

To Cite: Bulcar, K. (2025). Investigation of the Thermoluminescence Properties and Kinetic Parameters of Natural Salt Extracted from Kozluk, Batman after Exposure to Beta Radiation. *Journal of the Institute of Science and Technology*, 15(3), 928-945.

Investigation of the Thermoluminescence Properties and Kinetic Parameters of Natural Salt Extracted from Kozluk, Batman after Exposure to Beta Radiation

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Highlights:

- Dose response and reusability were examined for thermoluminescence properties.
- The TL kinetic parameters were calculated using IR, VHR, T_m-T_{stop} , and CGCD methods.
- Kozluk natural salt is a candidate for radiation dosimetry.

Keywords:

- Thermoluminescence
- Kozluk natural salt
- Anomalous heating rate
- Beta irradiation

ABSTRACT:

In the present research, thermoluminescence properties and kinetic parameters of Kozluk natural salt obtained by the evaporation method were investigated. The irradiation of the Kozluk natural salt samples was carried out using a $^{90}\text{Sr}/^{90}\text{Y}$ β source in the Lexyg Smart TL/OSL reader device. This source provides a dose rate of 0.097 Gy per second to the sample. The TL glow curves obtained in the dose interval of 0.1 to 10 Gy show two distinct main peaks around 92 and 205°C. The dose-response relationship of the material exhibited super-linear characteristics in the 0.1–10 Gy range, as indicated by a slope of 1.1921. The reusability of the material was observed by irradiating 10 times under the same conditions, with the standard deviation remaining within the 5% dosimetric limit; this indicates that it provides high accuracy and reliability. The TL kinetic parameters were determined using the initial rise (IR), various heating rates (VHR), T_m-T_{stop} , and computerized glow curve deconvolution (CGCD) methods. It has been predicted that the entire TL glow curve consists of at least nine energy levels according to the CGCD analysis. The Figure of Merit (F.O.M), derived from the CGCD analysis, was 0.61%, demonstrating a good agreement between the experimental and theoretical data.

INTRODUCTION

The salt, known as sodium chloride (NaCl) in chemical science, has been an indispensable part of human life since prehistoric times and has covered a wide area of history and culture. In early times, it was used to enhance the flavor of foods, to preserve them for a long time, and to tan leather. With the development of the chemical industry over time, its usage area has expanded considerably and it has become one of the important inputs of the industry in pulp and paper manufacturing, textile dyes, the process of ice melting, soap production, washing powder and many other fields. Sodium chloride is usually observed as a white crystalline solid; nevertheless, it may also display different colors, such as gray, reddish, or brownish. These color differences arise from impurities elements like Mg, Mn, K, Li, and Cu, which can either be incorporated into the crystal structure or found on the surface (De Galan et al., 1973). The type of impurities may differ based on the geological formation of the sample's origin. Luminescence properties of sodium chloride depend on these impurities, as they introduce localized energy levels within the forbidden energy gap, making NaCl a sensitive TL phosphor. Naturally occurring sodium chloride (NaCl) salt possesses a broad band gap of around 8.5 eV (Poole et al., 1975).

Industrial countries use 50% of their salt consumption in the chemical industry, 30% in highway melting and the remaining in the food industry (Geertman, 2000). In addition, sodium chloride (NaCl) is not only significant in industrial fields but also serves as a potential candidate for radiation dosimetry due to its luminescent properties. A wide range of studies has investigated the dosimetric properties of thermoluminescence (TL) and optically stimulated luminescence (OSL) in both commercially processed household salt and naturally sourced rock salt. NaCl, recognized as a responsive TL phosphor, had its luminescent properties thoroughly reviewed in earlier studies (McKeever, 1985). McKeever extensively examined the defects in these crystals and proposed that the physical basis of NaCl's thermoluminescence is due to the recombination of trapped electrons (F and F aggregate color centers) and interstitial halogen atoms (H centers) formed during irradiation. This TL mechanism indicates that NaCl has a high sensitivity to radiation, making it a suitable candidate for radiation dosimetry. Subsequently, prominent researchers such as Gartia et al. (2004) and Murthy et al. (2006) demonstrated that the luminescent properties of NaCl are well-suited for radiation dosimetry and highlight its potential as a radiation dosimeter material (Gartia et al., 2004; Murthy et al., 2006). Gartia et al. (2004), reported the TL response of iodized salts from ten different Indian brands, namely Ankur, Annapurna (Kissan Annapurna), Captain, Century, Dandi, Shudh, Sungold, Taja, Tata, and Tiptop. It was revealed that the TL glow curve exhibits distinct high-intensity peaks at approximately 145 ± 2 °C and 167 ± 3 °C, along with lower-intensity peaks above 250 °C in all samples. Samples of the Taja brand were irradiated and their TL signals were read five times under the same conditions, showing good reusability with a 4% standard deviation. The sample examined in detail shows promise for dosimetry applications. Murthy et al. (2006), examined the thermoluminescence dosimetric properties of common salts collected from the market in India after a 20 Gy test dose. It was observed that the TL glow curve exhibits three peaks located at approximately 133, 205, and 238 °C. The isolated peak at 238 °C was obtained using the T_{stop} method, and TL glow curves were recorded immediately post-irradiation and at subsequent intervals of 24, 75, 96, 150, 250, and 350 hours. During fading, the humidity level in the laboratory was measured to be approximately between 50-60%. After being kept for approximately 14 days, both the peak maxima of all glow curves and the maximum of the isolated peak decreased by about 50 times. Since humidity effects were observed on the investigated material, it can be considered that, following detailed studies, common salt may serve as an accidental dosimeter for approximately a two-week period. Bailey et al. (2000), also demonstrated that the optically-stimulated luminescence (OSL) of NaCl shows significant

potential for use in dating and dosimetry applications (Bailey et al., 2000). Recently, researchers have thoroughly studied the TL properties and kinetic characterizations of natural NaCl from various regions, revealing the potential use of NaCl in the field of dosimetry in a more comprehensive and detailed manner. Several research works have concentrated on the TL dosimetric properties of common household salt (Ekendahl & Judas, 2011; Polymeris et al., 2011; Spooner et al., 2011; Hunter et al., 2012; Mesterházy, et al., 2012; Rodriguez-Lazcano et al., 2012; Spooner et al., 2012; Christiansson et al., 2014; Yüce & Engin, 2017; Elashmawy, 2018; Singh et al., 2018; Ogundare & Mashaba, 2025), natural rock salt (Ademola, 2017; Ahmad et al., 2022; Anjum et al., 2022; Bulcar et al., 2022; Gonzales-Lorenzo, et al., 2022; Avci et al., 2024; Ullah et al., 2024), and dead sea salt (Azim et al., 2020; Wahib et al., 2020; Khamis & Arafah, 2021). These studies reveal that household salt, natural rock salt, and dead sea salt luminescence characteristic making it a potential a suitable candidate for luminescence dosimetry.

In this study, thermoluminescence properties and kinetic parameters of natural salt extracted from Kozluk, Derince village were analyzed to investigate whether this salt is a potential candidate material in the field of radiation dosimetry.

MATERIALS AND METHODS

Salts, of natural origin, occur in seawater, lakes, saline groundwater, and as rock salt in nature, where they can either crystallize from these sources or be extracted as solid rock. In this study, natural salt obtained from the evaporation of natural spring water collected in enclosed ponds in the village of Derince, located in the Kozluk district, was used. Kozluk district is located in the southeastern part of Türkiye and is a district of Batman province. Figure 1 shows the a) region of Derince Village, Kozluk District, Batman, where the Kozluk natural salt was extracted, b) salt evaporation ponds, c) the obtained salt, and d) its ground form.



Figure 1. The region where Kozluk natural salt was extracted and the stages examined in the study. **a)** Derince Village, Kozluk District, Batman Province, **b)** salt evaporation ponds, **c)** the obtained salt, and **d)** ground salt in an agate mortar

The solid samples were pulverized in an agate mortar to attain uniform particle size and prevent triboluminescence effects. For each measurement, about 5.3 mg of the powdered sample was used. The salt powders prepared for measurement were placed on stainless steel planchet (discs) with a radius of approximately 10 mm, a thickness of 0.5 mm, and a maximum height of 2.5 mm, and after the measurement, they were normalized by mass.

The thermoluminescence (TL) properties of the natural Kozluk salt were investigated using a Lexyg Smart Thermoluminescence/Optically stimulated luminescence (TL/OSL) reader system (Richter et al., 2015), which can be seen in Figure 2. This device is located in the Thermoluminescence (TL)/Optically Stimulated Luminescence (OSL) Dating Laboratory at the Physics Department of Çukurova University.

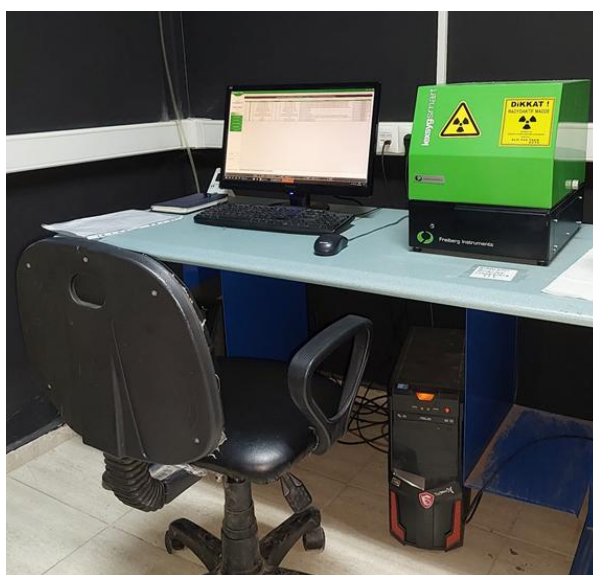


Figure 2. Lexyg Smart TL/OSL reader device

The reader has one photomultiplier tube (PMT) including UV-VIS bi-alkaline cathode with detects photons in the wavelength range of 300-650 nm (Richter et al., 2015). Various filter combinations were used to obtain TL glow curves with the most optimal TL intensity and the least noise. The TL reader has variable band-pass filter combinations, such as BSL, TL- 365nm (U340 + BP365/50 EX), IRSL, TL- 410nm (BG39 + HC414/46), IRSL, TL- 565nm (BG39 + HC575/25), IRSL, and TL wideband blue filter (BG39 + BG25+ KG3), which are placed between the PMT and the aliquots. Irradiation of the Kozluk salt samples was carried out using a $^{90}\text{Sr}/^{90}\text{Y}$ β -source, providing a dose rate 0.097 Gy per second in the system. The beta particles emit a maximum energy of 2.27 MeV. One aliquot was utilized for TL measurements. All TL measurements were systematically documented at a uniform heating rate of 2 °C/s, progressing from room temperature (RT) to 450 °C within a nitrogen (N_2) atmosphere. A background (black body) signal was consistently recorded before and after each TL signal readout. The background signal was subsequently subtracted from the TL signal, thereby yielding the net TL signal. The data of the net TL signal was utilized for analyzing the experiments conducted in this study. The natural salt sample from Kozluk was tested to evaluate various levels of irradiation doses and their corresponding linearity.

Assessing the dose sensitivity of a potential thermoluminescence dosimeter material is a crucial test to determine its suitability for use as a dosimeter. The effective activation energy was computed from the experimental data of the various heating rates (VHR) experiment, first using Hoogenstraaten's method (Hoogenstraaten, 1958), followed by a method developed and separately reported by Booth,

Bohun, and Parfianovitch in 1954 (Bohun, 1954; Booth, 1954; Parfianovitch, 1954). The overlapping TL glow curve was analyzed for individual peaks using the thermal cleaning technique, based on the data from the T_m - T_{stop} experiment (McKeever, 1980). The activation energies were calculated using the repeated Initial Rise Technique (McKeever, 1980) to analyze the data obtained from the T_m - T_{stop} experiment. Finally, Computerized Glow Curve Deconvolution (CGCD) analysis was applied to determine energy levels and kinetic orders for the T_m - T_{stop} experiment.

RESULTS AND DISCUSSION

Determining Optical TL Band-Pass Filter

The precision and dependability of the experimental results are strongly influenced by the efficiency of the measuring apparatus and in conjunction with the thoughtful selection of filter settings applied during measurements. Various optical bandpass filters are crucial due to their impact on the shape and/or intensity of the readout signal. Figure 3 presents the results for the Kozluk natural salt phosphor, which was irradiated with a $^{90}\text{Sr}/^{90}\text{Y}$ beta radiation source at a dose of 5 Gy to determine the optimal filter. The glow curves exhibit no significant shift in peak positions depending on the filter used, while showing notable differences in intensity and shape. Based on these results, the IRSL-TL-565 nm filter was chosen as the optimal optical filter due to its highest TL intensity.

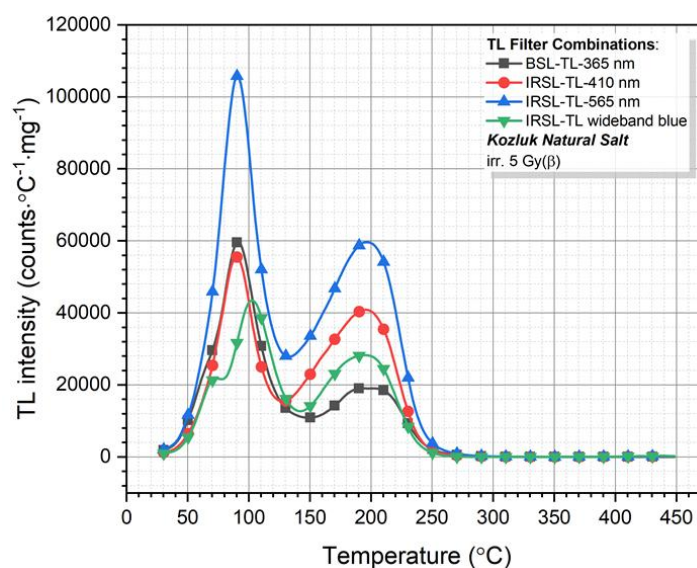


Figure 3. TL glow curves of Kozluk natural salt phosphor measured with band-pass filter combinations

Dose Response And Linearity

In TL dosimetry, the correlation between dose response behavior and the absorbed radiation dose is crucial for determining the material's potential applications (Kitis et al., 2000). Figure 4-a illustrates the TL glow curves of Kozluk natural salt phosphor obtained after exposure to different beta doses, varying from 0.1 to 10 Gy. The maximum TL intensity is recorded at the highest applied dose of 10 Gy. Because of the excessive photon emissions occurring at dose levels exceeding 10 Gy, the PMT shut down. An inset graph is also included in Figure 4-a for better visualization of the maximum peak temperatures.

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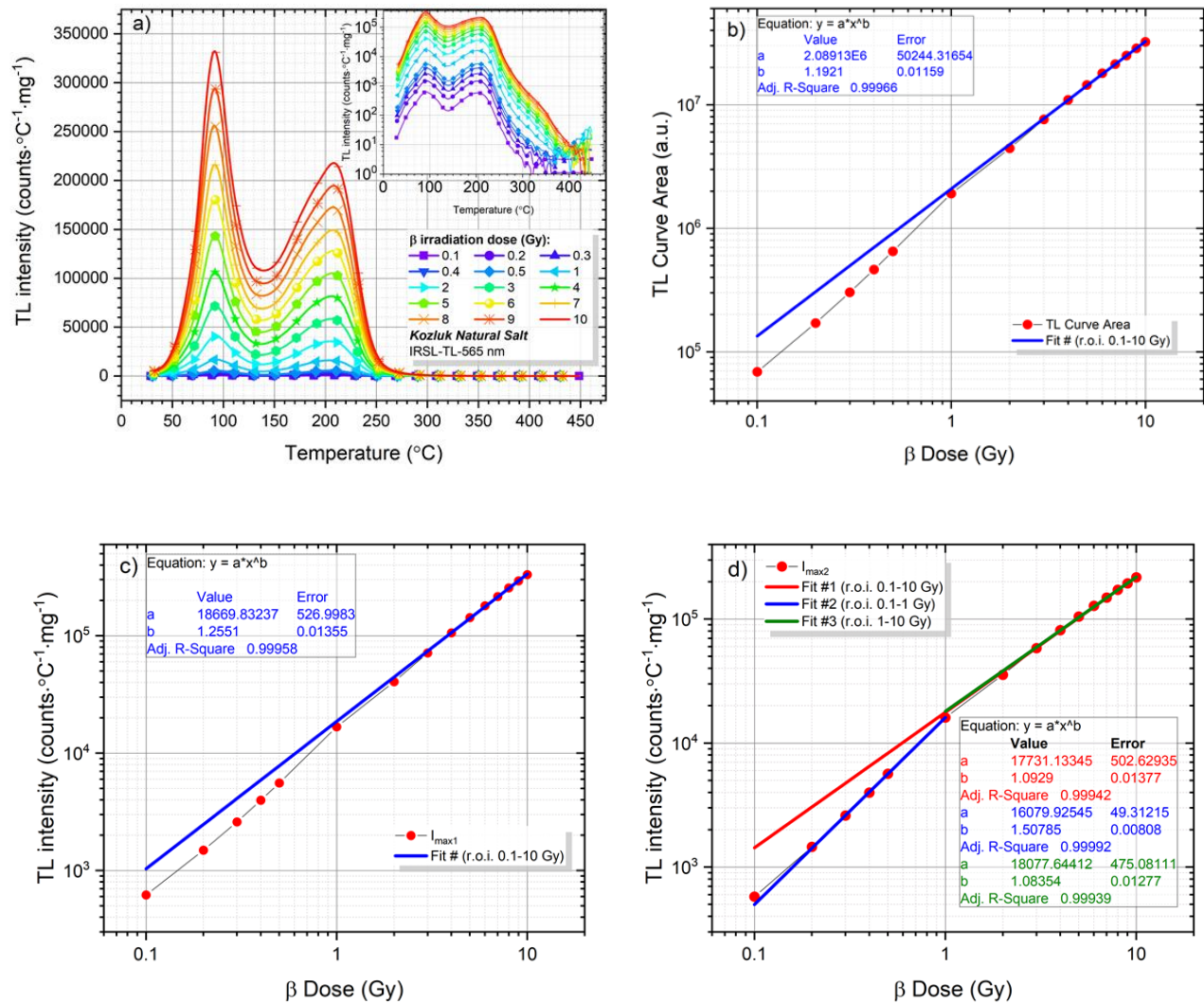


Figure 4. a) TL glow curves of Kozluk natural salt obtained after exposure to doses spanning from 0.1 Gy to 10 Gy. Additionally, an inset graph is included to provide a clearer observation of the variation in the maximum peak temperatures b) A logarithmically scaled plot of dose response curve in terms of total TL glow area c-d) A logarithmically scaled plot of the dose response of the peak intensity for Peak 1 ($I_{\max1}$) and Peak 2 ($I_{\max2}$)

As clearly seen in the figure, the intensity of the TL peaks increases with rising radiation dose. This can be explained by the increase in the number of trapped electrons due to the applied dose, followed by the release of these trapped electrons upon heating, where they recombine with holes at recombination centers, resulting in an increase in the number of emitted photons. In addition, the peaks consist of two main peaks located at approximately 92 (Peak 1) and 205 °C (Peak 2). The empirical findings from the dose-response curve provide initial insights into the kinetic order. According to the well-known TL theory, it is suggested that the peak temperature associated with general order kinetics decreases with increasing doses, while the peak temperature related to first-order kinetics is expected to remain unaffected by dose variations (Pagonis et al., 2006). For Peak 1, no significant shift in peak positions is observed with increasing dose. However, for Peak 2, it has been observed that their positions shift towards the high temperature region with increasing dose. However, considering the possibility that the glow curve consists of complex peaks, these results are not sufficient to determine the kinetic order. The dose-response results indicate that the natural salt mineral exhibits promising characteristics as a radiation dosimeter. In particular, the behavior of Peak 2, due to the delayed release of charge

carriers from deep traps, provides a stable and distinguishable response in this dose range, making it more suitable for measuring higher radiation doses.

In any TL dosimetric application, the linearity characteristics of the material can be evaluated by constructing a logarithmically scaled plot of either TL intensity (or curve/peak area) versus the per irradiation dose, and this plot can be fitted with the $I_m = aD^k$ ($y = ax^k$) equation (Pagonis et al., 2006). Where I_m represents the TL intensity, D is the applied beta dose, k indicates the linearity factor, and a is a proportionality constant. The k value (denoted as b in the graph) provides crucial information regarding the dose-response behavior. According to TL theory, if k is close to 1 ($b \approx 1$), the relationship is linear, if $k < 1$, it is supralinear, and if $k > 1$, it represents a superlinear behavior. Dose response trend is graphed in Figure 4, where (b) the TL glow curve area, (c) the TL intensity $I_{\max 1}$ (Peak 1), and (d) the TL intensity $I_{\max 2}$ (Peak 2) are shown on a log-log scale, each fitted with an allometric function. From curve area trend given in Figure 4-b, considering the entire dose range (0.1–10 Gy), the overall response is distinctly superlinear ($b=1.19$), suggesting that different mechanisms may contribute to the TL signal, leading to a non-linear dose response. It can be seen from TL intensity trend given in Figure 4-c, when considering the entire dose interval of 0.1–10 Gy, the overall response is superlinear ($b = 1.25$). Based on the TL intensity trend shown in Figure 4-d, the region of interest (r.o.i.) for the fitting equation is segmented into three distinct dose intervals. For the dose range of 0.1–10 Gy of β radiation, the trend can be considered nearly linear. For the 0.1–1 Gy interval, the response is superlinear, while for the 1–10 Gy interval, the trend is again nearly linear.

Reusability

One of the other important properties of phosphor materials in terms of dosimetric characteristics is reusability. Reusability indicates how stable and reliable a dosimetry candidate material is in terms of its measurement performance. For this purpose, the reusability property of powdered Kozluk natural salt was investigated by exposing the identical sample to a 1 Gy beta dose. TL signals were measured from RT to 450 °C at a heating rate of 2 °C/s, and the process was repeated consecutively 10 times under the same TL conditions. The TL glow curves measured after 10 cycles are displayed in Figure 5-a. The shape and location of the TL glow curve stay virtually unchanged over the course of 10 cycles. This indicates that the characteristics of the trap and recombination center are stable.

The standard deviations (SD) from the mean value and the first value were calculated using Equation (1) and Equation (2), based on a single measurement, considering the total area beneath the TL glow curve obtained following each cycle and the maximum TL intensity ($I_{\max 2}$) of the main dosimetric peak around 205 °C. Since the energy levels below 150 °C are considered shallow traps that hold electrons for a short duration, the focus is solely on the Peak 2 (~ 205 °C) (Pagonis et al., 2006).

Standard deviation of mean value

$$SD = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2} \quad (1)$$

Standard deviation of first value

$$SD = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - x_1)^2} \quad (2)$$

Here, x represents the average value of the ten reuse distributions, N indicates the overall count of readouts, and i refers to the readout index. The TL glow curve area and intensities were normalized against the first readings (Fig. 5-b and 5-c). The deviations from the mean and the initial values were found to be approximately 1.575% for the change in the glow curve area (both), and around 0.897% and

1.416% for the change in $I_{\max 2}$, respectively. As a result, the standard deviations obtained for the variations in both $I_{\max 2}$ and glow curve area after normalization are, as observed, below the 5% tolerance limit (Furetta, 2003). This demonstrates a good reusability level for the Kozluk natural salt sample.

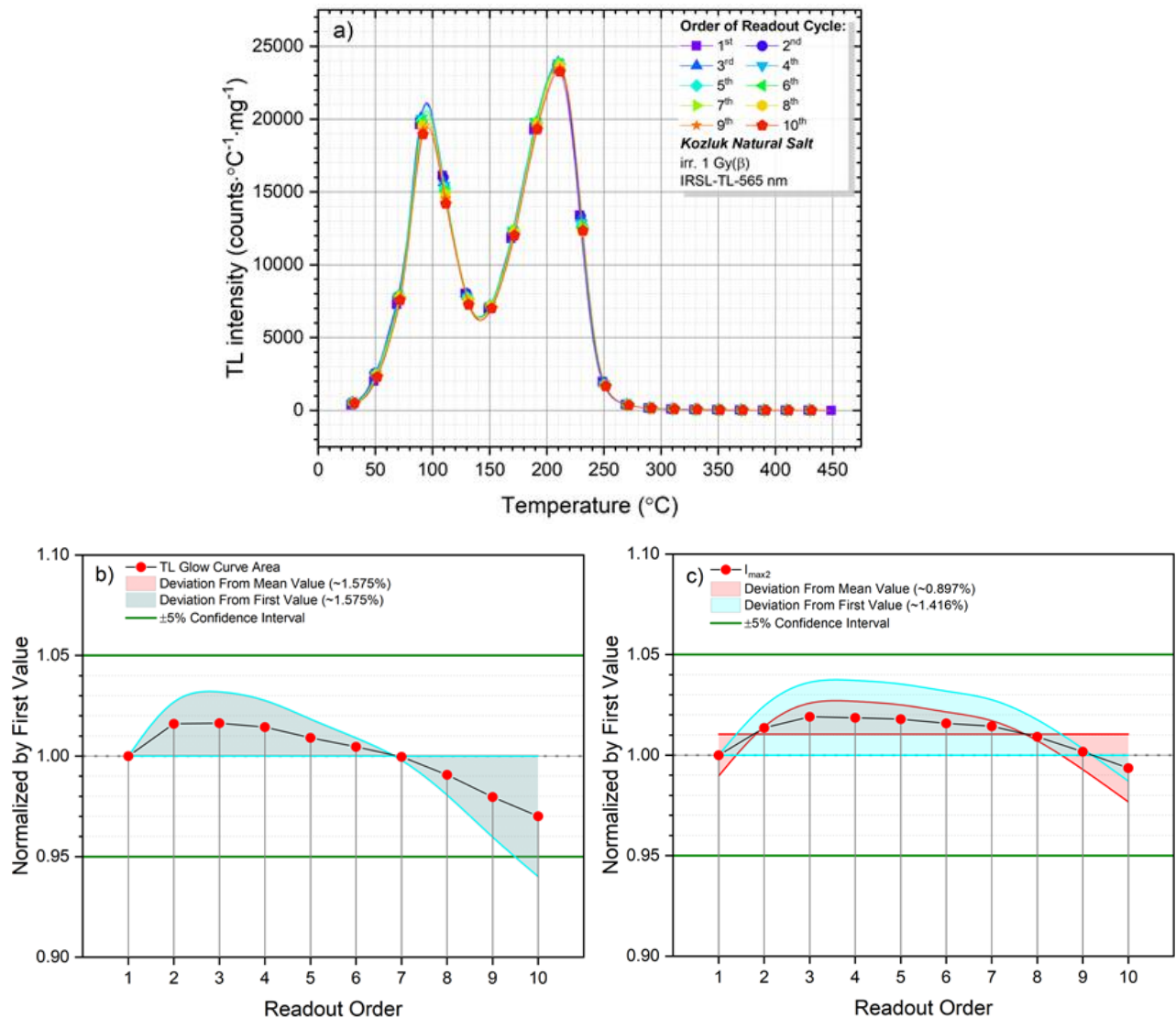


Figure 5. a) Repeatability plots obtained from Kozluk natural salt after a 1 Gy dose under the same conditions, with 10 repeated cycles b) Deviations from the mean and first value of the total area of the normalized glow curve relative to the first readout after ten cycles. c) Deviations from the mean and first value of the normalized maximum TL intensity ($I_{\max 2}$) relative to the first readout after ten cycles

Various Heating Rates

The heating rate (HR) is one of the most important methods influencing the shape and position of TL glow curves. Under a fixed dose of 1 Gy, TL glow curves obtained from RT to 450 °C with heating rates varying between 0.2 to 10 are shown in Figure 6-a. Each TL experiment was conducted with the same parameters, while the heating rates were altered during the measurement of the TL glow curves.

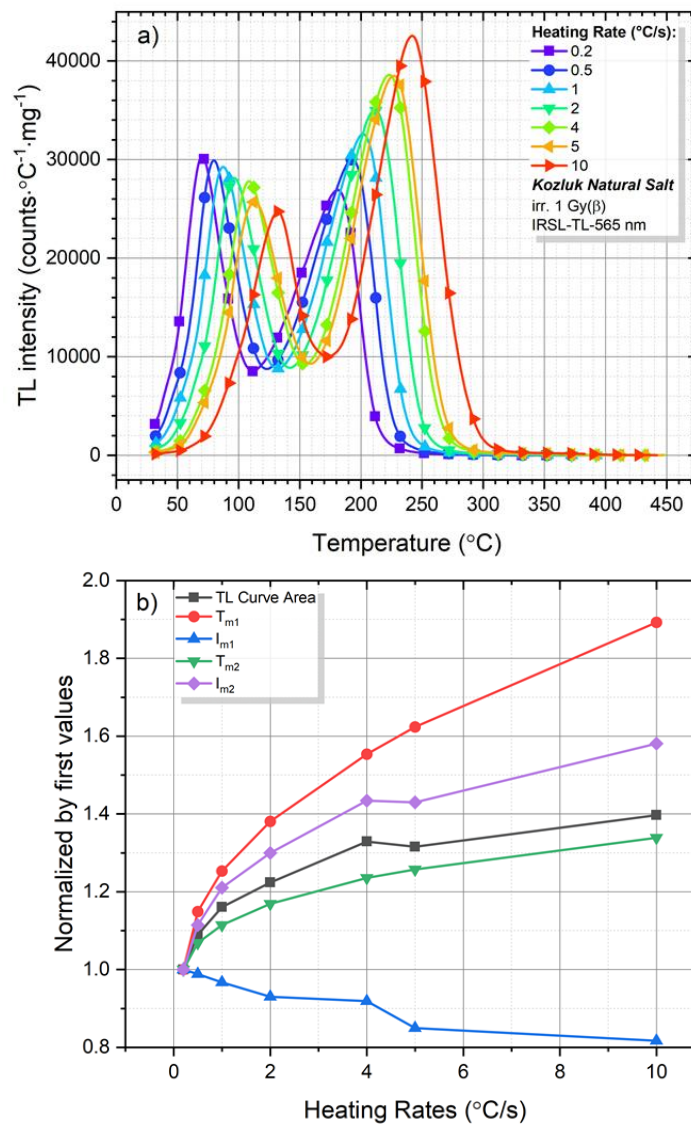


Figure 6. a) TL glow curves of Kozluk natural salt obtained under the same conditions with a 1 Gy dose at varying heating rates **b)** Heating rate trend for TL glow curve area, TL peak temperature (T_{m1} and T_{m2}), and TL peak intensity (I_{m1} and I_{m2}) versus the heating rate

According to thermoluminescence theory, as the heating rate increases, the peak temperatures shift towards higher temperature regions, the peak maximum intensity decreases, and the glow peak area becomes broader (Chen and Winer, 1970; Bos, 2001). As seen in Figure 6 (70-130 °C), the Peak 1 is consistent with this theory. In contrast to the TL theory, Peak 2 exhibits an unexpected increase in TL intensity as the heating rate rises. This phenomenon is termed the anomalous heating rate effect. It is accounted for through localized transitions (Mandowski, 2004; Mandowski and Bos, 2011; Pagonis et al., 2013) or the inverse thermal quenching effect (Chen and Pagonis, 2017).

As seen in the Figure 6-b, as the heating rate increases, the area under the glow curve shows an increase. This indicates that more energy is being released as the heating rate rises. It has been observed that as the heating rate increases, the intensity of I_{m1} decreases, while the intensity of I_{m2} increases. As the heating rate (HR) rises, the T_{m1} and T_{m2} values shift towards higher temperatures. This shift can be attributed to the phenomenon of temperature lag (Kitis and Tuyn, 1998). Temperature lag is based on the temperature difference between the thermocouple (heater strip) and the sample material while the TL readings are taken. To reduce the temperature lag, samples with the smallest possible mass should

be used, and heating rates should be kept low. However, when trap parameters are calculated with different heating rates (VHR), the thermal lag effect will be inevitable due to the high heating rates. Therefore, temperature lag correction is necessary to obtain more accurate results. The Hoogenstraaten method (Hoogenstraaten, 1958) is a widely used technique for determining the kinetic parameters of traps, such as activation energy (E) and frequency factor (s), by utilizing changes in the peak temperature (T_m) values of the TL glow curve at different heating rates. The Hoogenstraaten method was originally developed for TL systems exhibiting first-order kinetics, but it can also be applied to general-order glow peaks. For this investigation, the sample was heated at heating rates of 0.2-10 °C/s. The peak temperatures of the glow curves were measured for every heating rate. In Equation 3, the activation energies of the peaks are computed from the slope of the line based on the distribution of $\ln\left(\frac{T_m^2}{\beta}\right)$ versus $\left(\frac{1}{kT_m}\right)$, using both corrected and uncorrected (T_m) values, while the frequency factor of trapped electrons is calculated from the y-intercept, which corresponds to $\ln\left(\frac{E}{ks}\right)$.

$$\ln\left(\frac{T_m^2}{\beta}\right) = (E)\left(\frac{1}{kT_m}\right) + \ln\left(\frac{E}{ks}\right) \quad (3)$$

Here, (T_m) is the maximum peak temperature; β is the linear heating rate; k is the Boltzmann constant; s is the frequency factor, and E is the activation energy. As seen in Figures 7-a and 7-b, the relationship between $\ln(T_m^2/\beta)$ and $1/kT_m$ has been fitted to a linear equation using the Hoogenstraaten method, where the slope of the fitted line corresponds to the activation energy of the trapping levels. The other method used for calculating activation energy was proposed in the same year by three different researchers, Booth, Bohun, and Parfianovitch, with their contributions (Bohun, 1954; Booth, 1954; Parfianovitch, 1954). As given in Equation 4, in this method, two distinct heating rates and their corresponding peak temperatures were used.

$$E = k \frac{T_{m1}T_{m2}}{T_{m1}-T_{m2}} \ln\left[\frac{\beta_1\left(\frac{T_{m2}}{T_{m1}}\right)^2}{\beta_2}\right] \quad (4)$$

Here, k is the Boltzmann constant, and T_{m1} and T_{m2} denote the peak temperatures for heating rates β_1 and β_2 , in that order. Initially, β_1 (0.2 °C/s) was chosen as the reference heating rate and paired with the other heating rates. This procedure was repeated for each heating rate to pair all values and calculate their averages.

Table 1. Trap parameters obtained using the Booth-Bohun-Parfianovitch and Hoogenstraaten methods

β (°C/s)	<i>Maximum 1</i>		<i>Maximum 2</i>		
	<i>UnCorrected</i>	<i>Corrected</i>	<i>UnCorrected</i>	<i>Corrected</i>	
0.5	0.86	0.86	1.27	1.27	Booth-Bohun-Parfianovitch Method
1	0.91	0.88	1.37	1.29	
2	0.88	0.90	1.35	1.32	
4	0.81	0.92	1.28	1.34	
5	0.78	0.93	1.27	1.36	
10	0.69	0.95	1.20	1.38	
<i>Average E</i>	0.82±0.08	0.91±0.03	1.29±0.06	1.32±0.04	
<i>E (eV)</i> (0.2-10 °C/s)	0.70±0.05	0.94±0.02	1.22±0.03	1.38±0.02	Hoogenstraaten's Method
<i>s (s⁻¹)</i>	3.57x10 ⁸	1.34x10 ¹²	5.66x10 ¹¹	3.19x10 ¹³	

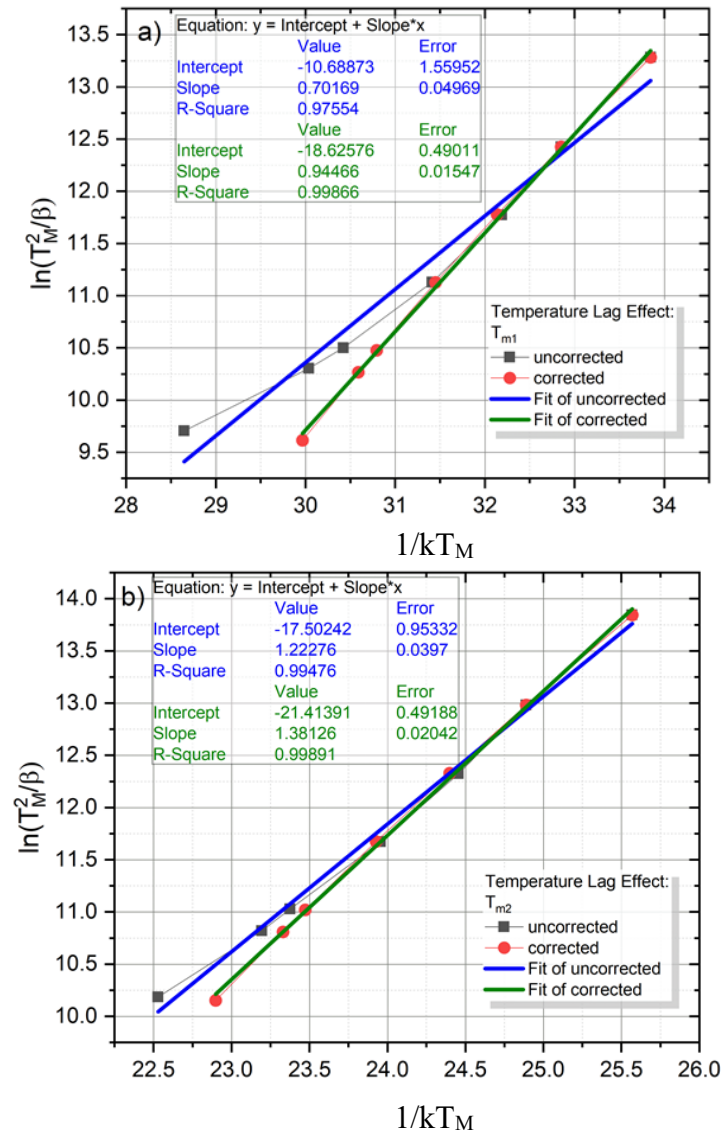


Figure 7. Changes in $\ln(T_m^2/\beta)$ with respect to $1/kT_m$ for (a) Peak I and (b) Peak II with temperature lag effect corrected and uncorrected T_m values at heating rates between 0.2 and 10 °C/s

T_m-T_{stop}

The T_m-T_{stop} experiment is commonly used for identifying the quantity peaks and the possible locations of those peaks in any TL glow curve that has multiple emission peaks close to each other (McKeever, 1980). In the T_m-T_{stop} experiment, to analyze the entire TL glow curve, ~5.3 mg of Kozluk natural salt was irradiated with a 1 Gy β dose. Then, a thermal cleaning step (preheating) was applied. For this purpose this experiment was firstly applied up to 50 °C (T_{stop}) the lower limit of the first glow peak, where some traps are fully or partially emptied at a heating rate of 2 °C/s. Then the sample was rapidly cooled back to RT. Immediately afterward, it was heated again using the same rate to obtain the remaining portion of the glow curve, and the maximum temperature (T_m) of the glow peak was recorded. The cycle of irradiation, preheating, and TL reading was conducted repeatedly under the same conditions for different T_{stop} values within the span of 50-395 °C, with intervals of 5 °C. A graph of T_m against T_{stop} is plotted based on the completed cycle, revealing a pattern similar to a 'staircase' or a 'continuous line', which indicates the presence of multiple traps within the Kozluk natural salt (Figure 8). This experiment allows for the assessment of the number of overlapping peaks, their estimated locations, and the trap levels related to every peak (Chen and Kirsh, 1981; McKeever, 1980; McKeever, 1985). After the completion of the T_m-T_{stop} test, the initial rise (IR) method was employed to determine the activation

energies from the obtained glow curves (Garlick and Gibson, 1948). In this method, the range between 5% and 15% of the highest intensity of the first glow peak on the low-temperature side of the TL glow curve was selected. In Figure 9, as shown in the example range, Arrhenius plots were created by applying the IR method to the glow curves measured at every T_{stop} temperature. The activation energies were calculated from the slopes of these Arrhenius plots.

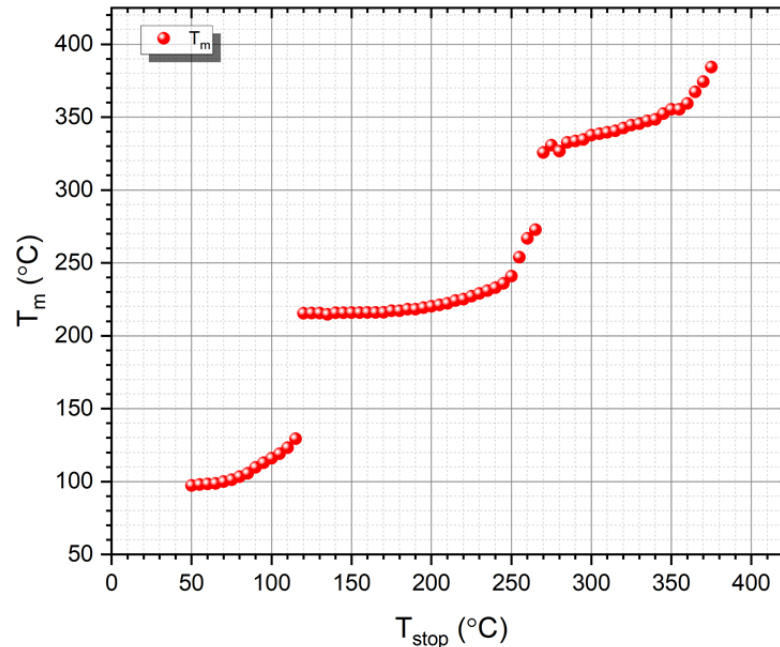


Figure 8. The graph of T_m against T_{stop} displays different regions in the form of staircase and continuous line

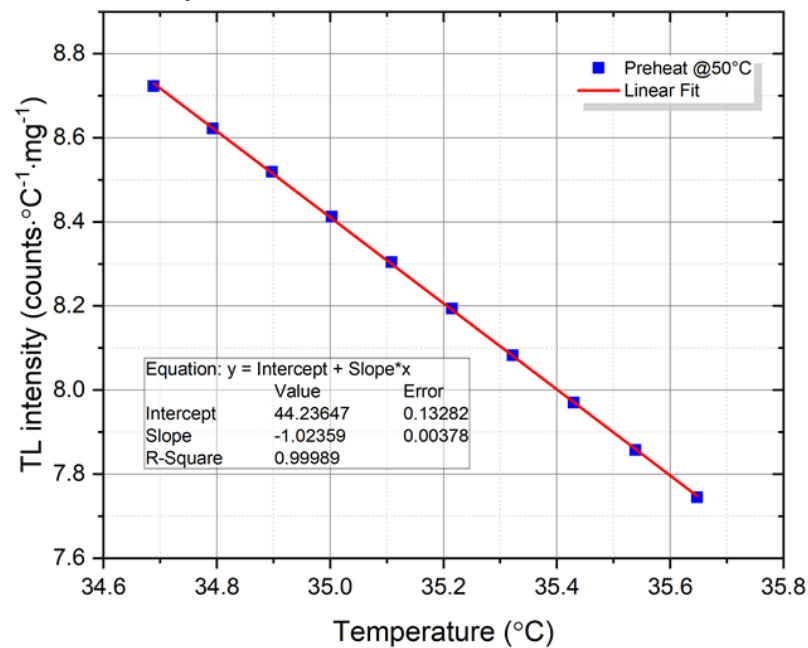


Figure 9. Arrhenius plot recorded for $T_{\text{stop}} = 50$

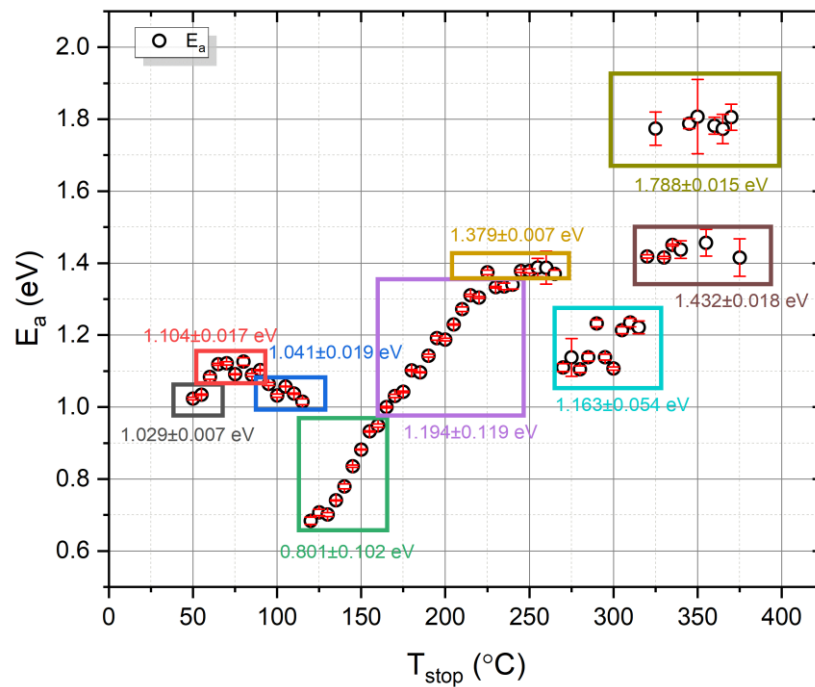


Figure 10. The graph of activation energies of T_{stop} against the IR approach

As shown in Figure 10, there are nine distinct trap levels at approximately 1.02, 1.10, 1.04, 0.80, 1.19, 1.37, 1.16, 1.43, and 1.78 eV. Based on these results, it can be stated that the glow curve of Kozluk natural salt is complex, as only two distinct maxima are observed when examining the entire curve.

Computerized Glow Curve Deconvolution (CGCD)

In experimental TL glow curves, it is quite rare for materials to have only one glow peak (corresponding to a single energy level). Most materials exhibit glow curves consisting of two or more glow peaks. Furthermore, these glow peaks often feature complex structures, closely spaced and overlapping. Each glow peak corresponds to particular trapping regions with distinct kinetic properties, such as E , s , and b . CGCD method can be effectively used to separate these overlapping TL glow peaks and determine the trap parameters of each peak. The application of the CGCD method is determined based on the experimental data derived from the T_m - T_{stop} and IR methods. It has been determined that the TL glow curve consists of nine tightly closely positioned and overlapping glow peaks through the T_m - T_{stop} and IR methods. Using the CGCD method, the number, position, and compatibility of the potential TL peaks and their trap parameters have been examined in detail. For this purpose, in this investigation, the open-access *tgcd* R package, written in the R statistical computing language, was used to analyze TL glow curves (Peng et al., 2016). This open-access package enables TL peak simulations by previously introducing equations referred to as first, second, and general order to the R programming language. Using the trap parameters obtained with the T_m - T_{stop} and IR methods, the general order kinetic model (Gomez-Ros & Kitis, 2002) was chosen to create a theoretical TL glow curve that fits the experimental glow curve, and this process was carried out using Equation 5.

$$I(T) = I_m \exp\left(\frac{E}{kT_m^2}(T - T_m)\right) \left[\frac{1}{b} + \frac{b-1}{b} \exp\left(\frac{E}{kT_m^2}(T - T_m)\right) \right]^{-\frac{b}{b-1}} \quad (5)$$

Here, I_m is the maximum intensity of the peak; s is the frequency factor; k is the Boltzmann constant; E is the activation energy, and b is the kinetic order ($1 \leq b \leq 2$). Figure 11 shows the

experimental and theoretical glow curves of Kozluk natural salt exposed to a 1 Gy β dose at a heating rate of 2 °C/s, along with the deconvoluted TL glow curve and its nine individual peaks. The Figure of Merit (F.O.M) value can be used to determine how well the experimental and theoretical glow curves match each other (Balian and Eddy, 1977; Misra and Eddy, 1979). This parameter was computed by applying Equation 6.

$$F.O.M = 100 \times \left(\frac{\sum_i^n N_i^{Experimental} - N_i^{fit}}{\sum_i^n N_i^{fit}} \right) \quad (6)$$

Here, $N_i^{Experimental}$ represents the experimental data, while N_i^{fit} denotes the corresponding theoretical (fit) data. The parameter F.O.M between 0% and 2.5% demonstrates a good fit, between 2.5% and 3% suggests compatibility, and F.O.M values greater than 3.5% indicate an incompatible fit (Balian and Eddy, 1977; Misra and Eddy, 1979). The process has been repeated by altering the trap parameters and using a trial and error method to achieve the best fit between the theoretical and experimental curves. In this study, the F.O.M value was found to be 0.61%, which is considered a good fit as it lies between 0% and 2.5%.

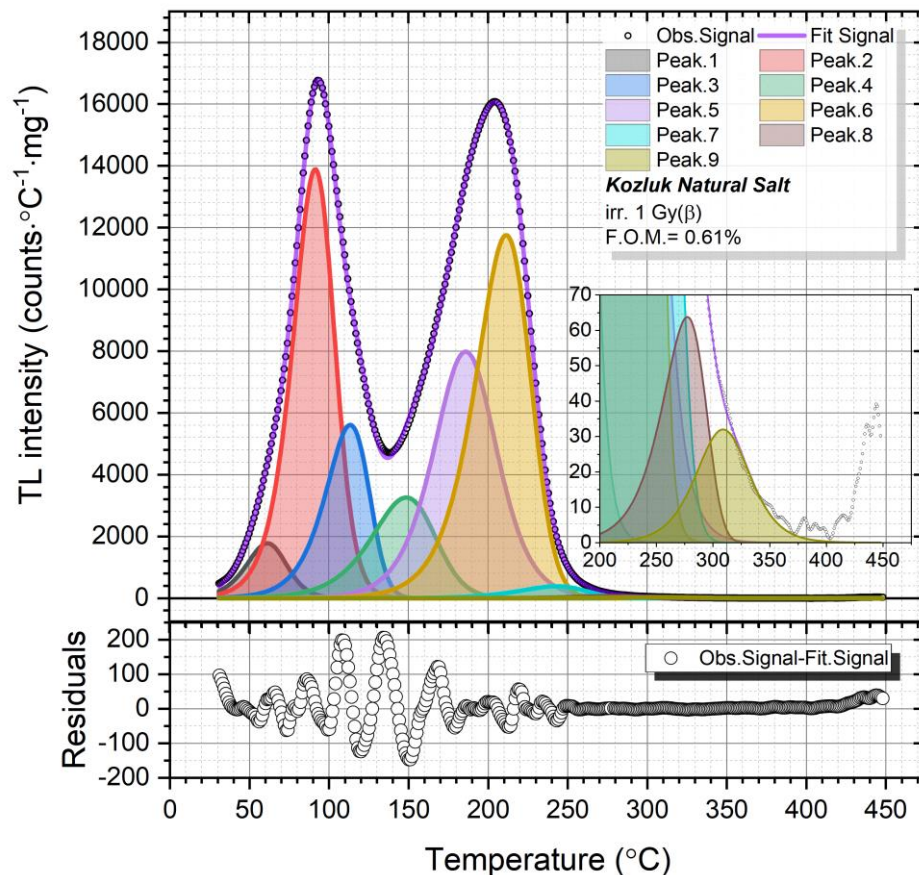


Figure 11. The TL glow curve of Kozluk natural salt, after 1 Gy β irradiation, has been deconvoluted using the CGCD method, resulting in at least nine glow peaks. An inset graph is also included for a better view of peak 8 and peak 9

For each peak, the activation energies E , symmetry factors μ , frequency factors s , kinetic orders b , and maximum peak temperatures T_m obtained by the CGCD method are presented in Table 2. Both experimental and theoretical results show consistency with the results obtained by the T_m - T_{stop} and IR methods regarding the probable activation energy levels and peak temperatures.

Table 2. Kinetic parameters of peaks obtained by the CGCD method for Kozluk natural salt

•	E_a (eV)	b	T_m (°C)	T_{m1} (°C)	T_{m2} (°C)	μ	s (1/s)
1 st Peak	1.03	1.68	61	45.8114	75.8677	0.4603	6.62×10^{14}
2 nd Peak	1.12	1.52	91	74.8634	105.9648	0.4480	5.66×10^{14}
3 rd Peak	1.06	1.21	113	94.8791	127.6625	0.4158	1.05×10^{13}
4 th Peak	0.94	1.41	148	122.6277	170.2577	0.4456	2.01×10^{10}
5 th Peak	1.33	1.90	185	162.3018	209.1231	0.4932	5.49×10^{13}
6 th Peak	1.38	1.29	211	188.5316	229.5703	0.4517	2.99×10^{13}
7 th Peak	1.23	1.18	243	214.6369	264.3236	0.4285	1.07×10^{11}
8 th Peak	1.45	1.09	277	250.3955	296.4121	0.4211	2.08×10^{12}
9 th Peak	1.80	1.94	308	280.5075	336.7275	0.4926	4.52×10^{14}

CONCLUSION

The thermoluminescence properties and kinetic parameters of the natural salt collected from Derince village in Kozluk district, Batman province, have been examined, and the potential of this salt as a candidate for radiation dosimetry has been discussed. The glow curve of the Kozluk natural salt, studied under beta irradiation, exhibited two prominent glow peaks around 92 and 205 °C, with an additional glow peak observed around 278 °C. The Kozluk natural salt showed a standard deviation of 3% after being irradiated and read ten times under the same conditions, compared to the first reading, with this value being below the 5% dosimetry acceptance threshold. The activation energy values obtained using the Hoogenstraaten and Booth-Bohun-Parfianovitch methods showed close agreement with each other, further strengthening the reliability of these approaches. At least nine different energy levels have been identified using the T_m - T_{stop} experiment. The temperature and activation energy values required for CGCD analysis were obtained using the T_m - T_{stop} and repeated initial rise methods, predicting that the entire TL glow curve is composed of at least nine energy levels. The trap depths obtained through CGCD analysis were determined to be 1.03, 1.12, 1.06, 0.94, 1.33, 1.38, 1.23, 1.45, and 1.80 eV, and these values demonstrate satisfactory agreement with the experimental data.

This agreement highlights the reliability and consistency of both analysis methods. This study contributes to the understanding of the TL properties and kinetic parameters of the salt, while also highlighting the need for further research into its potential use in radiation dosimetry.

ACKNOWLEDGEMENTS

The author would like to express great appreciation to Prof. Dr. Mustafa TOPAKSU from the Department of Physics at the Faculty of Arts and Sciences, Çukurova University, for his valuable support regarding all laboratory facilities.

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