

UDC 593.95-11

**ZIRCONS AND TITANOMAGNETITES  
OF THE SEA URCHIN *SCAPHECHINUS GRISEUS* (MORTENSEN, 1927)  
(ECHINODERMATA: ECHINOIDEA: SCUTELLOIDA)**

© 2026 Yu. Elkin<sup>1</sup>, S. Maksimov<sup>2</sup>, and A. Begun<sup>3</sup>

<sup>1</sup>G. B. Elyakov Pacific Institute of Bioorganic Chemistry FEB RAS, Vladivostok, Russian Federation

<sup>2</sup>Far East Geological Institute FEB RAS, Vladivostok, Russian Federation

<sup>3</sup>A. V. Zhirmunsky National Scientific Center of Marine Biology FEB RAS, Vladivostok, Russian Federation

E-mail: [andrejbegun@yandex.ru](mailto:andrejbegun@yandex.ru)

Received 23.07.2024; revised 18.11.2024;

accepted 21.11.2025.

Sea urchins, representatives of the suborder Scutelloida, accumulate in diverticula mineral particles of the sandy substrate. Juveniles of *Scaphechinus mirabilis* A. Agassiz, 1864 select and accumulate crystals of only very rare minerals: zircon and ilmenite. In this work, minerals in diverticula of the related species, *Scaphechinus griseus* (Mortensen, 1927), were determined for the first time. This species, the same as *S. mirabilis*, inhabits sandy substrate off the southern coast of the Russky Island (the Sea of Japan). Their co-existence is determined by the common structure of feeding behavior, which includes feeding on diatoms and, possibly, inorganic compounds. The mineral composition in diverticula was found to be the same for the two species of the genus *Scaphechinus* A. Agassiz, 1864. Our analysis showed the priority of zircon selection by *S. mirabilis* compared to *S. griseus*. The content of mineral oxides in bottom sediments at sampling sites was low. As revealed, the main organic food of the studied sea urchins from the bottom marine substrate is diatoms, represented by 17 species from the classes Coscinodiscophyceae (4 species), Fragilariophyceae (2), and Bacillariophyceae (11). Among them, solitary marine benthic forms, *Navicula dumontiae* Baardseth et Taasen, 1973 ( $128 \cdot 10^3$  cells·cm<sup>-3</sup>), prevailed, as well as planktonic forms settling from the pelagic zone, *Asterionella formosa* Hassall, 1850 ( $106 \cdot 10^3$  cells·cm<sup>-3</sup>). The high abundance of diatoms ( $245 \cdot 10^3$  cells·cm<sup>-3</sup>) in coastal bottom sediments in sea urchin habitats may contribute to the successful development of these two endemic species of echinoids in the Sea of Japan. These findings are important for expanding our understanding of the trophic preferences of two related sea urchin species living beneath the surface of the sandy seabed.

**Keywords:** diatoms, minerals, zircon, ferrotitanium, diverticulum, sea urchin

Burrowing sea urchins (Echinodermata: Echinoidea: Scutellidae) inhabit a niche of sandy substrates of seabed below the intertidal zone. Due to numerous chemoreceptors on arms of microscopic spines and tube feet on both sides of a slightly concave discoid endoskeleton, sea urchins are able to recognize weight, size, and chemical nature of food particles, before those enter the gut [Ghiold, 1983]. Sea urchins consume meiobenthos and detritus, along with mineral particles from surrounding sandy

substrate [Ellers, Telford, 1984]. Animals of the suborder Scutelloida have a voluminous diverticulum, where they accumulate collected mineral grains [Zachos, Ziegler, 2024; Ziegler, Barr, 2018]. Some researchers associated deposition of heavy iron minerals and silicon oxides, which are common in bottom sediments, with formation of a “weight belt” by sea urchins in shifting sandy bottom [Chia, 1973]. Later, doubts arose about the function of this ballast [Chen, Chen, 1994]. Discussion of the revealed discrepancy led to a conclusion that the ability of *Scaphechinus* A. Agassiz, 1864 representatives to select mineral grains from bottom sediment to form the “weight belt” results from evolutionary development of most species of this genus [Mooi, Chen, 1996]. As also reported in this paper, diverticula of large Scutelloida, *Scaphechinus mirabilis* A. Agassiz, 1864 and *Scaphechinus griseus* (Mortensen, 1927), were filled with fine sand and crystals (their mineral composition remained unknown). Later, it was established as follows: in *S. mirabilis* diverticula, only zircon (85% volume fraction) and ilmenite (15% volume fraction) were accumulated, although the grain content of these minerals in the bottom substrate amounted to hundredths of a volume percentage, *i. e.*, it was four orders of magnitude lower [Elkin et al., 2012]. Also, the question arose about the ability of a sea urchin to recognize zircons and ilmenites (a class of titanium-iron oxides) in bottom sediments. The animal’s capability to sort minerals in its gut involving the peristaltic diverter of the rectum and to direct them into diverticula has been reported recently [Zachos, Ziegler, 2024]. The phenomenon requires further study: it is necessary to determine yet unknown factors that enable *S. mirabilis* juveniles to select and double-sort these rare minerals (zircon being a priority) from the surrounding substrate before accumulating them.

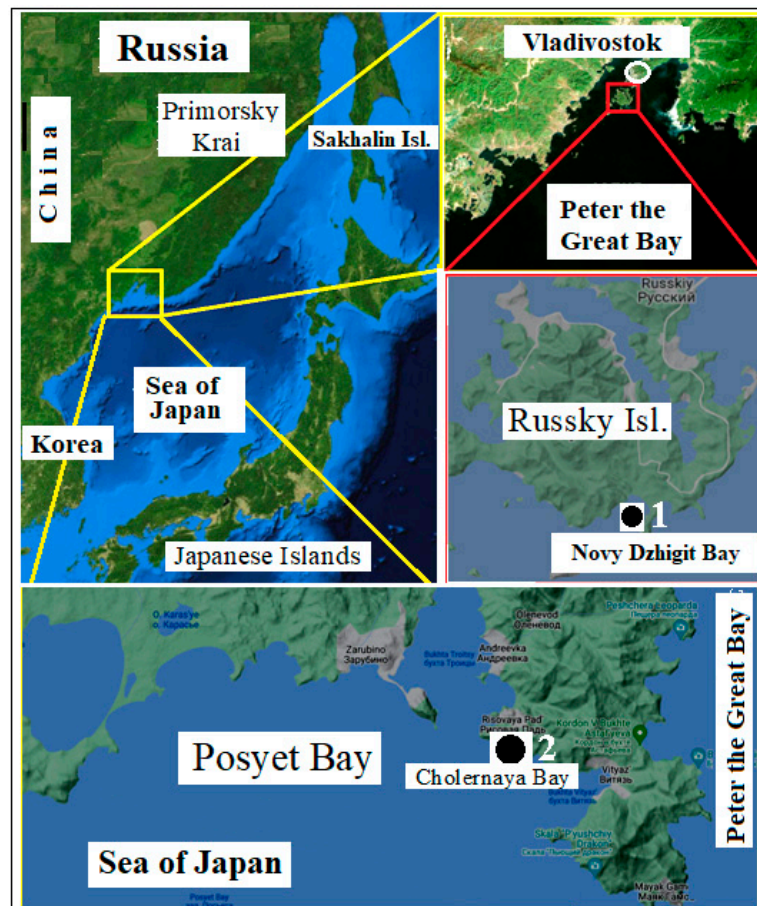
The emergence of new knowledge on *S. mirabilis* physiology has sparked interest in analyzing minerals from diverticula of a related species, *S. griseus*, within the same biogeocenosis, using *S. mirabilis* as an “internal standard.” Unfortunately, *S. griseus* does not form populations in bottom sediment of the Kholernaya Bay (the Sea of Japan), where the studied *S. mirabilis* specimens were sampled (in the vicinity of eroding Permian granodiorites of the Gamovsky massif) [Elkin et al., 2012]. The discovered coexistence of the two sea urchin species off the southern coast of the Russky Island, where Permian granite formations are exposed, provided an opportunity to analyze minerals *S. griseus* accumulates.

The aim of this study was to determine composition of minerals accumulated by *Scaphechinus griseus*. This will help in understanding preferences in mineral selection and its phenomenon, clarifying characteristics of accumulation, and establishing their role in sea urchin physiology.

## MATERIAL AND METHODS

The sea urchins *S. mirabilis* and *S. griseus* served as the study material (mean sizes were 45 and 30 mm, respectively). Eleven specimens of each species were sampled on 31 October, 2013, in the Novy Dzhigit Bay (southern area of the Russky Island, Sea of Japan) (N42.95°, E131.85°) at a depth of 5–6 m (Fig. 1). Sediments with sea urchins were sampled by divers at the animals’ habitat from the top 10-cm sand layer with a plastic cup of 30 cm<sup>3</sup>. Simultaneously, by a similar technique, sediments were sampled in the Kholernaya Bay (the Posyet Bay, Sea of Japan) from the top 10-cm sand layer at a depth of 5 m. The animals were fixed in 96% ethanol and then air-dried. Mineral grains were manually removed from diverticula under a binocular microscope. Bottom sediments – fine-grained sand – were also dried and sieved on standard sieves (> 0.063 and < 0.2 mm) to obtain a fine mineral fraction similar in size to that consumed by sea urchins. The heavy mineral fraction was separated by precipitation in tetrabromomethane (specific weight was 5 g·cm<sup>-3</sup>) diluted with acetone. Titanomagnetites were extracted

from the heavy fraction with a magnet. The technique for separation, extraction, and identification of minerals is described in [Elkin et al., 2012]. Mineral grains were identified under a Jenaval binocular light microscope (Carl Zeiss, Germany) at magnifications 40× to 400×. Volume percentage of registered minerals was calculated from their known specific weights.



**Fig. 1.** Schematic map of the study area. The dots mark sites of sampling of sea urchins and bottom sediment in the Novy Dzhigit Bay (1) and Kholernaya Bay (2) of the Sea of Japan

To determine the species composition and diatom abundance, a sandy sediment sample was washed with filtered seawater, suspended, and fixed in a 4% formalin solution. The suspension was then filtered on an 80- $\mu\text{m}$  Nitex nylon mesh (Sefar, Switzerland). Fractions of these washings were concentrated by precipitation to 4–5 mL. Laboratory and microscopic processing of the material was carried out according to previously described techniques [Ryabushko, Begun, 2015]. Microalgae were identified under an Olympus BX41 upright light microscope with a UPLanF1 100×/1.30 objective (Japan). For several Bacillariophyta species, we involved permanent preparations and used traditional methods of frustule cleaning [The Diatoms of the USSR, 1974]. Diatom species composition was clarified under a Sigma 300 VP scanning electron microscope (Germany). Microalgal cells were counted in a 0.9-mL Goryaev chamber, in five replicates; cell abundance was calculated *per* 1 cm<sup>3</sup> of bottom sediment. Species were identified according to several guides and atlases referenced in the monograph [Ryabushko, Begun, 2015]. The algal names follow AlgaeBase [2026].

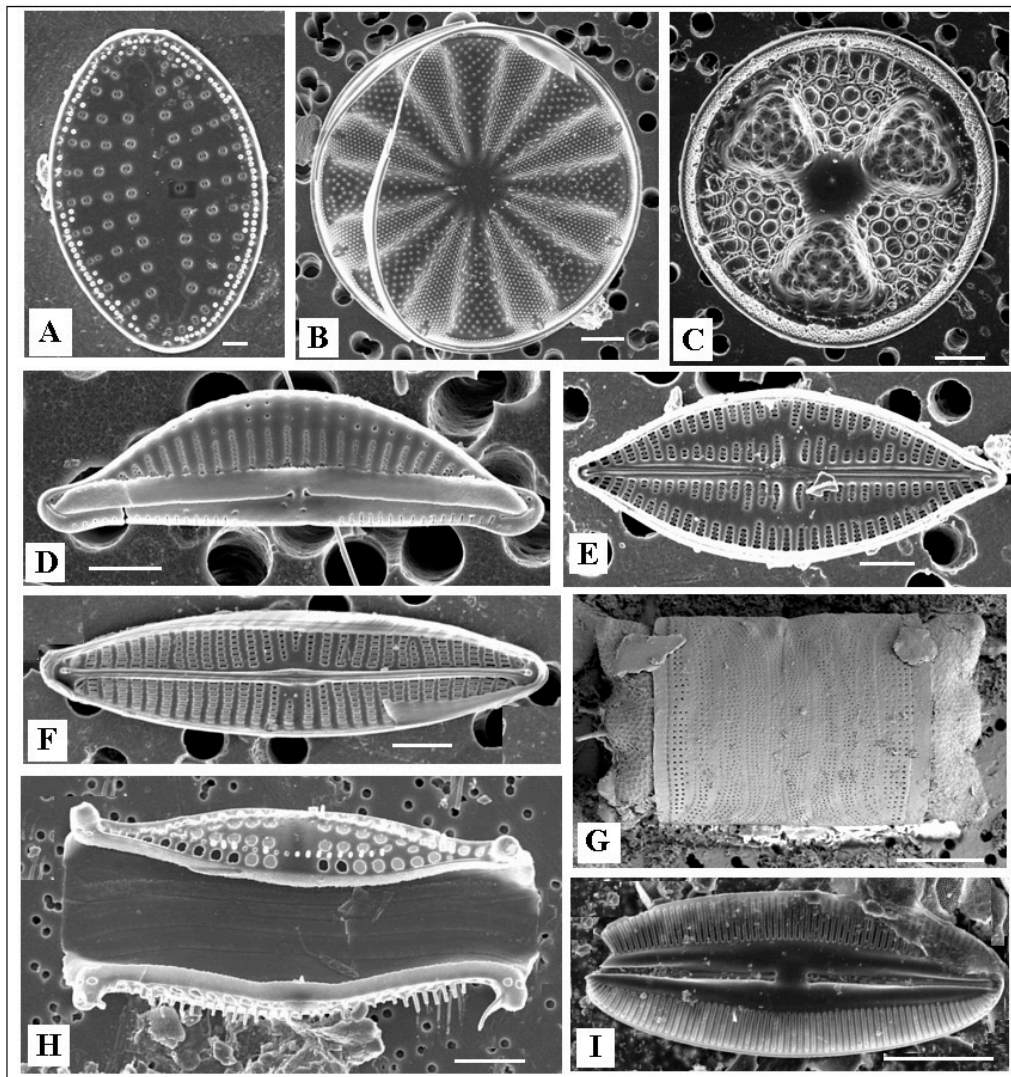
## RESULTS

The results of mineral analysis in bottom sand and diverticula of the sea urchins *S. mirabilis* and *S. griseus* are given in Table 1. The amount of ferrotitanium minerals (titanomagnetite and ilmenite) in the habitat of these species in the Novy Dzhigit Bay was 5–6 times higher than that in the previously studied Kholernaya Bay [Elkin et al., 2012], while the amount of zircon was slightly lower. The mineral composition of sediments sampled off the Russky Island and in the Kholernaya Bay differs in proportions of titanomagnetite and ilmenite alone. Animals of both species selected 4 out of 11 minerals of 0.063–0.2-mm fraction. The composition of minerals accumulated by these sea urchins was identical; however, in *S. griseus*, 5/6 of the minerals were titanomagnetites, and only 1/6 was zircon. The prevalence of titanomagnetites in diverticula of both sea urchin species is likely due to their high content in sediments. The fact that the volume fraction of light minerals in diverticula amounts to only 7–10% may be explained by the stress on animals because of high wave activity in their habitat.

**Table 1.** Composition of mineral particles of bottom sediments in the habitat of sea urchins *Scaphechinus mirabilis* and *S. griseus* and in their diverticula, % volume fraction

Mineral ( $\leq 0.2$ mm)	Bottom sediments	<i>Scaphechinus mirabilis</i>	<i>Scaphechinus griseus</i>
Quartz, feldspar	69.3	5.5	7.0
Rock particles	26.8	2.6	2
Amphibole	0.87		
Mica	0.99		
Epidote	1.9	1.4	1.0
Titanomagnetite	0.057	4.5	12.0
Ilmenite	0.052	40.4	64.0
Zircon	0.001	45.6	14.0
Andalusite	0.006		
Cordierite	0.004		
Sphene	0.011		

Analysis of bottom sand in *S. mirabilis* and *S. griseus* habitat revealed the presence of 17 diatom species from the classes Coscinodiscophyceae (4 species), Fragilariophyceae (2), and Bacillariophyceae (11): *Actinoptychus senarius* (Ehrenberg) Ehrenberg, 1843; *A. vulgaris* f. *vulgaris* Schumann, 1867; *Asterionella formosa* Hassall, 1850; *Delphineis surirella* (Ehrenberg) G. W. Andrews, 1981; *Diploneis smithii* (Brébisson) Cleve, 1894; *Fogedia finmarchica* (Cleve & Grunow) Witkowski, Metzeltin & Lange-Bertalot, 1977; *Halamphora cuneata* (Cleve) Levkov, 2009; *Lyrella clavata* (Gregory) D. G. Mann, 1990; *Lyrella lyra* (Ehrenberg) Karajeva, 1978; *L. spectabilis* (W. Gregory) D. G. Mann, 1990; *Navicula dumontiae* Baardseth et Taasen, 1973; *N. cancellata* var. *retusa* (Brébisson) Cleve, 1895; *N. perrhombus* Hustedt ex Simonsen, 1962; *Odontella aurita* (Lyngbye) C. Agardh, 1832; *Petroneis monilifera* (Cleve) A. J. Stickle & D. G. Mann, 1990; *Plagiogramma staurophorum* (W. Gregory) Heiberg, 1863; and *Plagiogrammopsis vanheurckii* (Grunow) Hasle, Stosch & Syvertsen, 1983 (Fig. 2). The total diatom population density in bottom sand was 245 cells·mL<sup>-1</sup>. The prevailing species were a benthic one, *N. dumontiae* (59%), and a planktonic one, *A. formosa* (25%).



**Fig. 2.** Diatoms in bottom sand in the habitat of sea urchins *Scaphechinus mirabilis* and *S. griseus* (a scanning electron microscope): A, *Delphineis surirella*; B, *Actinoptychus vulgaris* f. *vulgaris*; C, *A. senarius*; D, *Halamphora exigua*; E, *Fogedia finmarchica*; F, *Navicula dumontiae*; G, *Odontella aurita*; H, *Plagiogrammopsis vanheureckii*; I, *Diploneis smithii*. Scale bars are 1  $\mu\text{m}$  (A), 4  $\mu\text{m}$  (B), 2  $\mu\text{m}$  (C–G), and 10  $\mu\text{m}$  (H, I)

## DISCUSSION

Despite the difference in the quantitative content of ferrotitanium minerals, the sea urchin *S. mirabilis* was very conservative when selecting crystals [Dawkins, 1982]: in its diverticulum, the volume fraction of zircon amounted to 45%, the same as that of titanomagnetite. Interestingly, the content of both minerals in bottom sediments was 4 orders of magnitude lower.

Comparative analysis of minerals, especially zircon, in diverticula of the studied sea urchin species suggests their involvement in physiological processes of Scutelloida. The phenomenon of zircon and ilmenite agglutination is also known for protists [Capotondi et al., 2019; Sabbatini et al., 2016] from Adriatic sediments. We hypothesized that the processes resulting in crystal accumulation in Protozoa may be similar to the processes occurring on the cam collagen surface of Scutelloida miliary spines. Apparently, electrochemical and physical properties of zircon crystals are somehow related to physiological processes in protists and sea urchins: seabed dwellers that are distinctly different in their evolutionary

development. This refers to a supposed role of zircon in nutritional physiology of *S. mirabilis*, given that its species-specific gut microbiota is involved in bioleaching of mineral elements, *e. g.*, K, P, Ag, and Fe [Elkin et al., 2013]. On the other hand, accumulation of minerals geochemically related to Zr and Ti may be due to their yet unknown role in catalyzing biochemical processes in sea urchin diverticula [Pinsino et al., 2015].

Seabed facies, in the absence of river runoff, were also found to be poor in plant and algal detritus. However, in a “surf mill” of coastal pebbles above the sea urchin sampling site, benthic diatoms occur, which are the main group of microscopic autotrophs [Martin, Quigg, 2012]. Planktonic diatoms also settle in seabed facies in the case of active hydrodynamics; that is why phytoplankton and microphytobenthos in coastal areas are linked into a single ecological and floristic complex [Ryabushko, Begun, 2015]. Importantly, in addition to diatoms, food spectra of *S. mirabilis* and *S. griseus* cover meio-benthos. This was determined by comparing the growth rates of sea urchin juveniles near the river mouth and far from it [Brykov, Parysina, 1979].

Previously, near the Volchanka River mouth (Vostok Bay of the Sea of Japan), the sea urchin *Echinarachnius parma* (Lamarck, 1816) was studied, which occupies the same ecological niche as *S. mirabilis* and *S. griseus* [Ryabushko, Begun, 2015]. The analysis of its gut revealed the presence of diatoms from 22 taxa. Among them, there were species of the genera *Plagiogramma* R. K. Greville, 1859, *Navicula* J. B. M. Bory de Saint-Vincent, 1822, *Lyrella* N. I. Karayeva, 1978, *Halamphora* (Cleve) Z. Levkov, 2009, and *Diploneis* (C. G. Ehrenberg) P. T. Cleve, 1894, primarily benthic ones. Several of the species recorded in the aforementioned work were also registered by us during a survey of sandy bottom sediments of the Novy Dzhigit Bay (the Russky Island). Diatoms are known for their high levels of valuable lipids, such as long-chain polyunsaturated and monounsaturated fatty acids, polar lipids, triglycerides, steroids, and oxylipins [Maltsev et al., 2023; Yi et al., 2017]. This determines the high nutritional value of diatoms for sea urchins in sublittoral biotope of seas. Diatoms, along with detritus and remnants of macroalgae and seagrasses, are the key component of organic nutrition of *S. mirabilis* and *S. griseus* [Telford et al., 1983]. Probably, sea urchins receive mineral elements they need for nutrition from zircon and titanomagnetite crystals that accumulate in their diverticula. The benthic substrate inhabited by *S. mirabilis* and *S. griseus* consists of eroded granitoid coastal formations containing these minerals.

**Conclusion.** For the first time, minerals were identified in diverticula of burrowing sea urchins *Scaphechinus griseus* and *S. mirabilis* cohabiting sandy substrate off the southern coast of the Russky Island (the Sea of Japan). As established, both species accumulate in their diverticula zircons and titanomagnetites: extremely rare minerals in seabed substrates. *S. mirabilis* primarily accumulates zircon. Presumably, terrigenous crystals found in diverticula of these urchins are one of the components of the mineral nutrition of Echinodermata. Diatoms are important in organic nutrition of both *S. mirabilis* and *S. griseus*. In their habitat, a relatively high abundance of Bacillariophyta was recorded, and this can be considered one of the factors contributing to their confinement to this biotope. The results of this study are important for understanding the trophic preferences of these related sea urchin species.

*The work was carried out at the Resource Collection “Marine Biobank” core facility (NSCMB FEB RAS) within the framework of the state research assignment of the Ministry of Science and Higher Education of the Russian Federation No. 124021900009-6.*

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**ЦИРКОНЫ И ТИТАНОМАГНЕТИТЫ  
МОРСКОГО ЕЖА *SCAPHECHINUS GRISEUS* (MORTENSEN, 1927)  
(ECHINODERMATA: ECHINOIDEA: SCUTELLOIDA)**

**Ю. Н. Елькин<sup>1</sup>, С. О. Максимов<sup>2</sup>, А. А. Бегун<sup>3</sup>**

<sup>1</sup>Тихоокеанский институт биоорганической химии имени Г. Б. Елякова ДВО РАН,  
Владивосток, Российская Федерация

<sup>2</sup>Дальневосточный геологический институт ДВО РАН, Владивосток, Российская Федерация

<sup>3</sup>Национальный научный центр морской биологии имени А. В. Жирмунского ДВО РАН,  
Владивосток, Российская Федерация

E-mail: [andrejbegun@yandex.ru](mailto:andrejbegun@yandex.ru)

Морские ежи, представители подотряда Scutelloida, накапливают в дивертикулах минеральные частицы песчаного субстрата. Молодые особи *Scaphechinus mirabilis* A. Agassiz, 1864 выбирают и накапливают кристаллы только очень редких минералов — циркона и ильменита. В данной работе впервые определены минералы в дивертикулах родственного вида, *Scaphechinus griseus* (Mortensen, 1927), обитающего совместно с *S. mirabilis* в песчаном субстрате у южного побережья острова Русский (Японское море). Их сосуществование обусловлено общей структурой питания, включающей диатомовые водоросли и, возможно, неорганические соединения. Состав минералов в дивертикулах оказался одинаковым для двух видов рода *Scaphechinus* A. Agassiz, 1864. Проведённый анализ показал приоритет отбора циркона видом *S. mirabilis* в сравнении с *S. griseus*. Содержание оксидов минералов в донных отложениях в местах пробоотбора было небольшим. Установлено, что основной органический корм исследуемых ежей из придонного морского субстрата — диатомовые водоросли, представленные 17 видами из классов Coscinodiscophyceae (4 вида), Fragilariophyceae (2) и Bacillariophyceae (11). Среди них количественно преобладали одиночно живущие морские бентосные формы, *Navicula dumontiae* Vaardseth et Taasen, 1973 ( $128 \cdot 10^3$  кл.·см<sup>-3</sup>), и оседающие из пелагиали планктонные, *Asterionella formosa* Hassall, 1850 ( $106 \cdot 10^3$  кл.·см<sup>-3</sup>). Обилие диатомей ( $245 \cdot 10^3$  кл.·см<sup>-3</sup>) в прибрежных донных осадках в местах обитания морских ежей может способствовать успешному развитию в Японском море этих двух эндемичных видов эхиноидей. Полученные данные существенны для расширения знаний о трофических предпочтениях двух родственных видов морских ежей, обитающих под поверхностью песчаного морского дна.

**Ключевые слова:** диатомовые водоросли, минералы, циркон, ферротитан, дивертикул, морской ёж