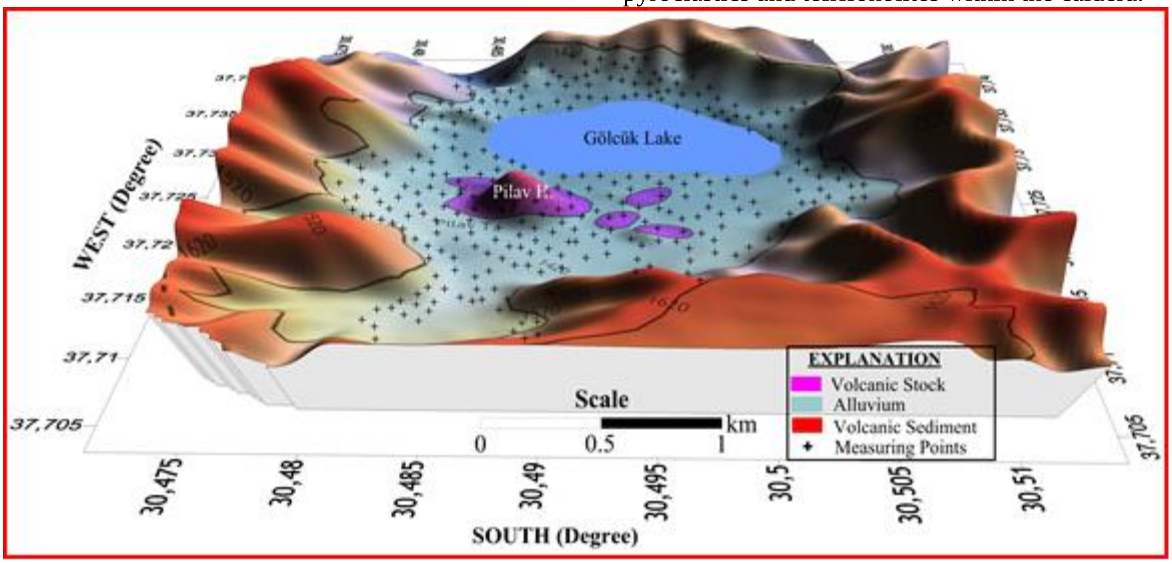


**Figure 3.** Simplified geology and measurement points of Gölcük Caldera and its surroundings (edited from [67])

## 4. Results and Discussion

### 4.1. Distribution of Radioactive Elements in Gölcük Volcanics

Looking at the maps created from gamma-ray spectrometry measurements (Figure 3) made at 305 different points on the Gölcük volcanics, the most striking feature is the high concentration of radioactive elements in all of the volcanics. Three different units are distinguished in the simplified geological map of the study area (Figure 3). These are volcanic stocks, Alluvial and Volcano sedimentary. It is observed that $^{40}$K, $^{238}$U and $^{232}$Th concentration values in the study area vary between 2.80-6.1%, 9-28.2ppm and 41.3-70.7ppm for all units, respectively (Table 1). The $^{40}$K, $^{238}$U and $^{232}$Th concentration values of trachyte in Pilavtepe and its southeast, which are specified as volcanic stock, vary between 3.9-5.3%, 15.8-23.2ppm and 49.1-66.6ppm, respectively. The average concentration values of these trachytic domes are 4.7%, 18.4ppm and 57.4ppm, respectively. The average values of the intra-caldera alluvial and volcanic sedimentary units are measured 4.4%, 17.2ppm and 51.9ppm, and 4.9%, 19.2ppm and 56.7ppm, respectively (Table 1). These values are considerably higher than the world average values. These changes in the concentration values of the radioactive elements reflect the geochemical differences of the Gölcük volcanics forming the Gölcük lake vicinity. In Figure 4, the distribution map of the study area and $^{40}$K, $^{238}$U, $^{232}$Th concentration values in the blue-red color range is presented. The blue color and the white areas indicate the area of the limestone block in the study area. Green, yellow and red colored areas show the products of Gölcük volcanic. The areas within the Gölcük volcanics with low (green colored areas) radioactive element concentration values can be interpreted as the fact that the older volcanic series are mafic (rock and silicate minerals rich in magnesium and iron). On the other hand, high (red colored areas) radioactive concentration values reflect the areas where the felsic (silicate minerals enriched with lighter elements such as silicon, oxygen, aluminum, sodium and potassium, and rocks rich in feldspar and quartz minerals) volcanics of the younger series outcrop. While rocks composed of mafic minerals (olivine, pyroxene, amphibole, biotite, etc.) are darker in color, felsic rocks are lighter in color and less dense. It is seen in Figure 4 that the $^{40}$K and $^{232}$Th concentration values are higher than the $^{238}$U concentration values in the study area in general. While the color red is more common in the $^{40}$K and $^{232}$Th maps, the $^{238}$U map has a red color (high concentration value) in a specific area in the northeastern and southern parts of the map. It is seen that high values of $^{40}$K and $^{232}$Th are also obtained in sections the high of the $^{238}$U concentration value in Figure 4, and these values correspond to areas where volcanic sediments are located. However, in Pilavtepe and in the Southeast of this hill where volcanic stocks are located, $^{40}$K and $^{232}$Th values are measured high values while $^{238}$U values are low. Areas with low $^{238}$U values may be caused by ultramafic or ultrabasic rocks due to low silica content.

**Table 1.** Concentration values of radioactive elements measured in Gölcük caldera.

| | **$^{40}$K (%)** | | | **$^{238}$U (ppm)** | | | **$^{232}$Th (ppm)** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | **Aver.** | Min. | Max. | **Aver.** | Min. | Max. | **Aver.** |
| **Volcanic Stock** | 3.9 | 5.3 | **4.7** | 15.8 | 23.2 | **18.4** | 49.1 | 66.6 | **57.4** |
| **Alluvium** | 2.8 | 5.9 | **4.4** | 9.1 | 20.9 | **17.2** | 41.3 | 55.8 | **51.9** |
| **Volcanic Sediment** | 3.6 | 6.1 | **4.9** | 15.0 | 28.2 | **19.2** | 46.5 | 70.7 | **56.7** |
| **World Average** | | **1.6** | | | **4.05** | | | **12.32** | |

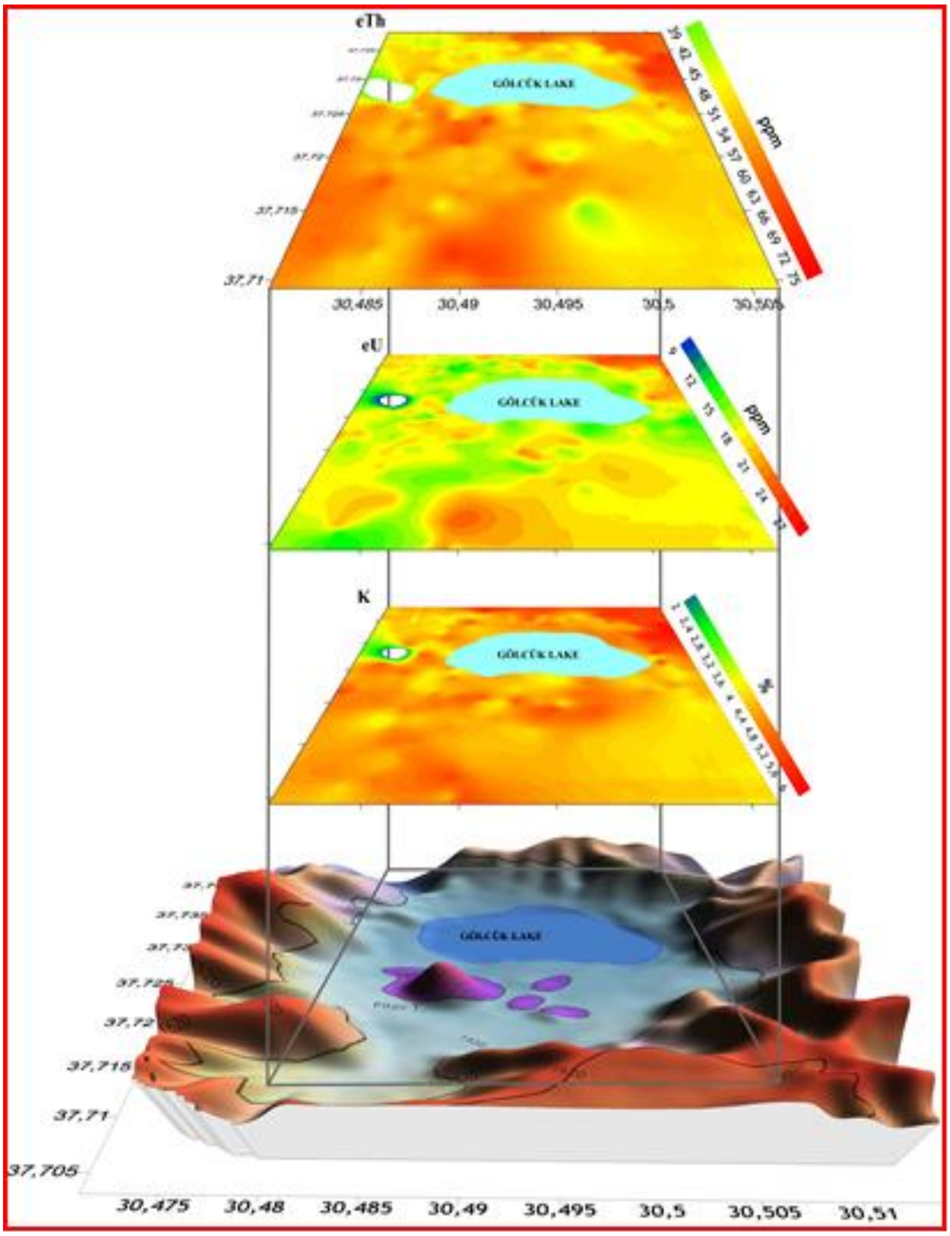


**Figure 4.** $^{40}$K, $^{238}$U and $^{232}$Th concentration distribution maps of Gölcük volcanics

## 4.2. An Approach to Determining the Formation Stages of Gölcük Volcanism

Many researchers have stated that Gölcük volcanism occurred in three different geological stages [36]-[38], [62]. Researchers generally refer to these three stages as extrusive volcanism in the first stage, explosive volcanism in the second stage, and extrusive volcanism consisting of trachyte and trachyandesite in the third stage. As it is known, the concentration values of radioactive elements in the old volcanic phase are lower than the values of the young volcanic stage. In this meaning, Figure 5 is obtained when the concentration values of radioactive elements are arranged and plotted from smallest to largest. When the distribution of $^{40}$K data is examined in Figure 5, these data are represented by three different lines (blue color) in three different regions (red circles). Similarly, the distribution of $^{238}$U and $^{232}$Th data also shows that there are three different straight-line. The correlation coefficient of these lines ($R \geq 0.95$) is over 95% and the intersection points of the lines give the limit values of the lines. If we look at it in line with this logic, three different lines can be three different phases and the intersection points of the lines can be also the limit values of the stages. Accordingly, Table 2 can be created if Figure 5 is used. According to the data in Table 2, the average values of $^{40}$K, $^{238}$U and $^{232}$Th concentrations of the volcanic products formed in the first stage of the Gölcük volcanism are obtained 3.5%, 13.4ppm and 44.0ppm, respectively. Similarly, the radioactive element values of the volcanic products of the second and third phases can be examined from Table 2. The variation in radioelement concentrations indicates the geochemical variation in the volcanic products. In general, the difference in the average values of $^{40}K$, $^{238}U$ and $^{232}Th$ in the first and second stages is 1.02%, 4.25ppm and 9.23ppm, respectively while the values in the second and third stages are 1.12%, 4.93ppm and 12.05ppm, respectively. As can be understood from these values, there is a concentration increase from the first and second volcanic phases to the third.

Figure 6 is created by using the limit values specified in Table 2 and the concentration values of radioactive elements measured on the Gölcük volcanics. The part seen as a white area on the maps in this figure is limestone and the data obtained in this area are not taken into account, so this area is white. Maps are created from the transitions of green, yellow and red colors. The inner areas of the sections indicated by the continuous lines on the maps show the first phase, the interior of the areas indicated by the dashed lines to the third phase, and the area between the continuous and dashed lines shows the second phase. In this case, the second phase volcanic units predominate in the study area. The areas where the high values of Uranium and Thorium overlap may be associated with shoshonitic composition rocks.

High Potassium values indicate that the volcanics of Isparta region are derived from the mantle containing lithospheric products due to stress tectonics, as indicated in [60]. It is stated that Gölcük volcanics are geochemically alkaline volcanic rocks and rich in silica, sodium, potassium and aluminum [38]. Figure 6 shows that the highest U value in the areas within the dashed line in the Southeast and South of the study area coincides with the high Th and K concentrations associated with the felsic (rich in silica, sodium, potassium) medium extruded volcanic rocks of the third phase.

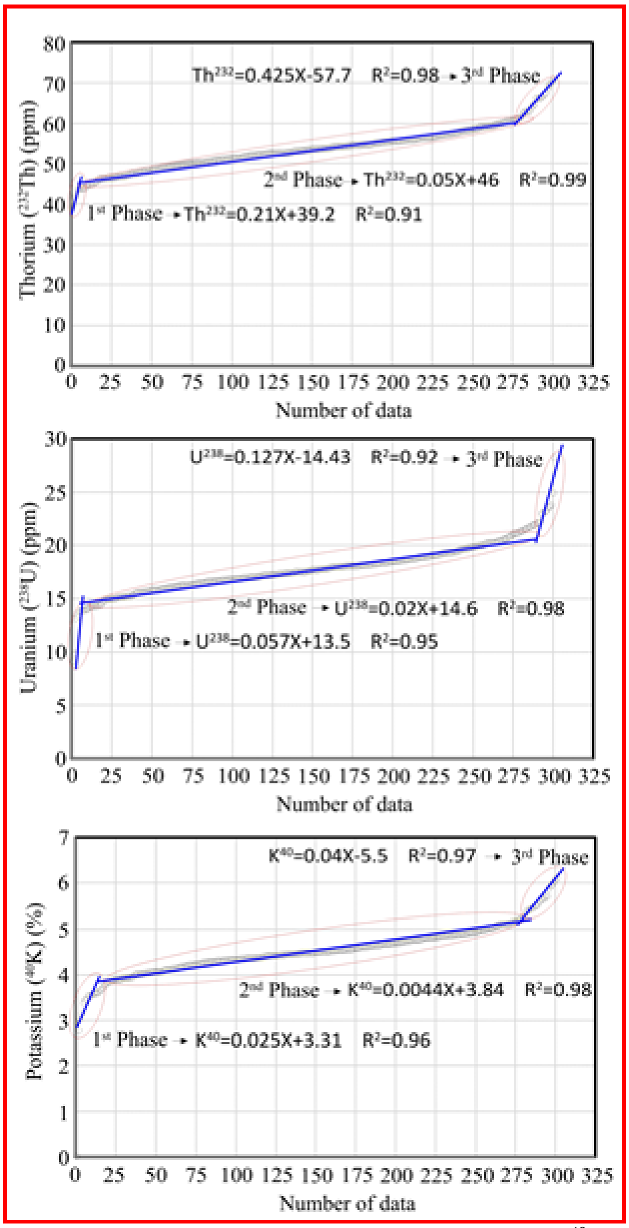


**Figure 5.** Separation of volcanism phases based on $^{40}K$, $^{238}U$ and $^{232}Th$ values ordered from smallest to largest

**Table 2.** The limits of radioactive elements belonging to the phases of Gölcük volcanism from the radioactive data in Gölcük volcanics

| | **Data Number** | **$^{40}K$** (%) Min.-Max. (Average) | **$^{238}U$** (ppm) Min.-Max. (Average) | **$^{232}Th$** (ppm) Min.-Max. (Average) |
|---|---|---|---|---|
| **1st PHASE** | 15 | 2.70 – 3.80 (3.48) | 9.00 – 14.30 (13.37) | 39.20 – 46.10 (43.98) |
| **2nd PHASE** | 260 | 3.80 – 5.20 (4.50) | 14.30 – 21.10 (17.62) | 46.10 – 60.90 (53.21) |
| **3rd PHASE** | 30 | 5.20 – 6.13 (5.62) | 21.10 – 28.23 (22.55) | 60.90 – 70.72 (65.26) |

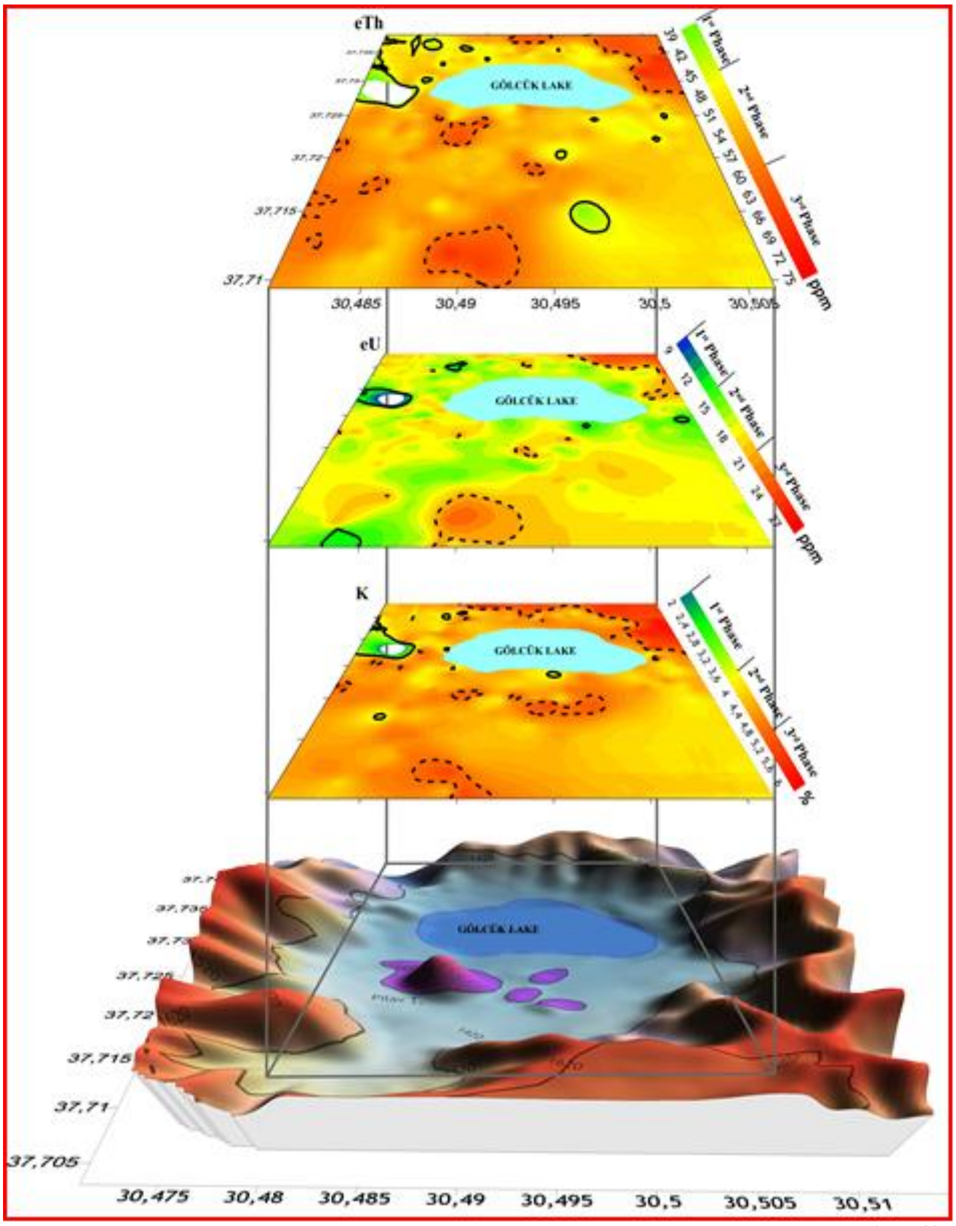


**Figure 6.** Maps showing the differentiation of volcanism phase products depending on the $^{40}K$, $^{238}U$ and $^{232}Th$ concentration values of Gölcük volcanics

## 5. Conclusions

For the measurement of $^{40}K$, $^{238}U$ and $^{232}Th$ in rocks or soils, in situ analysis, immediate and cost-effective good results are obtained with the gamma-ray spectrometer used in Geophysical engineering. Measuring, mapping and analyzing large areas in nature quickly and cheaply make gamma ray spectrometry a powerful tool.

As a result of natural gamma-ray spectrometry measurements on Gölcük volcanics, $^{40}K$, $^{238}U$ and $^{232}Th$ concentration values were obtained between 2.80-6.1%, 9-28.2ppm and 41.3-70.7ppm, respectively. The volcanics in the study area have a maximum concentration of $^{40}K$ and a minimum of $^{238}U$. The high $^{40}K$ indicates that it is a potassium-rich volcanism. It may be caused by ultramafic or ultrabasic rocks due to the low silica content in areas with low $^{238}U$ values.

Difference in $^{40}K$, $^{238}U$ and $^{232}Th$ concentration values reflect the geochemical differences of the rocks.

$^{40}K$, $^{238}U$ and $^{232}Th$ are related to each other and magmatic evolution is shown to be reflected by these three radioelements. Accordingly, the mean values of $^{40}K$, $^{238}U$ and $^{232}Th$ concentrations of the volcanic units formed in the first, second and third stages of the volcanism are obtained 3.5%, 13.4ppm and 44.0ppm, 4.5%, 17.62ppm and 53.21ppm, and 5.62%, 22.55ppm and 65.26ppm, respectively.

The most suitable sample locations for age determination of rocks in the laboratory can be made quickly and accurately with the gamma-ray spectrometer method.

## Acknowledgment

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## Statement of Research and Publication Ethics

The study is complied with research and publication ethics

## References

[1] UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), “Sources and biological effects of ionizing radiation,” New York, USA, 2000.

[2] I. R. Ajayi, and O. O. Kuforiji, “Natural radioactivity measurements in rock samples of Ondo and Ekiti states in Nigeria,” *Radiation Measurements*, vol. 33, pp. 13-16, 2001.

[3] L. Xinwei, “Natural radioactivity in some building materials and by-products of Shaanxi, China,” *Journal of Radioanalytical and Nuclear Chemistry*, vol. 262, pp. 775-777, 2004.

[4] S. Singh, A. Rani, and R. K. Mahajan, “$^{226}$Ra, $^{232}$Th and $^{40}$K analysis in soil samples from some areas of Punjab and Himachal Pradesh, India using gamma ray spectrometry,” *Radiation Measurements*, vol. 39, no. 4, pp. 431-439, 2005.

[5] N. Sulekha Rao, D. Sengupta, R. Guin, and S. K. Saha, “Natural radioactivity measurements in beach sand along southern coast of Orissa, eastern India,” *Environmental Earth Sciences*, vol. 59, pp. 593-601, 2009.

[6] R. Mehra, S. Kumar, R. Sonkawade, N. P. Singh, and K. Badhan, “Analysis of terrestrial naturally occurring radionuclides in soil samples from some areas of Sirsa district of Haryana, India using gamma ray spectrometry,” *Environmental Earth Sciences*, vol. 59, pp. 1159-1164, 2010.

[7] N. A. Uyanık, I. Akkurt, and O. Uyanık, “A ground radiometric study of uranium, thorium and potassium in Isparta, Turkey,” *Annals of Geophysics*, vol. 53, no. (5–6), pp. 25-30, 2010.

[8] N. A. Uyanık, O. Uyanık, and İ. Akkurt, “Micro zoning of the natural radioactivity levels and seismic velocities of potential residential areas in volcanic fields The case of Isparta Turkey,” *Journal of Applied Geophysics*, vol. 98, pp. 191-204, 2013a.

[9] N. A. Uyanik, Z. Öncü, O. Uyanik, and İ. Akkurt, “Determination of Natural Radioactivity from 232Th with Gamma-Ray Spectrometer in Dereköy-Yazır (Southwestern Anatolia),” *Acta Physica Polonica A*, vol. 128, no. No 2-B, pp. B441-442, 2015a.

[10] N. A. Uyanik, Z. Öncü, O. Uyanik, M. Bozcu, I. Akkurt, K. Günoglu, and F. Yagmurlu, “Distribution of Natural Radioactivity from $^{40}$K Radioelement in Volcanics of Sandıklı-Suhut (Afyon) Area,” *Acta Physica Polonica A*, vol. 128, no. No 2-B, pp. B438-440, 2015b.

[11] N. A. Uyanık, B. Kurt, and O. Uyanık, “Determination of the hot dry rock from radiogenic heat production for potential geothermal sources and example of Isparta-Yakaören,” *Pamukkale University Journal of Engineering Sciences*, vol. 26, no. 6, pp. 1170-1177, 2020.

[12] N. A. Uyanık, Z. Öncü, O. Uyanık, and M. Bozcu, “Determination of alteration zones and geological unit limits using natural radioactivity properties of Sandıklı-Suhut areas”. *Journal of Applied Geophysics*, vol. 196, art. no. 104525, 2022.

[13] S. Fares, “Measurements of natural radioactivity level in black sand and sediment samples of the Temsah Lake beach in Suez Canal region in Egypt,” *Journal of Radiation Research and Applied Sciences*, vol. 10, no. 3, pp. 194-203, 2017.

[14] A. Aziz, T. Attia, and M. Hanafi, “Radiological Impact and Environmental Monitoring of Gamma Radiations Along the Public Beach of Port Said, Egypt,” *Pure and Applied Geophysics*, vol. 177, pp. 2871-2876, 2020.

[15] G. Cinelli, E. Brattich, C. Coletti, V. De Ingeniis, C. Mazzoli, D. Mostacci, R. Sassi, and L. Tositti, “Terrestrial gamma dose rate mapping (Euganean Hills, Italy): comparison between field measurements and HPGe gamma spectrometric data,” *Radiation Effects and Defects in Solids*, vol. 175, pp. 54–67, 2020.

[16] A. S. Akingboye, A. C. Ogunyele, A. T. Jimoh, O. B. Adaramoye, A. O. Adeola, and T. Ajayi, “Radioactivity, radiogenic heat production and environmental radiation risk of the Basement Complex rocks of Akungba-Akoko, southwestern Nigeria: insights from in situ gamma-ray spectrometry,” *Environmental Earth Sciences*, vol. 80, no. 6, 2021.

[17] A. A. Abojassim, and L. H. Rasheed, “Natural radioactivity of soil in the Baghdad governorate,” *Environmental Earth Sciences*, vol. 80, no. 1, 2021.

[18] ATSDR (Agency for Toxic Substances and Disease Registry). “Toxicological Profile for Radon”. Public Health Service, U.S. Department of Health and Human Services, Atlanta, USA, 1990.

[19] H. Taskin, M. Karavus, P. Ay, A. Topuzoglu, S. Hindiroglu, and G. Karahan “Radionuclide concentrations in soil and lifetime cancer risk due to the gamma radioactivity in Kirklareli Turkey,” *Journal of Environmental Radioactivity*, vol. 100, pp. 49-53, 2009.

[20] B. A. Almayahi, A. A. Tajuddin, and M. S. Jaafar, “Effect of the natural radioactivity concentrations and $^{226}Ra/^{238}U$ disequilibrium on cancer diseases in Penang, Malaysia,” *Radiation Physics and Chemistry*, vol. 81, no. 10, pp. 1547-1558, 2012.

[21] N. A. Uyanık, “Determination of the Radiological Risk and the Cancer Effect Caused by Geological Units and Samples from Afyon, Turkey,” *Pure and Applied Geophysics*, vol. 179, pp. 1295-1308, 2022.

[22] S. Altundaş, and H. Çınar, “Uranium migration and radioactive characteristics of the Sariçiçek and Sarihan Granodiorites,” *Turkish Journal of Engineering*, vol. 7, no. 3, pp. 208-226, 2023.

[23] S. Altundas, “Investigation of natural radionuclide variations and the possible uranium migration by testing with gamma-ray spectrometer: An example from TuğIu Tepe and Deliler Sites in Sefaatli/Yozgat, Central Anatolia Region, Turkey,” *Joumal of Applied Geophysics* vol. 207, article no. 104866, 2022.

[24] M. Bolca, M. M. Saç, B. Çokuysal, T. Karalı, and E. Ekdal, “Radioactivity in soils and various foodstuffs from the Gediz River Basin of Turkey,” *Radiation Measurements*, vol. 42, pp. 263-270, 2007.

[25] M. Martini, and E.Sibilia, “Radiation in archaeometry: archaeological dating,” *Radiation Physics and Chemistry*, vol. 61, no. (3–6), pp. 241-246, 2001.

[26] F. Birch, “Heat from radioactivity, in Nuclear Geology”, ed. Henry Faul, New York, USA, John Wiley and Sons Inc., 1954.

[27] IAEA (International Atomic Energy Agency), “Guidelines for Radioelement Mapping Using Gamma-Ray Spectrometry Data”. Vienna, Austria, 1363p, 2003.

[28] P. Chiozzi, P. De Felice, V. Pasquale, D. Russo, and M. Verdoya “Field γ-ray spectrometry on the Vulcano island (Aeolian Arc, Italy),” *Applied Radiation and Isotopes*, vol. 51, pp. 247-253, 1999.

[29] İ. Aydın, “Jeofizikte Radyometrik Yöntem ve Gamma-Işın Spektrometrisi,”, SDU Publishing house, publication no.49, Isparta, Türkiye, 2004, p.150.

[30] İ. Aydın, M. S. Aydoğan, E. Oksum, and A. Koçak, “An Attempt to Use Aerial Gamma-Ray Spectrometry Results in Petrochemical of the Volcanic and Plutonic Associations of Central Anatolia (Turkey),” *Geophysical Journal International*, vol. 167, pp. 1044-1052, 2006.

[31] N. A. Uyanık, O. Uyanık, F. Gür, and İ. Aydın, “Natural radioactivity of bricks and brick material in the Salihli–Turgutlu area of Turkey,” *Environmental Earth Sciences*, vol. 68, no. 2, pp. 499-506, 2013b.

[32] R. Mazzuoli, L. Tortorici, and G. Ventura, “Oblique rifting in Salina, Lipari and Vulcano islands (Aeolian islands, southern Italy),” *Terra Nova*, vol. 7, pp. 444-452, 1995.

[33] P. Chiozzi, V. Pasquale, and M. Verdoya, “Ground radiometric survey of U, Th and K on the Lipari Island, Italy,” *Journal of Applied Geophysics*, vol. 38, pp. 209-217, 1998.

[34] P. Chiozzi, V. Pasquale, M. Verdoya, and S. Minato, “Natural gamma-radiation in the Aeolian volcanic arc,” *Applied Radiation and Isotopes*, vol. 55, pp. 737-744, 2001.

[35] A. Poisson, “Recherches géologiques dans les Taurides occidentales (Turquies),” PhD thesis, University of Paris, 795p., Paris, France, 1977.

[36] B. Platevoet, S. Scaillet, H. Guillou, D. Blamart, S. Nomade, M. Massault, A. Poisson, Ö. Elitok, N. Özgür, F. Yagmurlu, and K. Yılmaz, “Pleistocene eruptive chronology of the Gölcük volcano, Isparta Angle, Turkey,” *Quaternaire*, vol. 19, no. 2, pp. 147–156. 2008.

[37] B. Platevoet, Ö. Elitok, H. Guillou, J. M. Bardintzeff, F. Yagmurlu, S. Nomade, D. C. Poisson, and N. Özgür, “Petrology of quaternary volcanic rocks and related plutonic xenoliths from Gölcük volcano, Isparta Angle, Turkey: origin and evolution of the high-K alkaline series,” *Journal of Asian Earth Science*, vol. 92, pp. 53-76, 2014.

[38] K. Yılmaz, “Geochemistry of ultramafic, mafic, and felsic xenoliths from the Gölcük (Isparta, SW Turkey) alkali rocks: genetic relationship with arc magmas,” *Arabian Journal of Geosciences*, vol. 12, art. no. 306, 2019.

[39] D. Kalafat, “Güneybatı Anadolu ve Yakın Çevresinin Depremselliği, Aktif Tektoniği,” *Deprem Araştırma Bülteni*, vol. 63, pp. 5-98, 1988.

[40] S. A. Poyraz, “Isparta Büklümünü Oluşturan Tektonik Yapıların Sismolojik Yöntemlerle Araştırılması,” PhD. Thesis, İstanbul Üniversitesi, İstanbul, Türkiye, 2009.

[41] O. Pamukçu, T. Gönenç, O. Uyanık, H. Sözbilir, and O. Çakmak, “A microgravity model for the city of İzmir Western Anatolia and its tectonic implementations,” *Acta Geophysica*, vol. 62, no. 4, pp. 849-871, 2014.

[42] B. Oruç, “Structural interpretation of southern part of western Anatolian using analytic signal of the second order gravity gradients and discrete wavelet transform analysis,” *Journal of Applied Geophysics*, vol. 103, pp. 82-98, 2014.

[43] C. E. Toker, E. U. Ulugergerli, and A. R. Kılıç, “The Naşa intrusion (Western Anatolia) and its tectonic implication: A joint analyses of gravity and earthquake catalog data**,”** *Bulletin of the Mineral Research and Exploration*, vol. 156, pp. 247-262, 2018.

[44] Ç. Sarı, and E. Timur, “Interpretation of magnetic data using boundary analysis and inversion techniques: a case study from Gölcük/Isparta (Turkey) region,” *Turkish Journal of Earth Sciences*, vol. 30, no. 5, pp 611-627, 2021.

[45] E. Oksum, M. N. Dolmaz and L. T. Pham, “Inverting gravity anomalies over the Burdur sedimentary basin, SW Turkey,” *Acta Geodaetica et Geophysica*, vol. 54, pp. 445–460, 2019.
[46] E. Erbek Kiran, A. Ates and M. N. Dolmaz, “Upper Crustal Structure of Denizli Graben (Western Turkey) From Bouguer Gravity Data and Seismic Refection Sections,” *Surveys in Geophysics*, vol. 43, pp. 1947–1966, 2022.
[47] E. Ulugergerli, G. Seyitoğlu, A. Başokur, C. Kaya, U. Dikmen, and M. Candansayar, “The geoelectrical structure of Northwestern Anatolia, Turkey,” *Pure and Applied Geophysics*, vol. 164, no. 5, pp. 999-1026, 2007.
[48] Y. Öz, “Engineering Seismology with Application to Geotechnical Engineering,” ed. Richard D. Miller, *Investigation in Geophysics Series No. 17, Oklahoma, U.S.A.,* Society of Exploration Geophysicists, 2015.
[49] C. Glover, and A. H. F. Robertson, “Neogen Intersection of the Aegean and Cyprus Arcs: Extensional and Strike-Slipe Faulting in the Isparta Angle, SW Turkey,” *Tectonophysics*, vol. 298, pp. 103-132, 1998.
[50] M. E. Karaman, “Tectono-Stratigraphic Outline of the Burdur-Isparta Area (Western Taurides, Turkey),” *Geological Bulletin of Turkey*, vol. 43, no. 2, pp. 71-81, 2000.
[51] F. Yagmurlu, Y. Savascin, and M. Ergun, “Relation of alkaline volcanism and active tectonism within the evolution of the Isparta angle, SW Turkey,” *Journal of Geology*, vol. 105, no. 6, pp. 717-728, 1997.
[52] M. Y. Savaşçın, and T. Oyman “Tectono-Magmatic evolution of alkaline volcanics at the Kırka-Afyon-Isparta structral trend, SW Turkey,” *Turkish Journal of Earth Sciences*, vol. 7, pp. 201-214, 1998.
[53] M. M. Blumenthal, “Le Système Structural du Taurus Sud - Anatolien in Livre à la mémoire,” *Prof. Paul Fellot, Mém., hs-sér., Société Géologique de France*, vol. II, pp. 611-662, 1963.
[54] J. H. Brunn, “L’arc Concave Zagro-Taurique et les Arcs Convexes Taurique et Egeen. Collision et Arcs Induits,” *Bulletin de la Society Geology*, vol. 2, pp. 553-567, 1976.
[55] A. M. C. Şengör, “Türkiye’nin Neotektoniğinin Esasları,” *Türkiye Jeoloji Kurultayı Konferanslar Dizisi, vol. 2, 40p.*, 1980.
[56] F. Yağmurlu, and M. Şentürk, “Güneybatı Anadolu’nun Güncel Tektonik Yapısı,” *Türkiye Kuvaterner Sepozyumu*, İTÜ Avrasya Yer Bilimleri Enstitüsü, İstanbul, Türkiye, 02-03 Haziran 2005.
[57] N. Kazancı, and M. E. Karaman, “Gölcük (Isparta) Pliyosen volkanoklastik istifinin sedimantolojik özellikleri ve depolanma mekanizmalar,” *Akdeniz Üniversitesi Isparta Mühendislik Fakültesi Dergisi*, vol. 4, pp. 16-35, 1988.
[58] W. Nemec, N. Kazanci, and J. G. Mitchell, “Pleistocene explosions and pyroclastic currents in west-Central Anatolia,” *Boreas*, vol. 27, pp. 311-332, 1998.
[59] C. Lefèvre, H. Bellon, and A. Poisson, “Présence de leucitites dans le volcanisme Pliocène de la région d’Isparta (Taurides occidentales, Turquie),” *CR Acad Sci Paris* vol. 297, no. II, pp. 367-372, 1983.
[60] P. Alıcı, A. Temel, A. Gourgaud, G. Kieffer, and M. N. Gündoğdu, “Petrology and geochemistry of potassic rocks in the Gölcük area (Isparta, SW Turkey): genesis of enriched alkaline magmas,” *Journal of Volcanology Geothermal Research*, vol. 85, no. 1, pp. 423-446, 1998.
[61] A. K. Schmitt, M. Danışık, W. Siebel, Ö. Elitok, Y-W. Chang, and C. C. Shen, “Late Pleistocene zircon ages for intracaldera domes at Gölcük (Isparta, Turkey),” *Journal of Volcanology Geothermal Research*, vol. 286, pp. 24-29, 2014.
[62] H. Coban, “New geochronologic, geochemical and isotopic constraints on the evolution of plio-quaternary alkaline volcanism from Isparta district, SW Turkey,” *International symposium on the geodynamics of eastern Mediterranean: active tectonics of the Aegean region, Istanbul, Turkey, 15-18 June 2005.*
[63] İ. Aydın, “Bir Jeofizik Yöntem: Gama-Işın Spektrometresi,” *Jeofizik Dergisi*, vol. 7, pp. 109-122, 1993.
[64] R. L. Grasty, J. E. Glynn, and J. A. Grant, “The Analysis of Multichannel Airborne Gamma-Ray Spectra,” *Geophysics*, vol. 50, no. 12, pp. 2611-2620, 1985.
[65] S. Yalçınkaya, “Isparta-Ağlasun (Burdur) Dolaylarının Jeolojisi,” PhD. Tesis, İstanbul Üniversitesi Fen Bilimleri Ens., 176p., İstanbul, 1989.
[66] A. Koçyiğit, “Ağlasun-Gölcük (Isparta) Bölgesinin Aktif Tektoniği: Neotektonik Rejimin Türü ve Sagalassos Tarihsel Depremlerinin Kaynağı,” *Aktif Tektonik Araştırma Grubu 12. Çalıştayı, 7-8, Ankara, 2008*.
[67] N. A. Uyanık, “Isparta Alkali Volkanitlerinin Radyometrik ve Manyetik Yöntemlerle İncelenmesi,” PhD. Tesis, SDU Fen Bilimleri Enstitüsü, Isparta, 2011.