УДК 551.782.79 : 551.791(477) : 551.763-535 : 528.8:528.7:528.4:528.06
DOI: https://doi.org/10.24028/gj.v47i5.334806

Application of the thermoluminescence method and remotesensing techniques for studying quaternary sediments

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Received 7 June 2025

Quaternary sediments can be investigated by different physical, geophysical, and geochemical methods and modern remote-sensing techniques. The interpretation of remote-sensing imagery plays an efficient role in the study of geological objects and various geological processes. It is conditioned by the various technogenic factors and ea the composition and sequence of deposits of the area. The additional information from satellite images makes it possible to identify types of sediments. Combining satellite data with geological, geophysical, and geochemical approaches allows to analyze various types of anthropogenic deposits and to determine their main characteristics. It is proposed to apply remote sensing methods and the thermoluminescence method to anthropogenic sediments and determine their age. Thermoluminescence is applied to solve various geochronological tasks and to dateq Quaternary deposits. The main concepts of the thermoluminescence method have been considered. Our proposed approach for the dating of anthropogenic deposits is based on the Smakula-Dexter formula. The Smakula-Dexter formula calculates the concentration of radiation centers. A relation has been established between the age of the sample and the concentration of radiation centers. By solving a differential equation, a mathematical formula has been derived for the radiation coefficient, which is a component of the Smakula-Dexter formula. The higher the concentration of radiation centern, the older the sample is. Remote sensing methods and thermoluminescence can be combined to determine the age of rocks.

Key words: quaternary sediments, thermoluminescence method, remote sensing methods, Smakula-Dexter formula.

Introduction. Anthropogenic deposits can be identified and studied by different geophysical, geochemical, and physical approaches (thermoluminescence (TL), optically stimulated luminescence and other methods). Let us note that nowadays sediments can be studied by modern remote sensing (RS) methods and physical techniques, as well [Li et al., 2017; Wintle, Adamiec, 2017].

The interpretation of RS imagery plays an important role in the remote study of Quaternary deposits, because it provides valuable additionat information. By analyzing the relief of the Earth's surface, it is possible to identify and interpret various types of Quaternary sediments.

Alluvial deposits typically have striped and fan-shaped landforms. Aeolian formations, shaped by wind-driven processes, can exhibit a reticulate patteon.

For example, we can consider an application of digital RS data to the Quaternary de-

Citation: Prylypko, S.K., & Alpert, S.I. (2025). Application of the thermoluminescence method and remotesensing techniques for studying quaternary sediments. *Geofizychnyi Zhurnal*, *47*(5), 106—111. https://doi.org/10.24028/gj.v47i5.334806.

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posits in central Sweden (Fig. 1, 2). Modern techniques and approaches were applied to map Quaternary deposits associated with the soil surface in the area of investigation from the Landsat TM image. Six groups of quaternary deposits were distinguished: bog, fen, fluvial deposits, postglacial sand, postglacial silt, and glacial clay [Sedlák, 2002].

Fig. 1. The central part of Sweden from the Landsat TM image.

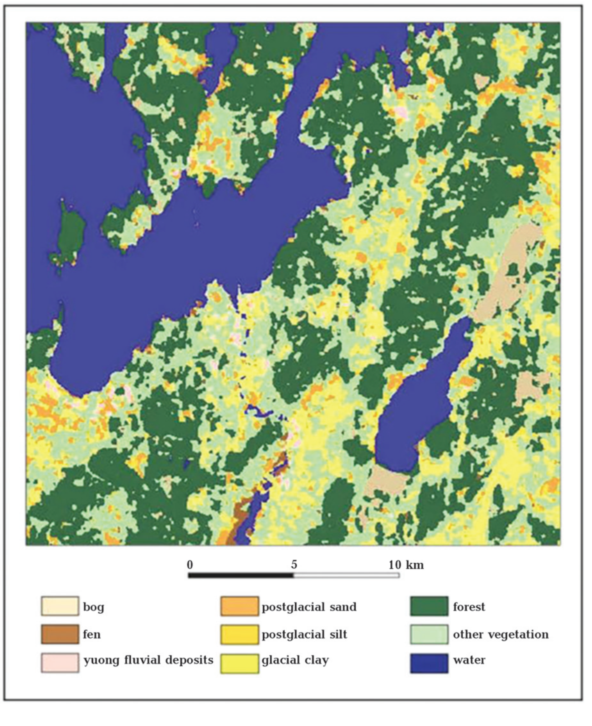

Fig. 2. The resultant map of Quaternary deposits in the central part of Sweden.

It should be noted that combining RS with traditional ground and laboratory methods increased the accuracy and objectivity of geological studies, such as: identification, decoding, and analysis of various types of sediments, establishing the distribution boundaries of the genetic types of sediments andstudying various geological processes. The combination of laboratory methods and modern technologies makes it possible to generalize and systematize information obtained about the geological object from different points of view.

The TL method covers the range of dating sediments from several thousand to hundred thousand years [Ekendahl, Judas, 2017; Kitis et al., 2019].

TL is based on the following formula: the age of the rock is equal to the ratio of the received dose of radioactive radiation by the timer mineral to the exposure dose power of the natural radiation field of the soil at the point of sample selection. As a timer, fractions containing quartz crystal:, such as clay, loam, or loess, are usually applied [Kitis, Pagonis, 2018].

The object of this study is the age of geological objects. The subject of the study is physical and mathematical methods and RS techniques.

This work aims to develop a new mathematical approach to dating Quaternary sediments. Our approach is based on a deep understanding of the physical process and applies a mathematical model of the radiation centers' accumulation in sediments.

We propose a new mathematical approach to determine the absolute age of Quaternary rocks based on a physical and mathematical model of the radiation centers' accumulation processes in quartz crystals under natural conditions and formation of the TL process kinetics, applying the physic-mathematical Smakula-Dexter formula [Mineli et al., 2021; Yukihara, 2023].

Main principles. Let us note that radiation centers are luminescence centers. Radiation centers are defects in the crystal lattice. These defects caus, tht mineral dosimeter to emit photons of light when heateg.

There are deviations from the ideal structure in the arrangement of atoms in crystals. These deviations are referred to asd lattice defects [Durcan et al., 2015].

Radiation centers are caused by lattice defects.

The mechanism of such defects' formation is explained by the internal gamma-electron photoeffect, as a result of which the electron receives energy (about 1 meV) sufficient to affect a crystal lattice and cause light emission [Prylypko, Alpert, 2023].

These radiation defecte accumulat in the sedimentss regardless of the concentration of impuritie' and defectn, leading to a stable TL peak.

Electron traps are atomic energy levels that can capturg electrons. Due to the additional thermal energy, these electron traps give electrons back as a stream of photons of light.

Before burial, rocks are bleached under the influence of external factors (solar radiation, temperature and others) during the move, as a result of which the traps are emptied. Main geochronological investigations appeared in the 1960s. These works were carried out by such scientists as: Z. Zeller, N. Grogler, F. Heiterman, H. Stauffer (1960), M. Aitken, M. Tait (1964), C.B. Lushchik (1955—1956), and E. Zeller (1956).

Researchers have identified several energy bands for electrons in crystals of various minerals, includin: the valence band, the conduction band, and the forbidden zone. Every electron fills its own atomic energy level. There are atomic energy levels without electrons; these are called forbidden.

Energy levels with electrons are called allowed.

In a solid, energy levels are transformed into the allowed and forbidden energy bands due to the interaction of atoms with each other.

The width of these bands varies within a few eV. Electrons can move almost freely from one energy level to another within the same band [Kitis et al., 2025].

The allowed energy band filled with valence electrons is called the valence band. It should be noted that a valence electron is an electron located in the outermost electron shell (energy level) of an atom. Valence electrons are photons of the light source.

The allowed band that is free from electrons is called the conduction band. Allowed zones in the crystal are separated by the forbidded zones. During the heating, electrons emit photons of light and enter a forbidden zone. Electron transitions occur when an electron moves from one energy level to anothee. This can happen if an electron absorbs energy such as a photonr it can also happe, when an electron emits a photon and loses energy. During the heating, we stimulate a flow of thermal infrared radiation photons that our sample emits. Next, we derive the formula for the linear emissivity coefficient.

Applying the Smakula-Dexter formula to TL dating. Consider a uniform parallel flow of thermal infrared radiatio, thah propagates from a heater (oven) and affects the sample by heating it. Then this sample emits energy, such as photons of light, which is recorded by a photoelectron amplifier.

Let us consider the following concepts: I — intensity of the thermal infrared radiation beam; dx — area of the cuvette for the sample; dI — energy flux radiated by the sample; k — linear emissivity coefficient.

Consider the following equation, which expresses the relations between the energy flux radiated by the sample and the intensity of heat provided by the heater:

$$-dI = kIdx \,, \tag{1}$$

where the coefficient of proportionality k is called the linear emissivity coefficient.

Then, we define determine the radiation-intensity of the heater by solving a first-order partial differential equation.

$$\frac{dI}{I} = -kdx \,. \tag{2}$$

Let us note that k is a constant. Equation (2) contains only the first derivative of the unknown function, which has two variables: I and x. It is a separable differential equation.

One should separate variables by moving all I terms to one side of the equation, and all x terms to the other side. The left side is divided by I.

Both sides of the differential equation should be integrated separately:

$$\int \frac{dI}{I} = \int (-kdx) .$$

Thus, $\ln|I| + \ln|C| = -kx$, where $\ln|C|$ is the constant of integration.

Let us take exponents of both sides: $e^{(\ln|I|+\ln|C|)} = e^{-kx}$.

Using the properties of the natural logarithms, we can make the following transformations: $e^{\ln|IC|} = e^{-kx}$.

From which,

$$IC = e^{-kx} . \quad (3)$$

The intensity of radiation coming from the heater is $I = 1/C\, e^{-kx}$.

Let us note that $1/C$ is just a constant, so we replace it with $\tilde{C}$: $1/C = \tilde{C}$.

Then the intensity of the thermal infrared radiation beam from the heater is defined as follows:

$$I = \tilde{C} e^{-kx} . \quad (4)$$

Then we define the emissivity coefficient k:

$$e^{-kx} = \tilde{C} . \quad (5)$$

We take the logarithms of the left and right sides:

$$\ln I/\tilde{C} = \ln e^{-kx}$$

$$\ln I/\tilde{C} = -kx$$

$$-\ln I/\tilde{C} = kx .$$

Applying the logarithmic property which states that $\ln 1/a = -\ln a$, we get:

$$\ln \tilde{C}/I = kx .$$

$$k = 1/x \ln \tilde{C}/I . \quad (6)$$

Then we convert the natural logarithm to the decimal logarithm, applying the logarithmic identity:

$$\ln x = \frac{\lg x}{\lg e} \approx \frac{\lg x}{0.43429} \approx 2.30259 \lg x . \quad (7)$$

Then, applying the expression (7), we can rewrite formula (6) as:

$$k = \frac{1}{x} \ln \frac{\tilde{C}}{I} \approx \frac{2,3}{x} \lg \frac{\tilde{C}}{I} \quad (8)$$

— emissivity coefficient.

The concentration of radiation centers is determined by the Smakula-Dexter formula:

$$n = 0.87 \cdot 10^{17} \frac{\alpha_0}{\left(\alpha_0^2 + 2\right)^2} \cdot \frac{\Delta E}{f} \cdot k_0 , \quad (9)$$

where n — concentration of radiation centers in cm^{-3}; α_0 — the emissivity coefficient of the sample, which is located near the maximum emission of the sample; f — heater energy delivered to the sample; ΔE — energy emitted by the sample.

It should be noted that the higher the value of ΔE, the older the sample.

k_0 — the emissivity coefficient at the maximum radiation intensity of the sample. The radiation energy of the light flux (concentration of radiation centers) is directly proportional to the age of the sample [Wintle, Huntley, 1982; Singhvi, Mejdahl, 1985].

Conclusions. Nowadays, quaternary sediments can be ndentified and investigated by known laboratory geological methods and modern RS methods and techniques. Identification of Quaternary sediments is based on the application of satellite images. RS data and the TL method give important information about Quaternary sediments. The photon of the satellite image allows us to research the genesis and composition of the Quaternary sediments.

The combination of RS and known geological, geochemical, geophysical, and geochronological approaches allows us to investigate various types of Quaternary sediments and systematize information about the geological processes.

It was proposed to apply the combination of remote sensing and thermoluminescence methods to investigate the genesis and composition of Quaternary sediments and determine their age.

The main principles of the thermoluminescence method were considered. It was noted that during the burial, energy accumulation occurs under the influence of the decay of radioactive elements. During heating, the accumulated energy of the sample is released, allowing us to determine the age of the studied sediments. The intensity height of the TL graph peaks depends on the time of accumulation and the energy accumulated by the sample during the formation and burial. Depending on the age and structure of the sample (loess, loam, clay, fossil soil), we obtain spectra of different intensities and configurations of peak shapes on the TL graphs. Each TL graph corresponds to a certain age of the sediments; it also has individual characteristics (width, height, intensity, and area). A solution of the first-order differential equation with separated variables was considered. This differential equation describes the relations between the energy flux radiated by the sample and the heat intensity. The formula for the radiation coefficient, which is a component of the Smakula-Dexter formula, was derived. The Smakula-Dexter formula can be applied to calculate the concentration of the radiation centern. In this paper, a direcy proportional relation between the concentration of radiation centers and the age of the sample was also established.

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Застосування термолюмінесцентного методу та методик дистанційного зондування Землі з метою вивчення четвертинних відкладів

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Четвертинні відклади досліджуються різноманітними фізичними, геологічними, геофізичними, геохімічними методами та за допомогою сучасних методик дистанційного зондування Землі. Дешифрування космічних знімків відіграє важливу роль у вивченні геологічних об'єктів і в розумінні різних геологічних процесів. На інтерпретацію супутникових даних впливають різні техногенні фактори досліджуваної території, склад відкладів та їх послідовність. Супутникові знімки надають додаткову інформацію про досліджувані об'єкти. Використовуючи супутникові дані, можна ідентифікувати типи відкладів. Застосування комбінації супутникових даних з геологічними, геофізичними, геохімічними підходами дає змогу аналізувати різні типи антропогенових відкладів і визначати їх основні характеристики. Для дослідження антропогенових відкладів і визначення їхнього віку пропонується застосувати комбінацію методів дистанційного зондування Землі та термолюмінесцентного методу. Останній застосовується для розв'язку різноманітних геологічних і геохронологічних задач та для визначення віку антропогенових відкладів. Авторами розглянуто основні концепції термолюмінесцентного методу. Запропонований підхід до розрахунку віку антропогенових відкладів базується на формулі Смакули—Декстера, яка використовується для обчислення концентрації центрів збудження в атомарній решітці. Встановлено залежність між віком зразка та концентрацією центрів випромінювання. Шляхом розв'язання диференціального рівняння отримано математичну формулу для коефіцієнта випромінювання, який є складовою формули Смакули—Декстера. Чим вище значення концентрації центрів випромінювання, тим більший вік зразка. Поєднання методів дистанційного зондування Землі та термолюмінесцентного методу може застосовуватися для визначення віку гірських порід.

Ключові слова: четвертинні відклади, термолюмінесцентний метод, методи дистанційного зондування Землі, формула Смакули—Декстера.