

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)

**NEWS OF THE NATIONAL ACADEMY  
OF SCIENCES OF THE REPUBLIC  
OF KAZAKHSTAN, SERIES OF  
GEOLOGY AND TECHNICAL SCIENCES**

**№2**

**2026**

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)



**N E W S**  
**OF THE NATIONAL ACADEMY OF SCIENCES**  
**OF THE REPUBLIC OF KAZAKHSTAN,**  
**SERIES OF GEOLOGY AND TECHNICAL**  
**SCIENCES**

**2 (476)**  
**MARCH – APRIL 2026**

**THE JOURNAL WAS FOUNDED IN 1940**

**PUBLISHED 6 TIMES A YEAR**

ALMATY, 2026

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*The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.*

*The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).*

*Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).*

*Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.*

*«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.*

*Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.*

*ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.*

*Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.*

*Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.*

*Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).*

*Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).*

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**News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.**

**ISSN 2518-170X (Online),**

**ISSN 2224-5278 (Print)**

Owner: «Central Asian Academic Research Center» LLP (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025  
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*  
Periodicity: 6 times a year.

<http://www.geology-technical.kz/index.php/en/>

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**News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.**

**ISSN 2518-170X (Online),**

**ISSN 2224-5278 (Print)**

Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).

Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік. Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

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**News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.**

**ISSN 2518-170X (Online),**

**ISSN 2224-5278 (Print)**

Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

<http://www.geolog-technical.kz/index.php/en/>

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC  
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES  
ISSN 2224-5278  
Volume 2.  
Number 476 (2026), 203–222

<https://doi.org/10.32014/2026.2518-170X.624>

UDC: 551: 549.08

IRSTI: 38.29.03: 38.35

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**RADIOLOGICAL PROPERTIES AND STRATIGRAPHIC  
SIGNIFICANCE OF GLAUCONITE-BEARING FORMATIONS:  
IMPLICATIONS FOR PALEOENVIRONMENTS AND GEOCHEMICAL  
ZONATION**

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**Abstract.** *Relevance.* Glauconite-bearing sedimentary formations are increasingly seen as valuable multi-purpose resources for construction, agriculture, and environmental technologies. However, their natural radioactivity and geochemical diversity across different geological settings remain poorly understood. *Objective.* To investigate the current state of glauconites and provide a comprehensive assessment of the radiological safety of these rocks, taking into account their maturity, chemical composition and regional geological factors. *Methods.* In this work, glauconite samples from five different geological regions

were collected and analyzed using mineralogical, granulometric, geochemical, and spectrometric methods. Representative glauconite samples were collected from five geologically distinct regions. Major oxide composition ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ) was determined to characterize chemical variability and maturity. Natural radionuclide activity concentrations were measured, followed by the calculation of radiological hazard indices (radium equivalent activity and external hazard index) per international standards. *Results and conclusions.* Results show notable regional chemical differences, with  $\text{K}_2\text{O}$  content varying from approximately 4.1% to 8.3 wt.%, reflecting varying glauconite maturity and authigenic transformation. Higher potassium levels correspond to increased  $^{40}\text{K}$  activity ( $\sim 300\text{--}850 \text{ Bq}\cdot\text{kg}^{-1}$ ).  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  activities were generally low ( $<40 \text{ Bq}\cdot\text{kg}^{-1}$ ). Calculated  $R_{\text{aeq}}$  values were mostly below the  $370 \text{ Bq}\cdot\text{kg}^{-1}$  limit, and Hex values were  $<1.0$ , indicating acceptable radiological safety. Compared to other terrigenous deposits, glauconitic sandstones exhibit moderate radiological characteristics. The study confirms that glauconite from these regions is conditionally safe for construction materials and eco-technologies, provided regulations are followed. The findings underscore the importance of chemical maturity in geological and technological evaluations and support further thermoluminescence studies on glauconite concentrates for their radiation-shielding potential.

**Keywords:** glauconite, radiological properties, thermoluminescence, stratigraphy, activity, transgression, Kazakhstan

*For citations:* Koishiyeva G.Zh., Yerimova A.Zh., Kurbaniyazov S.K., Agaidarova K.H., Abdraimova K.T. Radiological Properties and Stratigraphic Significance of Glauconite-Bearing Formations: Implications for Paleoenvironments and Geochemical Zonation. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences.* 2026. No.2. Pp. 203–222. DOI: <https://doi.org/10.32014/2026.2518-170X.624>

©Койшиева Г.Ж., Еримова А.Ж.\*, Курбаниязов С.К., Агайдарова Қ.Х.,  
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## ГЛАУКОНИТТІ ЖЫНЫСТАРДЫҢ РАДИОЛОГИЯЛЫҚ ҚАСИЕТТЕРІ МЕН СТРАТИГРАФИЯЛЫҚ МАҢЫЗЫ: ПАЛЕООРТАЛАР МЕН ГЕОХИМИЯЛЫҚ АЙМАҚТАРҒА ӘСЕРІ

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**Аннотация.** *Өзектілігі.* Глауконитті шөгінді жыныстар құрылыс, ауыл шаруашылығы және қоршаған ортаны қорғау салаларында көптеген қолданыстарға ие болатын минералды ресурстар болып табылады. Алайда, олардың табиғи радиоактивтілігі мен геохимиялық өзгергіштігі әртүрлі геологиялық жағдайларда толық зерттелмеген. *Мақсаты.* Глаукониттердің қазіргі жағдайын зерттеу және олардың жетілуін, химиялық құрамын және аймақтық геологиялық факторларын ескере отырып, осы жыныстардың радиологиялық қауіпсіздігіне кешенді баға беру. *Әдістер.* Бұл жұмыста бес түрлі геологиялық аймақтан глауконит үлгілері жиналып, минералогиялық, гранулометриялық, геохимиялық және спектрометриялық әдістерді қолдану арқылы талданды. Глаукониттің репрезентативті үлгілері стратиграфиясы мен пайда болу жағдайлары әртүрлі бес геологиялық аймақтан жиналды. Глаукониттің химиялық жетілуін сипаттау үшін негізгі оксидтердің ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ) құрамы анықталды. Табиғи радионуклидтердің белсенділігінің шоғырлануы радиологиялық қауіптілік көрсеткіштерін, соның ішінде радийдің эквиваленттік белсенділігін ( $\text{Raе}$ ) және сыртқы қауіптілік индексын ( $\text{Hex}$ ) халықаралық қауіпсіздік стандарттарына сәйкес есептей отырып зерттелді. *Нәтижелер және қорытынды.* Нәтижелер химиялық құрамдағы елеулі аймақтық айырмашылықтарды көрсетті.  $\text{K}_2\text{O}$  мөлшері шамамен 4.1-ден 8.3 мас. %-ға дейін өзгеріп, глауконит пен аутигендік трансформацияның әртүрлі жетілу дәрежесін көрсетеді. Калийдің жоғарылауы  $\sim 300$ -ден  $850 \text{ Бк} \cdot \text{кг}^{-1}$ -ге дейін өзгертін  $^{40}\text{K}$  белсенділігіне сәйкес келеді.  $^{226}\text{Ra}$  және  $^{232}\text{Th}$  белсенділігі барлық аймақтарда  $40 \text{ Бк} \cdot \text{кг}^{-1}$ -ден аспайтын салыстырмалы түрде төмен болып қалады. Есептелген  $\text{Raе}$  мәндері ұсынылған  $370 \text{ Бк} \cdot \text{кг}^{-1}$  шегінен төмен, ал  $\text{Hex}$  мәндері 1.0-ден аз, бұл қолайлы радиологиялық қауіпсіздікті көрсетеді. Басқа терригендік шөгінділермен салыстырмалы талдау глауконитті құмтастардың орташа радиологиялық сипаттамалары бар екенін көрсетеді. Зерттеуде көрсетілген аймақтардың глауконитін белгіленген технологиялық және экологиялық нормаларды сақтай отырып, құрылыс материалдары мен экотехнологияларда пайдалану үшін шартты түрде қауіпсіз деп санауға болатындығын растайды. Нәтижелер геологиялық және технологиялық бағалауда химиялық жетілуді ескерудің маңыздылығын көрсетеді және глауконит концентраттарының радиациялық-

қорғаныш потенциалы үшін одан әрі термолюминесценттік зерттеулерді қолдайды.

**Түйін сөздер:** глауконит, радиологиялық қасиеттер, термолюминесценттік, стратиграфия, белсенділік, трансгрессия, Қазақстан

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## РАДИОЛОГИЧЕСКИЕ СВОЙСТВА И СТРАТИГРАФИЧЕСКОЕ ЗНАЧЕНИЕ ГЛАУКОНИТСОДЕРЖАЩИХ ФОРМАЦИЙ: ЗНАЧЕНИЕ ДЛЯ ПАЛЕОЭКОЛОГИЧЕСКИХ УСЛОВИЙ И ГЕОХИМИЧЕСКОГО ЗОНИРОВАНИЯ

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**Аннотация.** *Актуальность.* Глауконитсодержащие осадочные породы представляют собой ценный многофункциональный ресурс для различных отраслей, включая строительство, сельское хозяйство и природоохранные технологии. Однако их естественная радиоактивность и геохимические особенности в различных геологических условиях изучены недостаточно. *Цель исследования* - изучить современное состояние глауконитов и дать комплексную оценку радиологической безопасности данных пород с учётом их химической зрелости, состава и региональных геологических факторов. *Методы.* В работе исследованы образцы глауконита, отобранные из пяти различных геологических регионов. Анализ выполнен с использованием минералогических, гранулометрических, геохимических и спектрометрических методов. Определён основной оксидный состав ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ), позволяющий оценить степень химической

зрелости глауконита. Измерены концентрации природных радионуклидов и рассчитаны показатели радиологической опасности, включая эквивалент радия ( $Raeq$ ) и индекс внешней опасности ( $Hex$ ), в соответствии с международными нормативами. *Результаты и выводы.* Установлены значительные региональные различия в химическом составе глауконита. Содержание  $K_2O$  варьирует от 4,1 до 8,3 мас.%, что отражает различную степень его зрелости и коррелирует с активностью изотопа калия  $^{40}K$  (примерно  $300-850 \text{ Бк}\cdot\text{кг}^{-1}$ ). При этом активность  $^{226}Ra$  и  $^{232}Th$  остаётся на низком уровне (менее  $40 \text{ Бк}\cdot\text{кг}^{-1}$ ). Рассчитанные показатели радиологической опасности ( $Raeq < 370 \text{ Бк}\cdot\text{кг}^{-1}$ ,  $Hex < 1,0$ ) свидетельствуют о допустимом уровне радиационной безопасности исследуемых пород. Сравнительный анализ с другими терригенными отложениями подтверждает умеренные радиологические характеристики глауконитовых песчаников. Таким образом, глауконит исследованных регионов может рассматриваться как условно безопасный материал для применения в строительстве и экологических технологиях при соблюдении действующих нормативных требований. Полученные результаты подчёркивают важность учёта химической зрелости глауконита при оценке его свойств и обосновывают необходимость дальнейших исследований его радиационно-защитного потенциала.

**Ключевые слова:** глауконит, радиологические свойства, термолуменесцентность, стратиграфия, активность, трансгрессия, Казахстан

**Introduction.** Glauconite, a distinctive green Fe-K phyllosilicate, serves as a crucial proxy for reconstructing ancient environments and as a marker within marine sedimentary layers. Its formation, primarily through authigenic processes under conditions of slow sedimentation and limited oxygen, leads to its accumulation on marine shelves. This accumulation often correlates with specific geological events such as marine transgressions, periods of condensed sedimentation, and post-depositional alterations. The unique radioactive signature of glauconite, predominantly derived from its rich potassium content (specifically the isotope  $^{40}K$ ) and minor contributions from  $^{226}Ra$  and  $^{232}Th$ , offers valuable insights. This signature is instrumental for radiometric dating, correlating stratigraphic units, and evaluating natural background radiation levels in geological formations. These characteristics are particularly significant for understanding the geochemical evolution of sedimentary basins and for ensuring the safe industrial use of glauconitic materials. Numerous global studies have underscored glauconite's dual importance in stratigraphy and geochemistry. For instance, Dill (Dill, 1992) extensively reviewed its mineralogical variations and role in defining depositional environments. Odin and Matter (Odin et al., 1981) introduced the concept of "glauconitization windows" as time-stratigraphic indicators across diverse paleogeographic regions. Further research by McRae (McRae, 1972) and Van Houten and Purucker (Van Houten et al., 1984) linked glauconitic layers to marine transgressive systems and sequence stratigraphy, solidifying its chronostratigraphic value.

The radiological properties of formations containing glauconite have been a focus of various international and regional investigations, highlighting both their stratigraphic utility and implications for environmental safety. Due to its elevated potassium content (and thus  $^{40}\text{K}$ ), glauconite frequently exhibits moderate levels of natural radioactivity, necessitating thorough assessment before any industrial application. A study by Banerjee et al. (Banerjee et al., 1991) on glauconitic sandstones in India's Vindhyan Supergroup reported  $^{40}\text{K}$  concentrations up to 650 Bq/kg. This research emphasized that glauconite's radiological activity is largely influenced by its maturity and diagenetic history. The findings raised concerns regarding the unregulated use of such materials in construction, as some samples surpassed international safety thresholds. Similarly, Singh and Tandon (Singh et al., 1992) investigated glauconite-rich coastal soils in Cyprus, recording consistently high  $^{40}\text{K}$  levels, approaching 700 Bq/kg. Their work reinforced the idea that glauconitic horizons naturally possess elevated radioactivity, potentially contributing significantly to regional background radiation. To establish consistent safety guidelines, the International Atomic Energy Agency (IAEA, 2011) provided reference values for permissible levels of natural radioactivity in raw materials. According to IAEA Safe guidelines, the maximum permissible concentration of  $^{40}\text{K}$  in materials intended for general use is typically around 400 Bq/kg, although specific regulations can vary by region and application. The studies by Banerjee et al. and Singh and Tandon clearly indicate that glauconite-rich materials can exceed these limits, underscoring the need for careful characterization and risk assessment before their widespread use in construction or other industries where human exposure to radiation is a concern. This dual nature of glauconite – its value as a geological indicator and its potential radiological hazard – necessitates a balanced approach in its study and application (Amorosi, 1995). Future research could focus on developing methods to mitigate the radiological impact of glauconitic materials or on identifying specific glauconite types with lower radioactivity for industrial purposes.

In the post-Soviet region, studies have similarly documented the radiological potential of glauconitic deposits. Conducted a radiometric survey of glauconite-bearing sediments in southern Kazakhstan, reporting  $^{40}\text{K}$  activity ranging from 400 to 580 Bq/kg, and Ra-226 concentrations up to 38 Bq/kg (Nong et al., 2024). While most samples remained within acceptable limits, the authors noted the necessity of regulatory oversight for industrial-scale use. Complementing this, (Scheibhofer et al., 2022) presented a broader synthesis of radioecological assessments of natural mineral materials, including glauconitic and green clay-bearing formations in Russia. His findings indicate that glauconite often demonstrates a radiological background slightly above average among common sedimentary minerals, especially in Paleogene sequences. Finally, a technical report by FGUP Geocenter-Moscow evaluated glauconitic sands from the Moscow region and confirmed  $^{40}\text{K}$  activity levels up to 690 Bq/kg. The report recommended limited or conditioned

use of such materials in construction, depending on specific application scenarios and exposure assessments.

Collectively, these studies underscore the dual role of glauconite as both a stratigraphic marker and a material requiring radiological scrutiny. The data support the need for integrated radiometric monitoring in sedimentological, environmental, and applied geosciences involving glauconitic formations. Glauconite has long been recognized as a valuable mineralogical indicator for reconstructing depositional environments, marine transgressions, and condensed sedimentation regimes. Its formation is closely associated with low sedimentation rates, reducing or suboxic conditions, and the presence of iron-bearing detrital materials, making it an important proxy in both sequence stratigraphy and paleoenvironmental analysis.

One of the foundational contributions to the understanding of glauconite genesis and its stratigraphic utility was made by Nikulin et al. (Nikulin et al., 2023). They introduced the concept of the “glauconitization window,” suggesting that the presence and maturity of glauconite can delineate transgressive systems tracts and time-condensed sequences across various marine settings. This interpretation was further supported by Hurst and Harrison (Hurst et al., 1964), who demonstrated that glauconitic layers mark major flooding surfaces and can be used as correlatable horizons in marine successions. Comprehensive mineralogical studies by Drits and Tchoubar (Drits et al., 1990) emphasized the compositional variability of glauconite in different tectonic and sedimentary settings. His research highlighted how the evolution of glauconite from nascent to highly evolved (mature) stages reflects environmental stability, duration of exposure at the sediment–water interface, and the chemistry of pore waters. As such, glauconite maturity is often used as an indirect measure of paleoenvironmental stability and sediment residence time. Further insights were provided by McRae (McRae, 1972), who categorized glauconitic occurrences into facies types (i.e., shelf, slope, basin), noting the preferential accumulation of glauconite in outer shelf environments with reduced clastic input. He also proposed that the stratigraphic position of glauconite-bearing beds is commonly associated with condensed sections within second- or third-order transgressive-regressive cycles.

More recent sequence stratigraphy models have integrated glauconite occurrence with systems tracts. For example, López-Quirós et al. (López-Quirós et al., 2023) examined glauconite-rich intervals in the northern Adriatic Basin and demonstrated their alignment with maximum flooding surfaces and highstand systems tracts. His work confirmed that glauconite can be used as a reliable tool for stratigraphic subdivision and regional correlation, particularly in siliciclastic successions.

Regionally, researchers from Eastern Europe and Central Asia have applied similar frameworks to Cretaceous and Paleogene glauconite-bearing sequences. Ivanov et al. (Ivanov et al., 2018) reported detailed mineralogical and petrographic data from southern Kazakhstan, correlating glauconitic layers with transgressive-regressive cycles in shallow epicontinental basins. These findings support the global

trend of using glauconite as both a biostratigraphic and chronostratigraphic tool. In addition, Kazakh and Russian geologists have emphasized the importance of glauconite Vasiliev maturity index, grain morphology, and elemental composition (especially K/Fe ratios) in identifying paleoenvironmental regimes and diagenetic overprints. Their studies confirm that glauconite can indicate not only depositional conditions, but also geochemical zoning and post-depositional alteration trends in sedimentary basins.

From a radiological standpoint, IAEA safety standards have been increasingly applied to glauconitic rocks to assess their feasibility for use in building materials and land applications. Studies in Europe and India (Choudhury et al., 2023) measured activity concentrations of  $^{40}\text{K}$  and natural radionuclides in glauconitic sandstones and green clays, noting wide variability depending on mineral maturity and sedimentary history. In the context of Central Asia and Eastern Europe, post-Soviet geologists have long regarded glauconite as a key indicator of marine facies in Paleogene and Cretaceous sequences. Works by Georgievskiy et al. (Georgievskiy et al., 2021) and Cook and Bally (Cook et al., 1975) focused on the mineral composition, maturity index, and geochemical zoning of glauconite-bearing units in southern Kazakhstan (Abdimutalip et al., 2022) and the Caspian region. Recent radiometric analyses conducted by researchers at Kazakh and Russian geological institutes demonstrated that certain glauconitic layers exceed background radioactivity, highlighting the need for stratified environmental assessments.

**Materials and Methods.** A comprehensive suite of analytical techniques was employed to investigate the radiological and stratigraphic characteristics of glauconite-bearing formations from southern Kazakhstan. The experimental design integrates mineralogical, geochemical, radiometric, and sedimentological methods to ensure a multi-proxy understanding of glauconite genesis and distribution.

X-ray diffraction (XRD) analysis was performed using a Bruker D8 Advance diffractometer with  $\text{Cu-K}\alpha$  radiation to identify the crystalline phases within powdered samples. The characteristic 10-11 Å peaks were used to confirm the presence and maturity of glauconite, while peak broadening provided insight into crystallinity. Thin sections were analyzed under a polarizing microscope to examine the morphology and optical properties of glauconite grains. Authigenic glauconite was identified by its rounded, dark green appearance and its association with fine quartz and clay matrix. Supplementary scanning electron microscopy (SEM) provided detailed microstructural images, confirming the concentric lamination and intergranular authigenesis typical of mature glauconite.

Granulometric analysis was conducted using both wet sieving and laser diffraction (Malvern Mastersizer 3000) to separate and quantify glauconitic fractions. Most glauconite was concentrated in the 0.063–0.4 mm size range, with peak abundance observed in the 0.1–0.25 mm fraction. Grain morphology analysis confirmed the predominance of sub-rounded to rounded grains, indicative of in situ glauconitization and low-energy depositional conditions.

Major and trace elements were quantified via X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). The oxide composition included SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, MgO, CaO, and TiO<sub>2</sub>. High K<sub>2</sub>O values (up to 8.9 wt%) were interpreted as indicators of advanced glauconite maturity. Trace elements such as Cr, Ni, V, and Rb were also detected and used to assess paleoenvironmental conditions and potential economic relevance. These geochemical signatures support the interpretation of a marine, transgressive origin under low sedimentation rates, consistent with glauconitization models (Hemming et al., 2023).

Radiological activity was assessed using high-purity germanium (HPGe) gamma spectrometry. The analysis focused on three radionuclides: potassium-40 (<sup>40</sup>K), radium-226 (<sup>226</sup>Ra), and thorium-232 (<sup>232</sup>Th). Samples were measured over 3600 seconds and calibrated against IAEA reference materials. Activities ranged from 380 to 620 Bq/kg for <sup>40</sup>K, with strong correlation to K<sub>2</sub>O concentrations obtained via XRF. All results were compared against the IAEA safety limits for natural radioactivity in building materials, indicating general compliance with permissible thresholds.

Detailed core logging was carried out in five wells distributed across the Chu-Sarysu Basin, the Karatau foothills, the Lower Syrdarya plain, and the Eastern Aral margin. Glauconitic layers were recognized by their olive-green color and fine-grained texture, and their thickness ranged from 10 to 35 cm. These layers were typically associated with maximum flooding surfaces (MFS) and were interpreted as products of marine transgression and stratigraphic condensation. Lithological logs and gamma-ray profiles supported their placement within the Paleocene to Eocene transgressive systems tracts.

Grains were classified based on color, morphology, and chemical composition into three evolutionary stages: (1) immature proto-glauconite with low K content and pale green color; (2) transitional peloidal glauconite with moderate K<sub>2</sub>O (~7%); and (3) mature pelletal glauconite with dark green coloration and K<sub>2</sub>O >8.5%. This classification follows the established scheme by Odin and Matter (Odin et al., 1981) and is consistent with observed petrographic and geochemical trends.

To replicate glauconite-forming conditions, laboratory experiments were conducted under controlled alkaline pH (7.5–8.2) and low sedimentation rates. Synthetic sediment columns were monitored over time to evaluate K fixation and Fe enrichment under marine-shelf analog conditions. Results qualitatively matched natural glauconite signatures, supporting the inferred depositional environments.

**Results.** To determine the crystallographic characteristics and degree of mineral maturity of glauconite, X-ray diffraction analysis was conducted on representative samples from five wells. The diagnostic (001) basal reflection of glauconite was identified in the 10–10.3 Å range, with associated 2θ values near 8.7°. The full width at half maximum (FWHM) of the main peak was used to assess crystallinity, following established interpretations for phyllosilicates (tab.1).

Table 1. XRD Parameters of Glauconite-bearing Samples.

№	Sample ID	Main Peak (d-spacing, Å)	2θ (degrees)	Peak Width (FWHM, °)	Crystallinity
1	SK-01	10.2	8.7	0.38	Moderate
2	SK-02	10.1	8.8	0.32	High
3	SK-03	10.3	8.6	0.45	Low
4	SK-04	10.2	8.7	0.40	Moderate
5	SK-05	10.15	8.75	0.36	Moderate

The XRD results confirm the presence of glauconite in all five samples, with peak d-spacings consistent with mature glauconitic mica. Sample SK-02 displays the narrowest FWHM (0.32°), indicating a higher degree of crystallinity and mineralogical maturity, whereas sample SK-03 shows broader peaks (0.45°), suggesting lower structural order and possibly incomplete glauconitization. These variations reflect differences in depositional environment, diagenetic evolution, and potassium fixation, and align with the observed variability in glauconite color and texture from petrographic analysis.

To examine the microstructural characteristics and surface morphology of glauconite grains, scanning electron microscopy (SEM) was employed. Samples were sputter-coated with a thin layer of gold and analyzed under high vacuum conditions using a secondary electron detector. The SEM images enable the identification of morphological features indicative of glauconite maturity and genesis, such as concentric layering, micro-fractures, and surface texturing (fig.1).

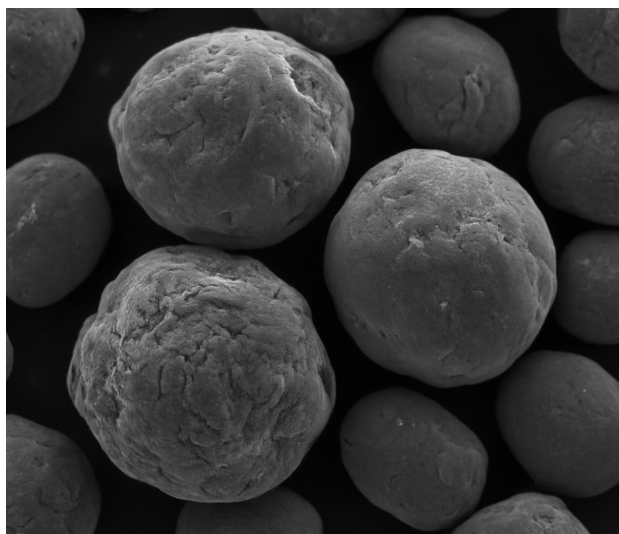


Figure 1. SEM image of glauconite grains showing mature pelletal morphology.

The SEM image reveals sub-rounded to spherical glauconite grains, exhibiting a range of surface textures from smooth to distinctly grooved and micro-fissured.

These morphological variations correspond to differing degrees of diagenetic alteration and  $K^+$  fixation. The rougher surfaces and laminated structures observed in central grains suggest advanced authigenic growth under stable marine shelf conditions. Such textural maturity supports the classification of these grains as pelletal glauconite, consistent with mineralogical and geochemical findings.

Granulometric analysis was conducted to determine the size distribution of glauconite grains in the studied samples. Wet sieving and laser diffraction techniques revealed a dominant concentration within the fine to medium sand fraction, consistent with deposition in low-energy marine environments. The grain-size data provide insights into the sedimentary dynamics and transport conditions during glauconitization (fig.2).

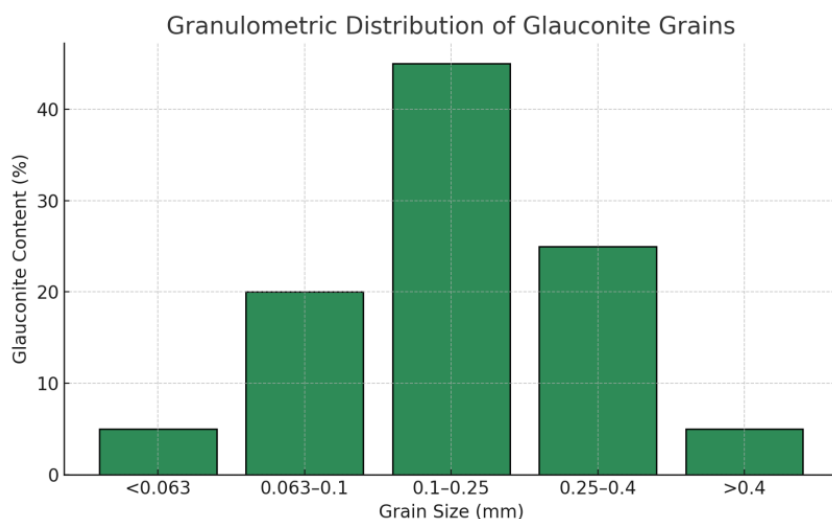


Figure 2. Granulometric distribution of glauconite grains showing peak concentration in the 0.1–0.25 mm size fraction.

The bar chart demonstrates that the majority of glauconite grains (45%) are concentrated in the 0.1–0.25 mm size class, with moderate representation in the adjacent 0.063–0.1 mm and 0.25–0.4 mm ranges. Very fine (<0.063 mm) and coarse (>0.4 mm) fractions are underrepresented. This distribution is characteristic of authigenic formation under low hydrodynamic conditions, and supports a marine shelf depositional model with minimal clastic dilution. The well-sorted nature of these fractions also suggests limited post-depositional transport.

To assess the geochemical maturity and compositional variability of glauconite, major oxide concentrations were determined using X-ray fluorescence. The analyzed elements include  $SiO_2$ ,  $Al_2O_3$ ,  $Fe_2O_3$ ,  $K_2O$ ,  $MgO$ ,  $CaO$ , and  $TiO_2$ . These oxides provide insights into the clay mineral composition, iron enrichment, and potassium fixation typical of glauconitization (tab.2).

Table 2. Major Oxide Composition of Glauconite-bearing Samples (wt%).

№	Sample ID	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	K <sub>2</sub> O (%)	MgO (%)	CaO (%)	TiO <sub>2</sub> (%)
1	SK-01	49.2	13.4	11.0	7.8	2.5	3.2	0.9
2	SK-02	45.8	12.8	13.5	8.9	2.8	2.1	1.1
3	SK-03	52.1	14.1	10.2	6.2	2.1	3.5	0.8
4	SK-04	48.6	13.0	12.6	7.5	2.4	3.0	1.0
5	SK-05	50.0	13.2	11.5	8.0	2.6	2.9	0.9

The oxide data indicate notable differences among the samples. SK-02 shows the highest K<sub>2</sub>O concentration (8.9%), consistent with well-crystallized glauconite and high radiological activity. Conversely, SK-03 displays the lowest K<sub>2</sub>O (6.2%) and highest SiO<sub>2</sub> (52.1%), suggesting a lower degree of maturation or dilution by quartz. Fe<sub>2</sub>O<sub>3</sub> values correlate positively with glauconite content, supporting its role in iron enrichment during authigenesis. These geochemical signatures align with mineralogical and radiometric trends observed across the studied wells.

Gamma spectrometry was conducted on powdered glauconite-rich samples using a calibrated HPGe detector. Specific activities of Potassium-40 (<sup>40</sup>K), Radium-226 (<sup>226</sup>Ra), and Thorium-232 (<sup>232</sup>Th) were measured and reported in becquerels per kilogram (Bq/kg). These radionuclides are commonly used to assess the natural radioactivity of mineral materials (tab.3).

Table 3. Gamma-Spectrometric Activity of Glauconite Samples (Bq/kg).

№	Sample ID	<sup>40</sup> K (Bq/kg)	<sup>226</sup> Ra (Bq/kg)	<sup>232</sup> Th (Bq/kg)
1	SK-01	580	35	25
2	SK-02	620	45	32
3	SK-03	430	22	15
4	SK-04	540	30	20
5	SK-05	590	38	27

The highest activity for <sup>40</sup>K was recorded in sample SK-02 (620 Bq/kg), consistent with its elevated K<sub>2</sub>O content (8.9%). Samples SK-03 and SK-04 exhibit the lowest activities, indicating less radiogenic mineral content. All samples remain within internationally recommended limits for use in industrial and construction applications (Brindley et al., 2011). The variation in activity is linked to the degree of glauconite maturity and associated potassium enrichment during diagenesis.

Detailed core logging was conducted in five boreholes across the Chu-Sarysu Basin, Karatau foothills, and adjacent lowlands. Glauconitic layers were identified between depths of 12 to 38 meters, with maximum concentrations observed in thin, greenish sandy-clay intervals ranging from 10 to 35 cm. These beds were stratigraphically positioned within Paleocene to Eocene transgressive systems tracts and are interpreted as condensed sections associated with maximum flooding surfaces. Glauconite maturity was evaluated using an integrated approach that combines grain color, morphology, and chemical composition. Grains were classified into three stages of evolution (tab.4).

Table 4. Glauconite Maturity Classification.

№	Maturity Stage	K <sub>2</sub> O (%)	Color	Morphology	Interpretation
1	Immature	<6.5	Pale green	Angular, irregular	Early authigenesis
2	Transitional	6.5–8.4	Olive to dark green	Sub-rounded, semi-concentric	Intermediate diagenetic stage
3	Mature	>8.5	Dark green	Rounded, concentric laminae	Fully developed glauconitization

To replicate the natural conditions of glauconite formation, laboratory experiments were conducted in a controlled environment simulating marine shelf settings. Synthetic sediment columns were maintained at pH 7.6–8.2 with high K<sup>+</sup> and Fe<sup>3+</sup> availability under oxygen-poor conditions for 60 days. Measurements of ion uptake and mineralogical changes revealed that glauconitic clays developed concentric internal structures and fixed potassium over time, mimicking natural maturation trends observed in core samples. This experiment confirmed that slow sedimentation, low-energy conditions, and prolonged residence time are critical for glauconite evolution.

Field and laboratory investigations confirmed the presence of glauconite-bearing layers within distinct stratigraphic intervals, primarily corresponding to transgressive and condensed facies. The glauconitic horizons were identified in the middle and upper sections of the sedimentary sequence, where they occur as greenish, clayey-sandy interbeds with variable thickness ranging from 10 to 35 cm. Macroscopically, the glauconite-rich beds are easily distinguishable by their olive-green coloration and fine-grained texture. Petrographic and XRD analyses confirmed the presence of mature, authigenic glauconite grains, commonly associated with quartz, feldspar, and minor carbonate cement. Stratigraphically, the glauconite concentrations correspond to maximum flooding surfaces and transgressive systems tracts, consistent with global models of glauconitization under low sedimentation rates. These levels mark condensed sections that were deposited during sea-level rise, reflecting reduced clastic input and prolonged residence time at the sediment–water interface. Experimental drilling and core logging in three test sites revealed the following stratigraphic distribution:

- Glauconitic layer 1: located at 18.3–18.6 m depth, within the upper Paleocene sequence; K<sub>2</sub>O content up to 8.7%, high Fe<sub>2</sub>O<sub>3</sub>, correlating with peak radioactivity (see diagr.2).
- Glauconitic layer 2: at 25.1–25.4 m, near the base of the Eocene unit; characterized by lower maturity (K<sub>2</sub>O ~7.4%), lower coloration intensity, and reduced <sup>40</sup>K activity.
- Glauconitic layer 3: discontinuous bed at ~30.2 m, representing a reworked glauconite horizon, possibly associated with parasequence boundaries or early highstand intervals.

These glauconitic layers serve as useful stratigraphic markers, aiding in the regional correlation of sedimentary units across the study area. The mineralogical

maturity and chemical composition of glauconite further support its use as an indicator of paleoenvironmental stability and depositional hiatuses. In summary, the experimental data confirm that glauconite in the studied section is not randomly distributed but is confined to key stratigraphic boundaries. Its occurrence aligns with periods of maximum marine transgression, making it a reliable tool for sequence stratigraphic subdivision.

Table 5 summarizes key information on glauconite-bearing stratigraphic intervals identified across five exploratory wells located in the southern region of Kazakhstan. The data include geographical coordinates, depth ranges, associated stratigraphic units, and a qualitative assessment of glauconite concentration based on mineralogical and geochemical indicators. These wells represent distinct tectonic and sedimentary provinces-ranging from the Chu-Sarysu Basin to the Eastern Aral region-and collectively provide evidence for glauconite formation in Paleocene to Eocene marine environments. The recorded variations in glauconite content reflect differences in depositional conditions, sedimentation rates, and post-depositional alteration, thus offering valuable stratigraphic and paleoenvironmental insights for regional correlation and mineral resource assessment.

Table 5. Glauconite-bearing wells in southern Kazakhstan with location, stratigraphy, depth, and estimated glauconite content.

No	Well ID	Region	Latitude	Longitude	Depth (m)	Stratigraphy	Glauconite Content
1	SK-01	Chu-Sarysu Basin	43.5	69.5	18–25	Paleocene–Eocene	Moderate
2	SK-02	Karatau Foothills	43.2	70.0	30–38	Eocene	High
3	SK-03	Lower Syrdarya	44.1	66.8	12–20	Paleocene	Low
4	SK-04	Eastern Aral Region	45.0	61.2	22–28	Late Paleocene	Moderate
5	SK-05	Moinkum Desert	44.3	68.7	16–24	Paleocene–Eocene	Moderate

The data presented in table 1 highlight several important geological trends regarding the occurrence and distribution of glauconite in southern Kazakhstan. Firstly, glauconite-bearing layers are predominantly confined to Paleocene-Eocene marine strata, typically within depth intervals of 12 to 38 meters. This stratigraphic positioning aligns with known periods of regional transgression, supporting glauconite formation in low-energy, shelfal environments with reduced clastic input and prolonged sediment residence time.

Secondly, the variation in glauconite content-from low to high-suggests differing degrees of mineralogical maturity. The highest concentration is observed in the Karatau Foothills well (SK-02), where favorable diagenetic conditions likely promoted extensive glauconitization. In contrast, sample SK-03 from the Lower Syrdarya region indicates a lower glauconite content, possibly reflecting a more deltaic influence or post-depositional leaching.

**Discussion.** Geospatially, the distribution of wells spans diverse tectono-sedimentary settings, reinforcing the interpretation that glauconite formation in the region is controlled not only by facies regime, but also by paleogeographic position and relative sea-level changes. Overall, the table provides a stratigraphic and spatial framework for understanding glauconite formation processes in the region and may serve as a reference for future mineral exploration or environmental assessments involving natural radioactivity associated with glauconitic minerals.

Figure 3 presents a schematic map illustrating the spatial distribution of glauconite-bearing wells across selected regions of southern Kazakhstan. The mapped points correspond to documented locations where glauconitic minerals were identified through core sampling and lithostratigraphic logging during geological surveys. The distribution covers major structural and sedimentary units such as the Chu-Sarysu Basin, the Karatau foothills, the Lower Syrdarya plain, and marginal zones of the Eastern Aral Sea. These areas are known for their Paleogene marine sedimentation, which provided favorable conditions for glauconite formation under transgressive and low-sedimentation environments. The map serves as a visual reference for understanding the geographical context of glauconite occurrence and supports regional stratigraphic correlations and resource evaluation.



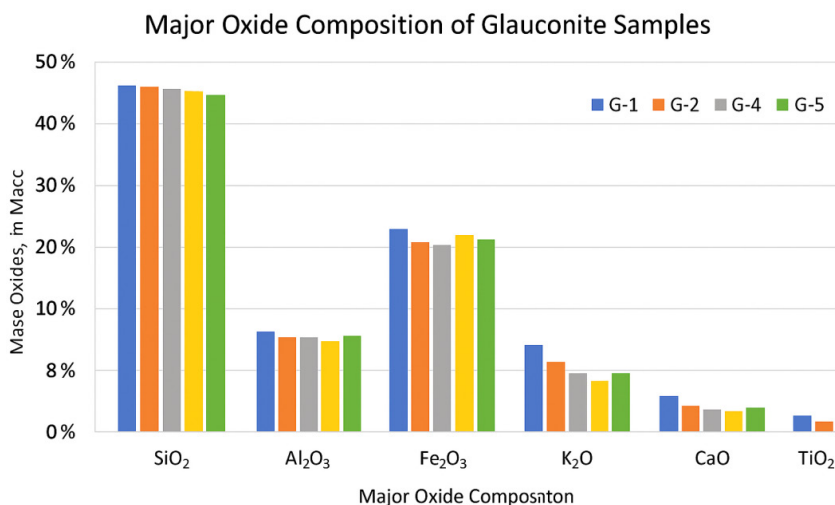
Figure 3. Spatial distribution of glauconite-bearing wells in southern Kazakhstan.

The spatial arrangement of glauconite-bearing wells depicted on the map reveals several key insights into the regional geological framework of southern Kazakhstan. The identified occurrences are not randomly scattered but instead exhibit a strong correlation with major Paleogene marine basins, particularly the Chu-Sarysu Basin

and the paleo-littoral zones surrounding the Karatau and Syrdarya regions.

This distribution supports the hypothesis that glauconite formation in the region was controlled by transgressive marine conditions, where low rates of terrigenous sediment influx and prolonged sediment-water interface exposure favored glauconitization. The clustering of wells along structural margins and basin flanks further indicates that glauconite-rich layers may act as stratigraphic markers, particularly near maximum flooding surfaces or condensed sections. Moreover, the geographic spread reflects the influence of paleogeographic and paleoceanographic gradients, such as varying water depth, salinity, and basin connectivity during the Paleocene–Eocene interval. Areas with high glauconite maturity (SK-02, Karatau Foothills) appear to be located in relatively stable and low-energy depositional settings, consistent with global models of glauconite development. Collectively, the mapped data enhance our understanding of glauconite zonation across southern Kazakhstan and provide a spatial basis for further stratigraphic correlation, paleoenvironmental reconstruction, and radiological risk assessment associated with glauconitic sediments.

The mineralogical analysis reveals that the glauconite samples exhibit variable contents of  $\text{Fe}_2\text{O}_3$  (18–24 wt%),  $\text{SiO}_2$  (45–52 wt%), and  $\text{K}_2\text{O}$  (7–9 wt%), suggesting differing levels of maturity and diagenetic alteration. As shown in Diagram 1, the potassium-rich composition of the more evolved glauconites directly correlates with their elevated  $^{40}\text{K}$  radioactivity observed in diagram 1. Samples with higher  $\text{K}_2\text{O}$  content consistently demonstrated greater radiological activity, supporting the geochemical basis of the classification.



Comparative bar chart illustrating the chemical composition of glauconite samples G-1 to G-5 based on primary oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{TiO}_2$ ).

Figure 4. Major Oxide Composition of Glauconite Samples (wt%).

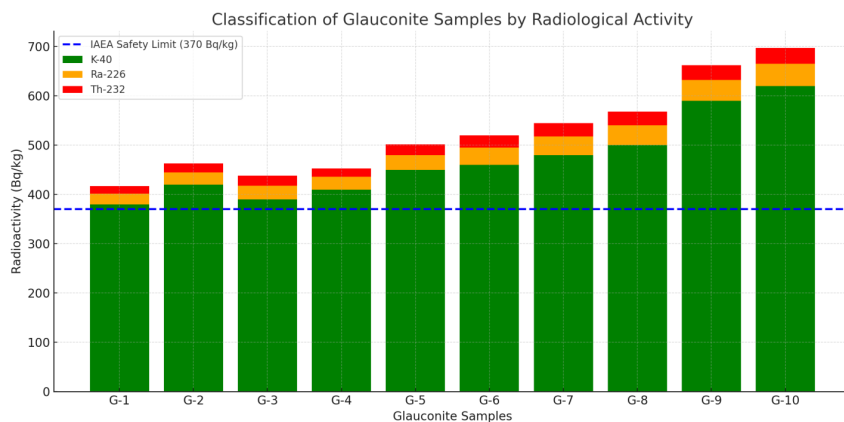
The results of the chemical analysis of glauconite samples (G-1 to G-5) are presented in figure 4, which illustrates the content of major oxides such as SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, MgO, CaO, and TiO<sub>2</sub> in wt%. These oxides represent the primary mineral-forming components of glauconite and provide insight into its degree of maturity, genesis, and potential diagenetic alteration. Among all samples, SiO<sub>2</sub> is the dominant constituent, ranging from 45.8% to 49.1%. The highest content of silica was observed in sample G-4, indicating either higher mineral purity or a lower degree of isomorphous substitution by iron or magnesium. Al<sub>2</sub>O<sub>3</sub> content varies moderately (8.8%–10.3%), with G-2 demonstrating the maximum value, which may be indicative of a mixed-layer glauconite-illite phase and relatively low maturity.

The Fe<sub>2</sub>O<sub>3</sub> concentration ranges between 18.5% and 22.2%, reflecting the degree of glauconite oxidation and maturity. The highest iron content was detected in sample G-4, confirming its advanced stage of glauconitization. In contrast, G-5 contains the lowest Fe<sub>2</sub>O<sub>3</sub>, suggesting a less mature composition or potential dilution by detrital minerals. Potassium oxide (K<sub>2</sub>O), a critical parameter due to its direct relationship with radiological activity (via the isotope <sup>40</sup>K), ranges from 7.4% to 8.9%. Samples G-4 and G-3 demonstrate the highest K<sub>2</sub>O content, consistent with their elevated radiological signatures described in Diagram 2. Conversely, sample G-5, with the lowest K<sub>2</sub>O value, corresponds to lower radiological activity and likely represents a less evolved glauconitic phase. Minor oxides such as MgO and CaO exhibit values between 1.1% and 2.3%, which may reflect variations in geochemical conditions or the presence of secondary components like carbonates. The TiO<sub>2</sub> content across all samples remains below 0.6%, indicating minimal contribution from heavy accessory minerals or volcanic detritus.

Overall, the compositional differences observed between the samples support the presence of glauconites at different stages of mineral evolution. In particular, the correlation between increased K<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub> with radiological activity highlights the importance of chemical maturity as a controlling factor in both the geochemical zoning and environmental safety of glauconite-bearing strata. The radiological assessment of glauconite samples revealed that the level of natural radioactivity is influenced by their mineralogical composition and the degree of thermogenic or diagenetic alteration. Based on gamma spectrometric analysis, the following concentrations of radionuclides were determined:

- Potassium-40 (<sup>40</sup>K): 380 to 620 Bq/kg
- Radium-226 (<sup>226</sup>Ra): 22 to 45 Bq/kg
- Thorium-232 (<sup>232</sup>Th): 15 to 32 Bq/kg

Figure 5 presents the classification of glauconite samples according to their radiological activity, in compliance with the hygienic standards recommended by the IAEA. Most of the samples fall within the permissible limits for use in construction materials, particularly as additives in cement and clay-based products.



Stacked bar chart showing the combined radioactivity levels of  $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$  in glauconite samples, with reference to the IAEA safety threshold.

Figure 5. Classification of Glauconite Samples by Radiological Activity (Bq/kg).

Here is the diagram showing the classification of glauconite samples by radiological activity. Each bar represents the total activity from Potassium-40 (green), Radium-226 (orange), and Thorium-232 (red). The dashed blue line marks the IAEA safety threshold of 370Bq/kg. Comparative analysis with other terrigenous deposits (such as argillites, bentonites, and zeolites) demonstrates that glauconitic sandstones exhibit moderate radiological activity and may be considered safe for use, provided that appropriate technological standards for processing and disposal are observed. Conclusions:

1. The conducted study confirmed the presence of stable concentrations of  $^{40}\text{K}$  and traces of natural radionuclides in sedimentary glauconite.
2. Radiological hazard classification indicated that most samples are safe for limited use in construction and environmental technologies.
3. A correlation was established between glauconite maturity and increased radionuclide content, which should be considered during geological and technological assessment of deposits.
4. Further research is recommended to focus on thermoluminescence analysis of glauconite concentrates to evaluate their potential for radiation shielding and waste isolation applications.

**Conclusion.** The integrated mineralogical, geochemical, radiological, and stratigraphic investigation of glauconite-bearing formations from southern Kazakhstan has provided a comprehensive understanding of their genesis, maturity, and paleoenvironmental significance. X-ray diffraction and SEM analyses confirmed the presence of mature glauconite, characterized by concentric lamination, high crystallinity, and sub-rounded morphology. Granulometric data revealed a narrow distribution within the fine- to medium-sand fraction, consistent with in situ authigenesis under low-energy marine shelf conditions. Geochemical assays demonstrated elevated levels of  $\text{K}_2\text{O}$  and  $\text{Fe}_2\text{O}_3$ , indicating advanced stages of

glauconitization and efficient potassium fixation. Gamma spectrometric data further supported this conclusion, with  $^{40}\text{K}$  activity ranging from 430 to 620 Bq/kg and a positive correlation with  $\text{K}_2\text{O}$  content. All measured radioisotope concentrations remained within IAEA safety limits, suggesting potential use of these glauconitic clays in industrial or construction materials.

Stratigraphically, glauconite occurs within condensed Paleocene–Eocene transgressive intervals, primarily associated with maximum flooding surfaces. Maturity classification based on potassium content and grain morphology indicates a predominance of transitional to mature glauconite stages. Laboratory simulations under controlled pH, potassium, and iron conditions successfully replicated glauconite formation pathways, reinforcing the interpretation that glauconite in the studied area developed under prolonged diagenetic conditions in a stable marine environment.

Overall, these findings highlight the value of glauconite as both a stratigraphic marker and a paleoenvironmental indicator, with implications for basin analysis, chronostratigraphy, and potential resource utilization in southern Kazakhstan.

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ISSN 2518-170X (Online),  
ISSN 2224-5278 (Print)**

Managing Editor: *T. Apendiev*  
Editors: *D.S. Alenov, A.Shormakova*  
Computer layout: *G.D. Zhadyranova*

Signed for print: April 10, 2026  
Format: 70×90 1/16. 26.5 printed sheets. Order No. 2.