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# A study of Quaternary deposits in the coastal zone of a continental shelf based on thermoluminescence and remote sensing

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Currently, systematic and comprehensive research is required in order to determine the age of geological deposits. This approach is based on a combination of ground, laboratory, and remote sensing techniques. This increases the accuracy, efficiency and objectivity of the results obtained. New remote sensing techniques and laboratory methods can be used to analyse and systematise information about the genesis, age and characteristics of sediments. Paleomagnetic, dosimetric, lithological, biostratigraphic, and remote sensing methods are used for geochronological tasks, determining the age of geological objects and the stratigraphic division of sediments. This combination of geological methods and remote sensing approaches is also used to study changes in river basins and the open sea. In this study, the remote sensing approach is the primary stage in research of Quaternary deposits in the coastal zone of the continental shelf. The second stage involves the usage of the thermoluminescence method to determine the age of the deposits. Sentinel-2 images were used to visualise the Quaternary deposits. It was determined that these deposits include marine and middle-lower Anthropocene alluvial and estuarine-marine deposits. We compiled and analysed two maps of Quaternary sand deposits between the mouth of the Dniester River and the Black Sea. The advantages of multispectral images are their wide coverage area and high monitoring frequency. After using the remote sensing approaches to determine the age of the deposits, a thermoluminescence method was applied, taking into account the rate of radiation defect formation and the accumulated energy of the sample under study. The thermoluminescence method is based on solving a first-order differential equation to derive a formula for the age parameter. The method is an effective technique for dating sediments and studying the correlation of various Quaternary sediments.

**Key words:** Quaternary deposits, Black Sea shelf, remote sensing, multispectral data, thermoluminescence method.

**Introduction.** Geochronology is the science of dating geological sediments. It studies the qualitative and quantitative changes of sediments that occur in the environment. Geochronological data determine the age of sediments. Usually, geochronological data is obtained through such methods as radiometric dating (applying radioactive isotopes of sediments), paleomagnetism dating, and thermoluminescence. Dating sediments re-

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quires a systematic approach to investigate fossil soils, loess, and other types of geological deposits [Sedlák, 2002]. The main goal of sampling for analysis of deep horizons is to investigate the sequence and regularities of geological processes. Geological processes that took place in the past affect the present. They are influenced by various long-lasting environmental factors. Currently, application of the complex of well-known laboratory, ground and remote sensing methods allows to increase the objectivity and accuracy of geological investigations (dating geological sediments and construction). These modern approaches and techniques can be used to decode and analyse geological objects. Combining laboratory methods with modern remote sensing technologies enable the study and systematisation of information on the age, genesis, and the main characteristics of geological objects from different areas [Alpert, 2020].

These methods include geological methods such as biostratigraphy, lithology, and isotope geochemistry, as well as physicochemical, dosimetric, paleomagnetic, and remote sensing methods [Gozhik et al., 2014; Maxwell, Haynes, 2001; Sedlák, 2002; Lehmkuhl et al., 2018; Zhipeng et al., 2023]. The main tasks of geological research include stratigraphic division of sediments, geochronology, palaeo-reconstruction of environmental conditions and sediment accumulation, and establishing correlations and resolving issues regarding the genesis of deposits that differ in external characteristics. Other tasks include identifying clear age boundaries, determining the volume of certain stratigraphic units, and searching for minerals.

To study changes in river basins and the open sea, researchers typically employ a mix of direct geological methods [Gozhik et al., 2014] and remote sensing techniques [Melnychenko, Solovey, 2024; Iemelianov et al., 2025].

A significant aspect of remote research is identifying and interpreting decipherable features as various types of Quaternary deposits. The genesis and composition of these deposits can be studied using phototones.

Remote sensing methods are widely used in various scientific investigations in geology and geochronology because surveying large territories using field methods is costly and time-consuming. Remote sensing applications in geology are mainly used in semiarid or arid regions. A ground surface without vegetation is one of the main conditions for geological research. Currently, some methods are being developed to apply remote sensing data to vegetation-covered areas in order to compile geological maps

In this study, the remote sensing approach is the first stage of investigating Quaternary sediments, while the laboratory thermoluminescence method is the second one.

Thermoluminescence dating (TL dating) is a laboratory method that can also be used for the absolute dating of geological objects. It can be used to analyse volcanic materials, aeolian, marine, fluvial, and coastal sediments [Gozhik et al., 2014]

Determining the age of Neopleistocene sediments using the TL method is one of the most pressing tasks of research. TL-dating determines the age parameter, T, the value of which is directly proportional to the time taken for the explored rocks to form. This is why we examine the main concepts of thermoluminescence dating of rocks and provide a formula for calculating the age parameter [Shelkoplias, 1971; Kitis et al., 2025].

A modern remote sensing approach is used to identify and decode Neopleistocene sediments. These methods are based on the study of the relations between the elements of the external landscape and geological objects. In this study, the standard remote sensing method is used to detect Quaternary deposits related to the soil surface. We consider the application of digital, remotely sensed data for mapping Quaternary deposits on the Black Sea shelf. Note that a soil reflectance spectrum is the superimposition of spectra from the soil's mineral components. All of a soil's optical properties are related to its mineral composition. Like minerals, soils have an increasing reflectance from visible to short infrared wavelengths. Soil absorption is related to soil moisture. This affects the optical properties of soils. The content of organic matter and the roughness of soils, related to their texture, also affect their optical properties. Coarse soil particles create a rough surface where light is trapped.

In this study, standard remote sensing methods were used to map the sediment on the Black Sea shelf from a Sentinel-2 image. Quaternary deposits are grouped according to factors such as the environment in which they were formed, their genesis, and particle size distribution. It should be emphasised that the satellite-classified map represents the soil surface. This soil surface is associated with Quaternary deposits.

Identifying Quaternary sand deposits using satellite images involves several stages: selecting satellite images, processing them, and analysing the results. For the study of anthropogenic deposits, which are recorded in open access (e.g., in coastal areas and areas with sand deposits), researchers mainly use multispectral data from Sentinel-2 or Landsat [Sedlák, 2002; Lehmkuhl et al., 2018; Zhipeng et al., 2023] in combination with RGB (false colour): NIR, red, green or SWIR-2, SWIR-1, red.

According to [Sedlák, 2002], combining the NIR, red and green bands provides the most information about soil characteristics. That was confirmed in field experiments involving the analysis of approximately 150 soil samples. Therefore, using a combination of NIR, red, and green channels will ensure the highest accuracy in identifying quartz sands in the coastal zone of the studied territory.

At the next stage of the study, multispectral data from the Sentinel-2 mission will be used to visualise Quaternary deposits on the shelf. This will be done using a combination of NIR, Red, and Green channels. It has been used as an example of the coastal zone — the spit between the Dniester Estuary and the Black Sea (Fig. 1). According to geological data [Gozhik et al., 2014], Quaternary deposits have been recorded here, including marine and estuarine-marine (ancient Euxine) deposits ($Q_I$), as well as middle-lower Anthropocene alluvial deposits ($Q_{II–I}$).

The advantages of Sentinel-2 multispectral data include high monitoring frequency, a wide coverage area of 29  km, coverage of water bodies, coastal areas, and land, and the archiving and availability of stored images. Multispectral data from the Sentinel-2 mission is available on the Copernicus portal. Sentinel-2 data comprises twelve spectral thematic channels, which are presented in

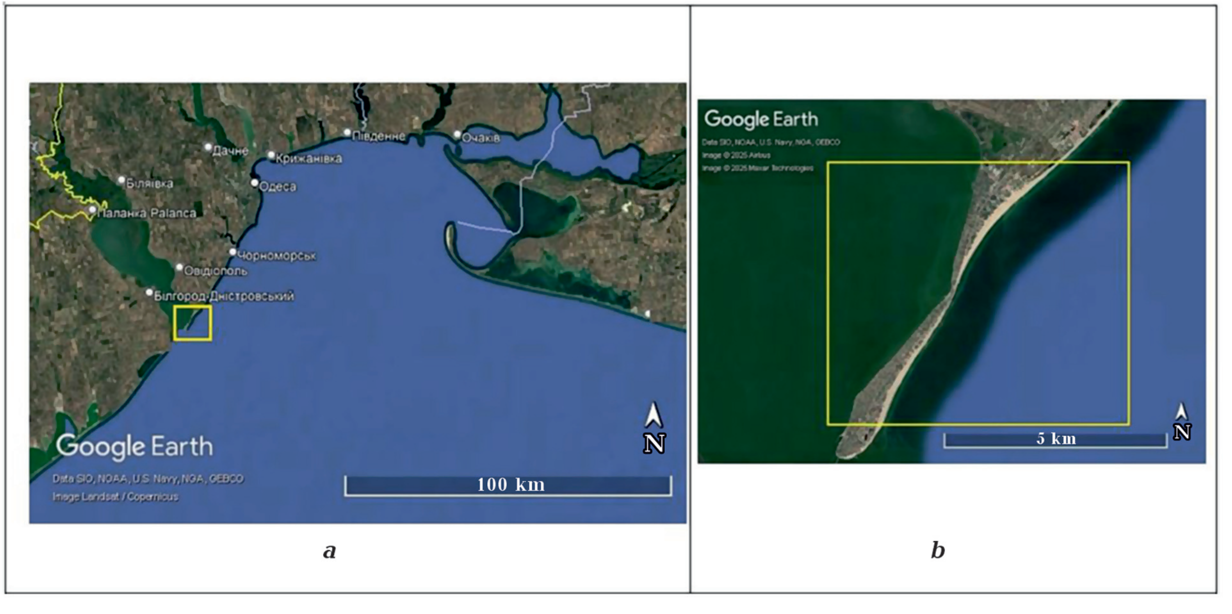


Fig. 1. Map illustrating the location of the study area: *a* — Overview map, *b* — Local map.

**Characteristics of the Sentinel-2 satellite's imaging channels**

| Band | Name | Central wave-length, nm | Resolution, m | Main use |
|---|---|---|---|---|
| B1 | Coastal aerosol | 443 | 60 | Coastal and atmospheric correction |
| B2 | Blue | 490 | 10 | Water, vegetation, soil, bathymetry |
| B3 | Green | 560 | 10 | Vegetation, water, soil discrimination |
| B4 | Red | 665 | 10 | Vegetation monitoring, urban areas |
| B5 | Red edge 1 | 705 | 20 | Chlorophyll content, vegetation health |
| B6 | Red edge 2 | 740 | 20 | Vegetation health monitoring |
| B7 | Red edge 3 | 783 | 20 | Vegetation structure |
| B8 | Near Infrared (NIR) | 842 | 10 | Biomass, vigour, vegetation analysis |
| B8A | Narrow NIR | 865 | 20 | Chlorophyll content, vegetation |
| B9 | Water vapor | 945 | 60 | Atmospheric correction, water vapor |
| B10 | SWIR — Cirrus | 1375 | 60 | Cirrus cloud detection |
| B11 | SWIR 1 | 1610 | 20 | Soil, snow, burnt area mapping |
| B12 | SWIR 2 | 2190 | 20 | Burnt areas, soil moisture |

Table. In this study, the following channels were used: NIR, Red, and Green (highlighted in yellow).

The research methodology can be divided into the following stages:

1. Selecting satellite imagery and the monitoring period. Application of cloud filters, identification of periods of water transparency and absence of snow cover, etc.
2. Downloading the images from the data portal (https://browser.dataspace.copernicus.eu/).
3. Processing the data using the open GIS platform SNAP (https://step.esa.int/main/download/snap-download/).
4. Georeferencing.
5. Building a raster image from composite channels (NIR, red, and green), classification, post-classification, and vectorization (if necessary).
6. Identification and mapping of objects of interest.
7. Analysis of the obtained data and description of the results.

The study area is located between the Black Sea and the Dniester Estuary. It consists of a 100- to 200-meter-wide sandy spit of Quaternary deposits. The area has almost no vegetation or buildings, so it is clearly visible on satellite images. This is a necessary condition for using multispectral data.

Using the described methodology and the composite of NIR, red, and green channels, a true colour map of Quaternary deposits was constructed (Fig. 2) as well as a false colour map (Fig. 3).

The result maps show sandy Quaternary deposits in the coastal zone, which are clearly highlighted in white. These deposits are located on a spit between the sea and the Dniester Estuary and extend up to 200 metres wide.

**Thermoluminescence method.** The main geochronometric techniques nowadays are based on the analysis of the different sediments' radioactivity and the processes associated with it. Most modern sediment dating methods are based on the phenomenon of radioactivity. These methods differ not only in their dating principles, but also in their sample selection techniques.

The thermoluminescence method is one of the most efficient methods for studying and determining the age of Quaternary rocks. This scientific research helps us to identify the laws and sequences of geological processes. The TL effect is shown in the form of thermal light curves. Then we analyse the

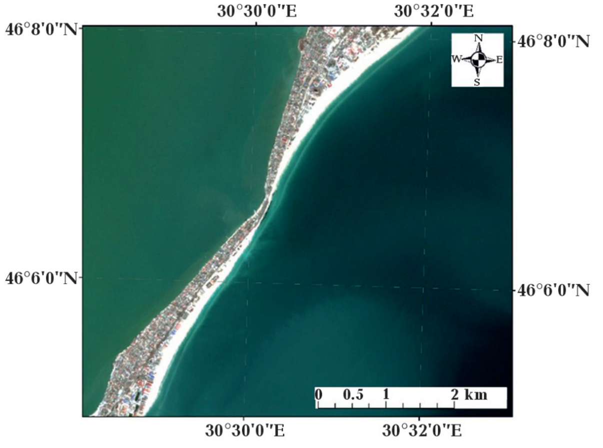


Fig. 2. Map of coastal Quaternary deposits in true colour based on Sentinel-2 data (survey date: 02.04.2020).

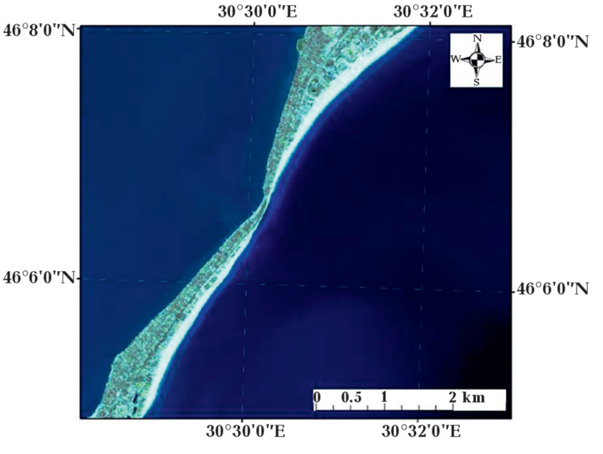


Fig. 3. Map of coastal Quaternary deposits based on Sentinel-2 data (date of imaging: 02.04.2020) in RGB false colour (NIR, red and green). White indicates Quaternary deposits (sand), dark blue — the sea surface, grey-blue — urbanisation.

peak intensity of the thermal light curve and the area it encloses. Older rocks have higher values of age indices and a higher intensity peak on the thermal light curve. Younger rocks have lower values of age indices. Applying the thermoluminescence method, we should use minerals that can act as a paleodosimeter.

It is important to note that the paleodosimeter accumulates age-related information for a long period of time. The preferred mineral timer is quartz because it is well studied, chemically stable and strong, and occurs in almost all sediments. All covering deposits in their natural position are constantly influenced by environmental factors. Aeolian sediments are zeroed because they are influenced by solar exposure during transfer before burial.

Quartz is one of the best-known minerals. Quartz crystals are characterised by structural defects that indicate sufficient depth of the trap to ensure the metastable state of electrons is maintained for a long period of time. The TL method has a wide age dating range. This method usually uses Quaternary formations as mineral timers. If the traps have been emptied and are starting to fill up again, this process can be used as a dosimeter timer. Therefore, the dating limits depend on the corresponding mineral dosimeter. Dosimetric research demands that the mineral dosimeter must be set to zero. This means bringing it to a state where all its traps are maximally emptied. It should be whitened primarily because only a whitened mineral dosimeter can be used as a dosimeter. It is important to emphasise that the accumulation of electrons in the traps acts as a timer [Mineli et al., 2021; Yukihara, 2023]. Once the age has been determined, new opportunities arise for comparing and correlating fairly remote territories and sections. The most important criteria for correlations are the age of the rocks, their mineral composition, and their physical properties.

The TL method of calculating the«absolute» and relative ages of subaerial sediments is based on crystals which store the energy of the various radioactive elements' decay and emitting it when heated. During the heating process, the stored energy in the crystalline lattice is emitted in the form of light photons. This luminescence is detected by our specialised devices. The TL method depends on the time of burial.

It should be determined that geological and geophysical processes fixed in the rocks of the sections are identical to analogous processes in other regions if these processes have been affected by the same external factors of the Quaternary period. The TL method is the best suited to determine the age of deposits that have been zeroed by the impact of solar radiation during transportation and deposition formation, redeposition. The filling of electron traps corresponds to a process of dynamic equilibrium [Mineli et al., 2021; Yukihara, 2023].

**The formula output for calculation of the age parameter.** For computation of the Neopleistocene sediments age we can use the age parameter *T*. The age parameter *T* is represented with the formula: *T*=*D*/*P*, where *P* is annual dose, *T* — time, *D* — the dose that has been accumulated by the sample. Alpha, beta, and gamma emitting during the entire burial period mold structural defects with invariable velocity ($V_{\alpha,\beta,\gamma}$) in quartz.

Let us emphasize that the velocity of the formation of radiation defects is computed as:

$$V_{\alpha,\beta,\gamma} = \beta E\,, \tag{1}$$

where β — the sensitivity of the dose of the rock, *E* — the capacity of the expositional dose of gamma emitting. The speed of annihilation is proportional to the concentration of localised electrons in quartz at the selected moment of time period:

$$V_A = kn\,, \tag{2}$$

where *k* is the constant of the annihilation speed of localized electrons. *k* is a coefficient of proportionality.

At saturation the formation speed of radiation defects is equal to the speed of their annihilation:

$$V_{\alpha,\beta,\gamma} = V_A\,. \tag{3}$$

Based on equations (1)-(3) we get such equation (4):

$$\beta E = kn\,. \tag{4}$$

Usually, the concentration of localised electrons is designated as *N* at the saturation:

$$\beta E = kN\,. \tag{5}$$

From equation (5) we derive the formula for the coefficient of proportionality. Let us note that *k* is constant of the annihilation speed of the localised electrons:

$$k = \frac{\beta E}{N}\,. \tag{6}$$

The variation speed of the localised electrons concentration should be equal to the first derivative from concentration of localised electrons:

$$\frac{dn}{dt} = V_{\alpha,\beta,\gamma} - V_A = \beta E - \frac{\beta E}{N} n\,. \tag{7}$$

In the next step we should construct the first-order partial differential equation:

$$\frac{dn}{\beta E - \frac{\beta E}{N} n} = dT\,. \tag{8}$$

A partial differential equation is a such mathematical equation that involves an unknown function of two or more independent variables and their partial derivatives with respect to those variables.

The first-order partial differential equation has only the first derivative of the unknown function which has *m* variables. In our differential equation (8) we have two variables: *n* and *T*. Then let us solve this first-order partial differential equation.

Then we derive the following formula:

$$T = \int \frac{dn}{\beta E - \frac{\beta E}{N} n} = \left| \begin{matrix} \beta E - \frac{\beta E}{N} n = z \\ dn = \frac{N}{\beta E} dz \end{matrix} \right| = \int \frac{N}{\beta E} \cdot \frac{1}{z} dz = \frac{N}{\beta E} \ln \left| \beta E - \frac{\beta E}{N} n \right|\,. \tag{9}$$

Then we should apply accumulated concentration value of localised electrons — $n_0$ and residual concentration of electrons after whitening — $n_{\min}$:

$$T = \frac{N}{\beta E}\left[\ln\left(\beta E - \beta E \frac{n_{\min}}{N}\right) - \ln\left(\beta E - \beta E \frac{n_0}{N}\right)\right] = \frac{N}{\beta E} \ln \frac{1 - n_{\min}/N}{1 - n_0/N}\,. \tag{10}$$

So, we have derived the equation (10) for age determination of Quaternary deposits.

**Conclusions.** Nowadays, a combination of laboratory methods and modern remote sensing technologies enables the investigation and analysis of the characteristics, properties and age of geological objects from different perspectives. To study changes in open seas and river basins, researchers typically use a combination of direct geological approaches and remote sensing methods. Modern remote sensing techniques and laboratory approaches can be used to identify, analyse, and interpret different types of Quaternary deposits.

The first step is to apply a remote sensing approach to identify and decode Quaternary deposits. Multispectral data from the Sentinel-2 mission was used to visualise Quaternary deposits on the shelf. The coastal zone (the spit between the Dniester-Bug estuary and the Black Sea) has been studied. A combination of NIR, red and green spectral bands has been used. The results have shown that Quaternary deposits include estuarine-marine and marine deposits, as well as middle-lower Anthropocene alluvial deposits. Then, true- and false-colour maps of Quaternary deposits were constructed. It should be emphasised that these two resulting maps describe sandy Quaternary deposits in the coastal zone, which are highlighted in white. Next, the laboratory thermoluminescence method was applied to determine the age of the sediments after a remote sensing approach usage.

The thermoluminescence method for determining the age of sediments has been examined in detail. It was determined that the velocity of annihilation, the velocity of formation of radiation defects and the accumulated energy of the sample were applied to determine the age. This TL approach is based on solving a first-order partial differential equation. A formula for the age parameter has also been derived. It has been determined that the TL method is an effective way of dating sediments, as it can accurately show which sediments in a section are older and which ones are younger.

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# Вивчення четвертинних відкладів у прибережній зоні шельфу за даними термолюмінесцентного методу та дистанційного зондування Землі

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Для визначення віку геологічних відкладень необхідне систематичне і комплексне дослідження. Цей підхід базується на поєднанні наземних, лабораторних та дистанційних методів. Це підвищує точність, ефективність та об'єктивність отриманих результатів. Нові методи дистанційного зондування та лабораторні методи можуть бути використані для аналізу та систематизації інформації про генезис, вік та характеристики відкладів. Палеомагнітні, дозиметричні, літологічні, біостратиграфічні та методи дистанційного зондування використовуються для геохронологічних завдань, визначення віку геологічних об'єктів та стратиграфічного поділу відкладів. Таке поєднання геологічних методів та підходів дистанційного зондування також використовується для вивчення змін у річкових басейнах та відкритому морі. У цьому дослідженні дистанційне зондування є первинним етапом вивчення четвертинних відкладів у прибережній зоні континентального шельфу. Другий етап передбачає використання термолюмінесцентного методу для визначення віку відкладів. Для візуалізації четвертинних відкладів були використані знімки Sentinel-2. Було визначено, що ці відклади включають морські, середньо-нижні антропоценові алювіальні та естуарно-морські. Було складено та проаналізовано дві карти з четвертинними піщаними відкладами між гирлом Дністра та Чорним морем. Перевагами мультиспектральних знімків є їх широка зона покриття та висока частота моніторингу. Після застосування підходів дистанційного зондування для визначення віку відкладів було задіяно термолюмінесцентний метод, який враховує швидкість утворення радіаційних дефектів та використовує накопичену енергію досліджуваного зразка. Метод термолюмінесценції базується на вирішенні диференціального рівняння першого порядку та виведенні формули для параметра віку. Застосований метод є ефективною технікою для датування відкладів та дослідження кореляції різних четвертинних відкладів.

**Ключові слова:** четвертинні відклади, шельф Чорного моря (Північне Причорномор'я), методи дистанційного зондування Землі, мультиспектральні дані, термолюмінесцентний метод, обробка даних дистанційного зондування Землі.