ГЕОМОРФОЛОГИЯ И ПАЛЕОГЕОГРАФИЯ, 2023, том 54, № 3, с. 67–80

НАУЧНЫЕ СООБЩЕНИЯ

УДК 551.435(440.46+440.47)

SEDIMENTARY CHARACTERISTICS OF BAER KNOLLS DEPOSITS IN THE VOLGA RIVER DELTA[#]

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Received October 21, 2022; revised October 21, 2022; accepted March 14, 2023

Baer knolls (BK) are elongated ridges often close to the sub-latitudinal orientation sometimes spatially isometric that are widespread in the entire Northern Caspian Region up to 0 m a.s.l. (the upper limit of the Late Khvalynian sea transgression). The goal of this study was to establish the genesis of BK based on interpretation of textural and lithologic characteristics of sediments and dating the material composing these landforms. Research has led to the following conclusions that BK have been formed during the transition of Late Khvalynian and Early Holocene time. Sediments of BK consists of three lithofacies (LF1, LF2, LF3). Chocolate clay (CC) and Volga alluvium were significant sources of material for knolls formation. Nonetheless, for lithofacies 1, it was also sandy material lying below the CC. The BK material cannot be attributed to the aeolian genesis because of its lithological, faunal and geochemical characteristics. The knolls formed in brackish subaquatic conditions of the lagoon floor, where a low-energy currents occurred due to the descent of Late Khvalynian basin waters through the Manych Strait. Thus, BK are analogues of river bedforms appearing as the result of turbulent flow, like ripples and river dunes, where, in concordance with the accumulation of sandy material and detritus of redeposited shells, clay particles were deposited under the mixing of the brackish water of the lagoon and the fresh water of the rivers flowing into it.

Keywords: Late Pleistocene, the Caspian Sea, underwater bedform accumulation, Khvalynian time, Stratigraphy, the Volga Delta

DOI: 10.31857/S2949178923030052, **EDN:** WDAEYY

INTRODUCTION

Baer knolls (BK) are landforms named after a member of the Russian Geographical Society, Carl von Baer, who described its morphometrical characteristics and origin for the first time (Baer, 1856). The study of these landforms dates back to more than 150 years (Pravoslavlev, 1929; Yakubov, 1952; Svitoch, Klyuvitkina, 2006; Badyukova, 2018; Lavrushin et al. 2019). Researchers interpret the material composing a particular landform, the features of its spatial distribution and orientation very differently. The aeolian origin is the most popular among the scientific community (Fedorovich, 1941; Volkov, 1960; Leontyev and Foteeva, 1965; Belevich, 1979; Kroonenberg et al., 1997). There are also fluvial, deltaic, (Pravoslavlev, 1929; Zhukov, 1935; Doskach, 1949; Yakubov, 1952), marine, including interference of longshore currents, surges-drives phenomena (Berg, 1908; Britzina, 1955; Nikolaev, 1955; Zhindarev et al., 2001; Svitoch and Klyuvitkina, 2006; Rychagov, 2009), tectonic (Aristarkhova, 1980; Leonov and Lavrushin, 1995; Lavrushin et al., 2019) and permafrost hypothesis (Ryabukha, 2018). The article summarizes all the current views that are complemented by an extensive bibliography and presents scrupulous results of various analyzes, mainly based on the research of the Lower Volga Region and its delta.

The relevance of this research is in studying Baer knolls as landforms dated back to the Late Khvalynian stage of the Caspian Sea transgression as a key to reconstructing the history of the Caspian Region, and environmental features that existed on its shores during the Late Pleistocene – Holocene transition. BK are a natural heritage of the landscape that existed close to the Caspian Sea.

The Caspian Lowland was chosen as a study area because of a large volume of published material, covering several key sections along the Volga River Region and peripheral territory. Baer knolls are relict landforms but are remarkably well-preserved in the studied landscape. The research objective is a detailed study of the internal structure of the Baer knolls and their lithological features for a more reliable interpretation of their genesis. It will help to clarify the history of the Caspian Sea fluctuations during the Late Pleistocene

[#] *For citation:* Lobacheva D.M., Badyukova E.N., Makshaev R.R. (2023). Sedimentary characteristics of Baer knolls deposits in the Volga River Delta. *Geomorfologiya i Paleogeografiya*. Vol. 54. No. 3. P. 67–80. https://doi.org/10.31857/S2949178923030052; https://elibrary.ru/WDAEYY

and Early Holocene. The main problem of this research is incomplete and often ambiguous data. The article aims to revise the previous interpretations presented by various researchers on the proposed genesis by receiving new data based on modern methods as a supplement to an earlier publication (Badyukova, 2018). For the first time, result of X-ray fluorescence analysis of sediments from several Baer knolls at the Volga Delta is presented.

SITE INFORMATION

Caspian Sea setting and palaeogeography. The Caspian Sea is the largest inland water basin on Earth, which occupies 378400 km^2 and contain more than 78000 km^3 of water (Svitoch, 2014). The water catchment area is up to 3.6 million km^2. The present surface elevation of the Caspian Sea is – 27 m below sea level and the average depth is 180 m. The average salinity of the Caspian Sea is 12.7‰, that varies between 1–3‰ near the Volga River Delta to 20.3‰ in the Balkhan Gulf. The basin is subdivided into three sections, North, Middle and South. The area of the North Caspian basin is 95000 km^2 with an average depth of 5 m and contain only 1% of the total water volume of the basin. River discharge into the North Caspian basin contributes 88% of total inflow to the basin (Svitoch, 2014).

During the Pleistocene, several transgressions (Akchagylian, Apsheronian, Bakunian, Urundzhikian, Early Khazarian, Late Khazarian, Hyrcanian, Early Khvalynian, Late Khvalynian and Novocaspian) and regressions (Tyurkyanian, Chelekenian, Singilian, Chernoyarian, Atelian, Enoetaevkian and Mangyshlakian) of the Caspian Sea occurred (Svitoch, 2014; Krijgsman et al., 2019). The Caspian Sea and the Black Sea were connected through the Manych passage during large transgression events (Fedorov, 1957; Svitoch, Yanina, 1997).

Geographical and geological setting. The Baer knolls area is located in the southeast part of the Northern Caspian Lowland occupying a south part of the Lower Volga River region, its Delta, the south-part of the Ural River Delta and a small area in north-west Caspian Lowland (fig. 1). The Baer knolls area covers approximately 55.5 km^2 and is limited by 0 m asl contour line.They are elongated ridges often close to the sublatitudinal orientation, sometimes spatially isometric. Ridges 3–10 m in height are spread throughout the Caspian lowland from the Emba River mouth on the eastern coast to the mouth of the Kuma River on the western coast of the Caspian Sea. Baer knolls have not been identified anywhere above the upper limit of the Late Khvalynian transgression (0 m asl).

In the Northern Caspian Region, the stratigraphy of Quaternary deposits in the study area is represented by the Bakunian, Khazarian, Atelian, Khvalynian and Novocaspian regional horizons (Fedorov, 1957; Svitoch, Yanina, 1997; Svitoch, 2014; Zastrozhnov et al., 2018). The marine deposits are predominated with an exception of Atelian sediments, which are represented by loess (Fedorov, 1957). The Baer knolls deposits are presented by Khvalynian sediments. The Khvalynian horizon corresponds to one of the largest transgression events in the Caspian Sea during the Pleistocene, when the sea level of the Khvalynian basin reached +45–50 m asl and occupied an area of 872000 km^2 (Fedorov, 1957; Aladin, Plotnikov, 2006; Svitoch, 2014).

The Khvalynian horizon is presented by the Lower Khvalynian and Upper Khvalynian sub horizons divided by Enotaevkian continental layer that correspond to eponymous regression event of the Caspian Sea (Svitoch, 2014).

MATERIAL AND METHODS

Field investigation. This study is based on interpretation of remote sensing data (satellite imagery and DEM SRTM arc-second global 1) and field investigations of the Baer knolls carried out in 2017–2019 in the Lower Volga River Region. We selected the group of knolls, where artificial and natural outcrops were identified (tabl. 1). Textural and lithological features of the Baer knolls were described during the detailed geomorphological investigations, based on a comprehensive interpretation of BKs position and landform configuration.

Sedimentological and geochemical analysis. Three lithofacies (LF) based on sedimentary structures and visual characteristics were identified during the investigations of the Baer knolls deposits in the Volga River Delta. Fifty samples for sedimentological analysis were collected from Yaksatovo (18), Mirnii (14), Nartovo (8), and Troitsky (10) knolls using a mini shovel. Seven samples for lithofacies 3, seventeen for lithofacies 2 and twenty-six for lithofacies 1. That BK possess three lithological formations (lower lithological formation (lithofacies 1), upper lithological formation (lithofacies 2), and chocolate clays (CC, lithofacies 3). However, in some BK there are only lithofacies 2, due to erosion of the lithofacies 1. All samples were dried at 50°C for 3 hours and then pretreated with 10% hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2) to remove carbonates and organic particles. To avoid coagulation, sodium pyrophosphate 5% ($Na_4O_7P_2$) was added into samples as a dispersion agent. Grain-size analysis for prepared samples (<1 mm) was conducted using Laser Diffraction Particle Size Analyzer Fritsch Analysette 22. The measurements were carried out with two lasers in the range from 0.8 to 2000 μm three times for 4 minutes each. Grain-size classes were presented according to Kachinskiy classification with limits by <1 μm, 1–5 μm, 5–10 μm, 10–50 μm, 50–250 μm, and 250–1000 μm (Kachinskiy, 1965). The sample analysis with using of sieves set (1000–

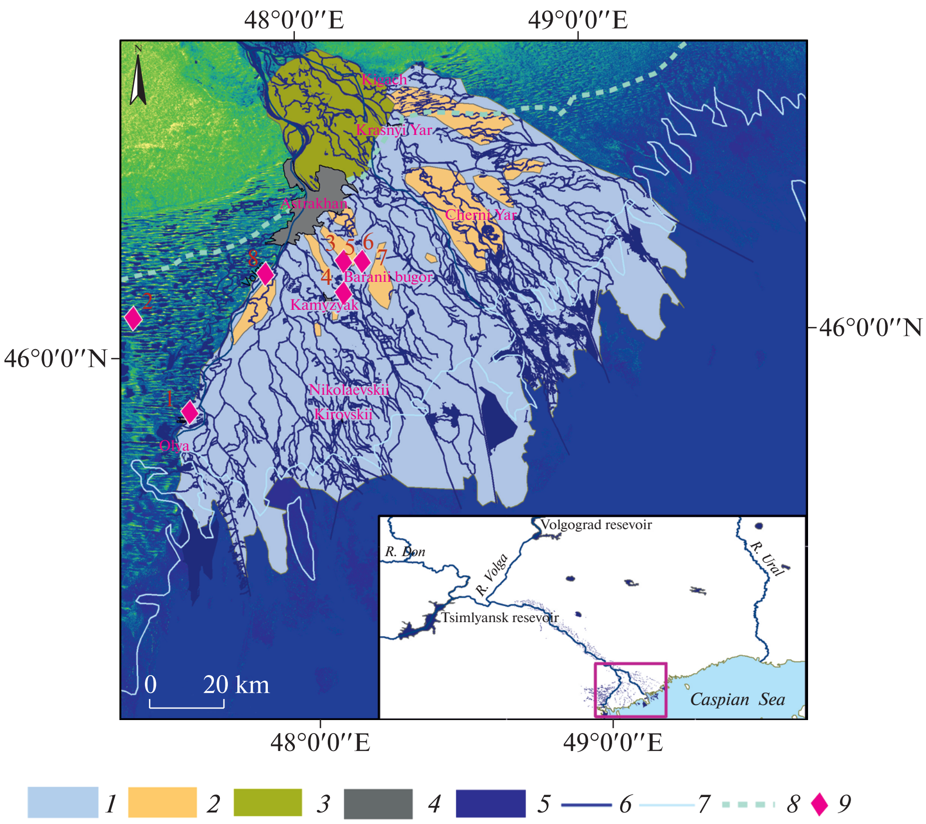

Fig. 1. Geological sketch and geographical setting of the Volga Delta: *1* – Holocene alluvial-marine deposits (Q_{4am}); *2* – Late Pleistocene alluvial-marine outliers (Q_{3am}); *3* – Volga floodplain (Q_{4a}); *4* – Settlements; *5* – Ilmeni and broad river deltaic channels; *6* – Rivers and channels; *7* – Coastline; *8* – New Caspian marine boundary (Q_{4m}); *9* – work area.

Рис. 1. Геологическая схема дельты Волги: *1* – голоценовые аллювиально-морские отложения (Q_{4am}); *2* – позднеплейстоценовые останцы бэровских бугров (Q_{3am}); *3* – пойма Волги (Q_{4a}); *4* – населенные пункты; *5* – ильмени и протоки дельты; *6* – реки и каналы; *7* – современная береговая линия моря; *8* – граница новокаспийской трансгрессии (Q_{4m}); *9* – участки работ.

2000 μm) showed the absence of fraction larger 1000 μm. Textures were determined using high-resolution photographs. Sedimentary bedding and depositional environments were defined according to L.N. Botvinkina (1962) and Reinek and Singh (1981). Major elements (TiO_2, CaO, Al_2O_3, SiO_2, Fe_2O_3, K_2O, MgO) were identified in 20 samples using induction-coupled plasma atomic emission spectrometry (ICP-AES).

Macrofaunal analysis. Twenty-five sediment samples containing mollusk shells were collected from investigated knolls (Yaksatovo, Mirnii, Nartovo, and Troitsky). Mollusk shells were extracted, measured, and then photographed. Sediment samples (1 kg) containing detritus were rinsed and then sieved using 1 mm mesh. Mollusk shells were selected for radiocarbon dating.

Radiocarbon dating. Mollusks shell samples of *Didacna protracta, D. parallella, D. praetrigonoides, Monodacna caspia, Dreissena polymorpha* were dated in a Radiocarbon dating laboratory at the Saint Petersburg State University (Russia, lab. index LU) according to scintillation technique (Arslanov, 1987). Radiocarbon ages were calibrated using CALIB 8.1. software (http://calib.org/calib/) and IntCal20 calibration curve (Reimer et al., 2020) with standard deviation 2σ. In table 2 below, in addition to the authors' own results, the calibrated dates obtained earlier are given (Svitoch and Klyuvitkina, 2006). In order to clearly display the available dates for the strata composing the knolls.

RESULTS

Lithofacies. Three main lithofacies (fig. 2, (a–e)) were identified basis on sedimentary structures, visual characteristics, colours, lamination type, grain-size (and geochemical composition (WD-XRF) in the studied Baer Knolls.

Lithofacies 1 (LF1). Cross-laminated sand is composed of 1 to 3 m thick light-pale brown to yellow-grey, very fine to medium quartz sand, with thin (2–5 mm) lenses of coarse sand. Silt lenses 1–4 mm thick sporadically alternate with 10–15 cm beds of very fine

Table 1. Studied Baer Knolls in the Volga River Region
Таблица 1. Изученные бугры Бэра в дельте Волги

No.	Section name	Year of investigation	Latitude	Longitude	Lithofacies
1	Troitsky	2018	45°59′58.49″ N	47°38′34.93″ E	LF1, LF2, LF3
2	Basy	2019	46°08′29.54″ N	47°02′19.01″ E	LF2
3	Yaksatovo	2018	46°14′44.25″ N	48°01′26.37″ E	LF1, LF2, LF3
4	Nartovo	2018	46°14′02.79″ N	48°02′15.34″ E	LF1, LF2
5	Funtovo-1	2019	46°14′03.62″ N	48°06′22.39″ E	LF1, LF2
6	Funtovo-2	2019	46°13′26.00″ N	48°08′06.83″ E	LF1, LF2
7	Kirpichnyy zavod	2019	46°16′21.64″ N	48°04′12.62″ E	LF1, LF2, LF3
8	Mirnii (Dolgii)	2018	46°22′14.76″ N	47°55′30.14″ E	LF1, LF2, LF3

sands. Coarse sand lenses usually contain detritus and rounded shell fragments of brackishwater mollusks. Sediments also contain rare mollusk species *Didacna protracta* and *Monodacna caspia*. Bird burrows *(Riparia riparia*) are typical in these sediments. High-angle crossbedding stratification is presented in this stratum. Often it correlates well with an angle of the slopes (fig. 3).

Lithofacies 2 (LF2). Criss-cross-laminated sand consists of approximately from 2 to 6 m thick brown-yellow and grey very fine to medium sand with horizontal planar lamination along the ridge of yellow-grey silt clay 1–3 cm thick (fig. 2, (b)). Low to high-angle cross lamination of sand and clay is presented in these sediments, especially along the knoll margins. In the upper part of deposits, rare large mollusk shells *Didacna protracta* are presented. In that lithofacies, *Ophiomorpha* burrows are presented too (fig. 2, (d)).

Lithofacies 3 (LF3). Chocolate clay is 1 to 2 m thick and dominated by brown to dark brown clay with thin (1–3 cm) lenses of yellow-grey very fine to fine sand. Low-angle cross lamination of sand and clay with thickness 50–80 cm are presented in the upper part of sediments. Sand layers usually contain shell fragments and whole shells species *Didacna protracta*, *D. parallella, Dreissena rostriformis* (fig. 2, (c)). These lithofacies present the chocolate clay stratum (CC) of Baer knolls.

Granulometric composition. Average grain-size composition of studied Baer knolls sediments is represented by <1 μm (13%), 1–5 μm (42.4%), 5–10 μm (13.7%), 10–50 μm (21.7%), 50–250 μm (8.7%) and 250–1000 μm (0.3%) The ternary diagram on fig. 4. reveals the distribution of granulometric composition of fifty BK sediments samples. LF2 is a mixture of sand, clay, and silt particles. In CC clay and silt fractions prevail. A few LF1 samples from the lower part demonstrate a composition similar to CC and LF2. The upper part of LF2 is enriched by sand and is similar to LF1.

Geochemistry. The bulk geochemical composition (wt %) of Baer knolls sediments are presented in table 3. The concentration of SiO_2 in CC, LF2, and LF1 ranges between 67–82%. SiO_2 content is higher in LF1. Meanwhile, concentrations of TiO_2, Fe_2O_3, Al_2O_3, K_2O are lower, because of decreasing of clay fraction in LF1. Otherwise, samples from LF2 and LF3 are characterized by a relatively higher concentration of TiO_2, Fe_2O_3, Al_2O_3 that are confined to clay fraction.

Malacological examination. Seven mollusks' species *Didacna protracta, D. ebersini, D. parallella*, *D. parallella borealis, D. praetrigonoides, Dreissena rostriformis, Dr. polymorpha* represent freshwater, and brackish water environments were identified in investigated knoll sediments. The upper part of LF3 is presented by brackish water assemblages with *Didacna protracta*, *D. parallella*, *D. parallella borealis, D. praetrigonoides.* Large and thick shells of *Didacna protracta*, *D. parallella* indicate long-term optimal living conditions with 8–13‰ paleo salinity (Yanina, 2012). However, the abundance of shells *Dreissena rostriformis* in the sand interlayers could indicate a regular supply of fresh water and a decrease in paleo salinity to 3–8‰. At contact between LF3 and LF2 the presence of a rich detritus layers and rare small shells *Didacna protracta, Dreissena polymorpha* could indicate an increase of current flows with suspended load water and slow stream environment conditions. Sand layers in LF2 and more often in LF1 are affluent in detritus of redeposited mollusk shells *Didacna catillus, D. praetrigonoides, Dreissena rostriformis, Hypanis plicatus,* etc. (fig. 5).

Radiocarbon dating. Five radiocarbon dates from Yaksatovo, Mirnii (Dolgii), and Sarai-Batu knolls ranges from 16.4 to 13.8 ka cal B.P. Results demonstrate that deposition of LF3, and LF2 correspond to the period from Oldest Dryas cold event to Bølling-Allerød warm stage. Two radiocarbon dates from the contact between LF3–LF2 suggest that deposition of LF1 corresponds to Bølling-Allerød warm stage. All dates with previous results for BK sediments are submitted in table 2.

Table 2. Absolute ages of Khvalynian deposits in the Baer knolls (the Volga Delta)
Таблица 2. Радиоуглеродные датировки отложений бэровских бугров (дельта Волги)

Lab. No.	Location	Material	Altitude (m Baltic absolute altitude system)	Depth, m	Lithofacies	^{14}C age, B.P.	(±) yr	Mean ^{14}C age (cal B.P.)	± yr (2σ)
Radiocarbon dates from this paper									
LU-8739	Yaksatovo	*Didacna praetrigonoides, D. parallella*	–20	4.5	Upper part LF3	12800	100	15296	298
LU-9200	Yaksatovo	*Didacna protracta*	–20	4.5	Contact LF2/LF3	12210	140	14221	427
LU-8740	Sarai-Batu	*Didacna ebersini, D. protracta, Dreissena rostriformis*	–21	7.5	LF3	13560	250	16365	700
LU-9201	Dolgii	*Didacna protracta, Dreissena polymorpha*	–19	3	Contact LF2/LF3	12000	120	13865	271
LU-9201	Dolgii	*Didacna protracta, Dreissena polymorpha*	–19.3	3.3	Contact LF2/LF3	12070	120	14019	287
Radiocarbon dates (Svitoch, Klyuvitkina, 2006)									
MSU-1609	Kudrino	–	–	–	Undivided knoll stratum	10900	100	12898	170
MSU-1488	Olya	*shells*	–	–	Undivided knoll stratum	9600	500	11082	1405
MSU-1439	Sergievka	*shells*	–	–	Undivided knoll stratum	11636	121	13532	236
MSU-1487	Sergievka	*Didacna praetrigonoides*	–	–	Undivided knoll stratum	18100	1950	21713	4267

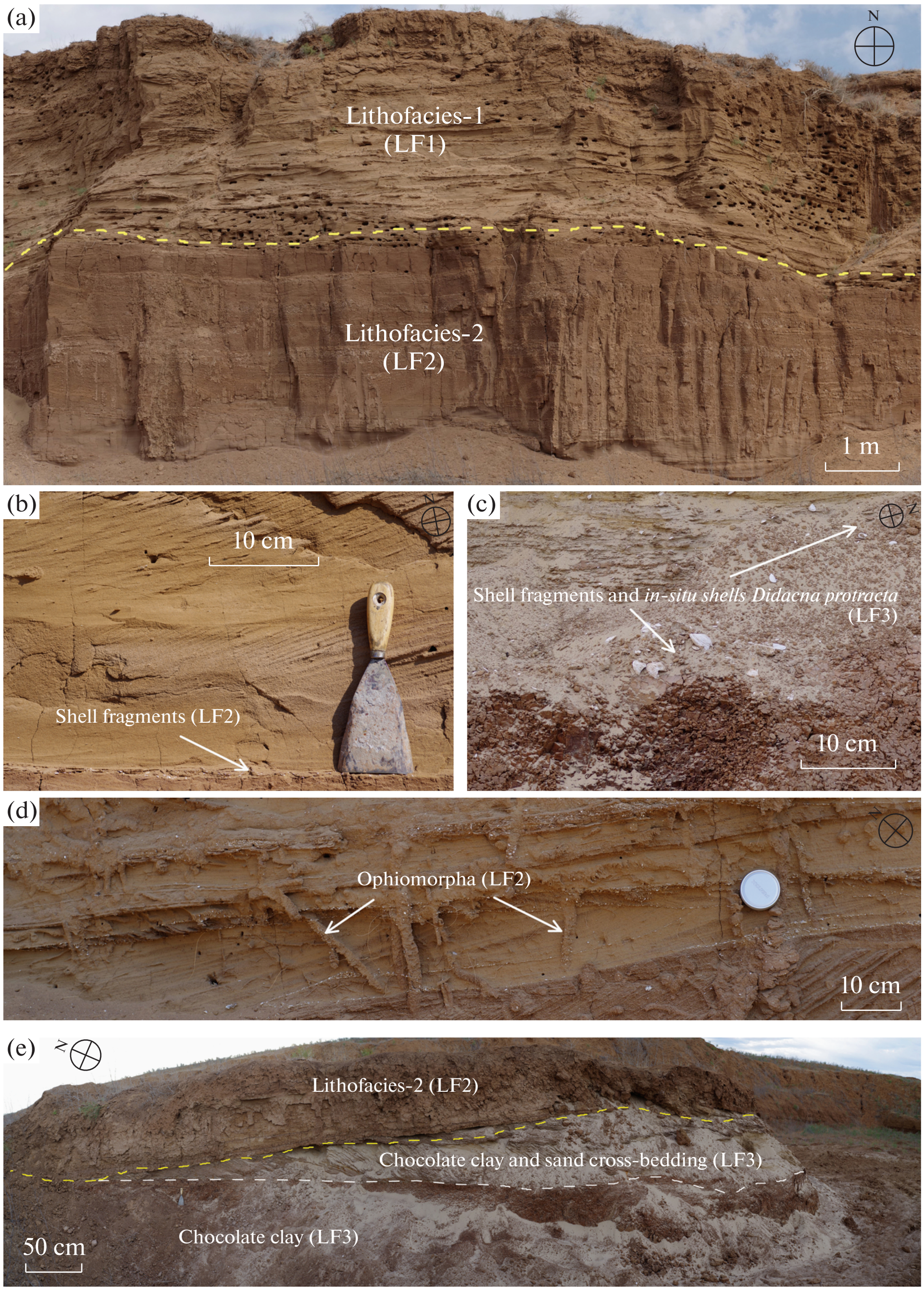

Fig. 2. Sedimentary architectures and lithofacies of Baer knolls: (a) – Yaksatovo knolls erosional contact between LF1 and LF2; (b) – cross-lamination sand and compacted coarse sand layer with shell detritus (LF1); (c) – mollusk shells *Didacna protracta, Dreissena rostriformis* in sand lenses (LF3); (d) – *Ophiomorpha* burrows presented in LF2 in Nartovo knoll; (e) – Mirnii knolls cross-lamination of sand and chocolate clay and erosional contact between LF2 and LF3.

Рис. 2. Литофациальное строение бугровых отложений: (a) – эрозионный контакт между ЛФ1 и ЛФ2, бугор Яксатово; (b) – прослои детрита и косая слоистость в ЛФ2, бугор Яксатово; (c) – раковины *Didacna protracta, Dreissena rostriformis* в песчаных прослоях ЛФ3, бугор Мирный; (d) – ходы *Ophiomorpha* в ЛФ2, бугор Нартово; (e) – литофациальное строение основания бугра Мирный, контакт между ЛФ2 и шоколадными глинами.

DISCUSSION

Sedimentary environments. The aeolian BK origin is prevalent among the scientific community (Fedorovich, 1941; Volkov, 1960; Leontyev and Foteeva, 1965; Belevich, 1979; Kroonenberg et al., 1997). It contradicts several statements: high cementation of the knoll strata, variety of lamination types, interlayers and lenses rich in shell detritus (fig. 6), erosional contacts between LF2 and LF1 (fig. 2, (f)), clay and silt

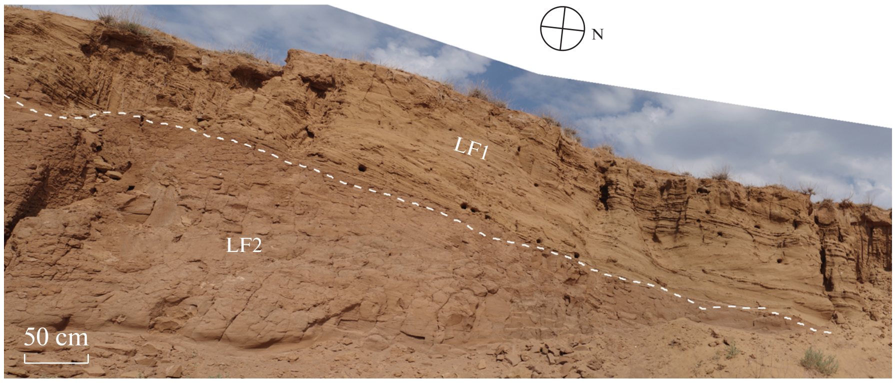

Fig. 3. Sedimentary architectures and LF1 and LF2 contact of west outcrop in Yaksatovo knoll.
Рис. 3. Строение толщ ЛФ1 и ЛФ2 на западной оконечности бугра Яксатово.

prevail, ripple marks in silty clay of LF2. If the Aeolian origin was relevant and the wind carried the clay particles, the question arises as to where such an amount of deposit would come from. O.K. Leontiev (1965) argues that fragments and whole shells could be transported over some distances by strong winds. However, we are not aware of the simultaneous aeolian transport of clay, silt, and sand mixture with shell fragments and detritus. Aeolian transport from the surface of the takyr is low because of the very gritty texture due to the high density and cementation. If it occurs, elementary dunes will be forming, approximately 1–1.5 m high (Makeev, 1933; Bowler, 1986). According to geochemistry and micromorphology of quarts grains, aeolian processes of sedimentation are mostly presented in the upper part (app. 60–80 cm) of BK deposits (Svitoch, Kluivitkina, 2006; Shaldybin et al., 2015).

Saltation or rolling, both causing frequent collisions of transported particles, would round the grains. However, the clay component of the knoll strata consists of flakes and clay pellets, often wholly unrolled. Thus, BK deposits cannot be attributed to aeolian origin (Badyukova, Lobacheva, 2020). Flakes and clay pellets often appear in brackish water due to particle coagulation (Botvinkina, 1962). According to malacofaunal analysis, the knolls are rich in organogenic content, particularly of shell detritus. We consider that such aeolian transport of whole shells and debris is impossible in the formation of detritus layers in BK. Based on fabric analysis, the most common lamination types of BK are oblique cross, multidirectional criss-cross (appeared by changing the direction of water jets), wavy with ripples, diagonal, horizontal. Such a variety of lamination is most likely reflecting the deltaic, estuarine, or lagoon type of aquatic sedimentation (Botvinkina, 1962). For the knolls on the north-eastern part of the Pre-Caspian lowland subhorizontal and gentle criss-cross fabrics are characteristic. In LF1 and LF2, the presence of sand and silt is noted together which is a feature of deltaic sediments (Badyukova, 2018). The presence of several modes in the grain-size distribution in LF2 is the same as in CC, which means that LF2 is inherited from the underlying CC. Oblique lamination is associated with the flowing reservoir, where currents occurred. They were slow and unstable, because of the existence of horizontal, weakly expressed lamination in sediments and the presence of ripple marks.

We assume that the deposition of the knoll strata occurred in water where was a mixture of river and sea waters (lagoonal environments). The absence of *in situ* shells or their extremely rare presence in the knoll's strata is on the one hand associated with increased turbidity of the reservoir and on the other with a low temperature of the water. Salt instigates the coagulation of

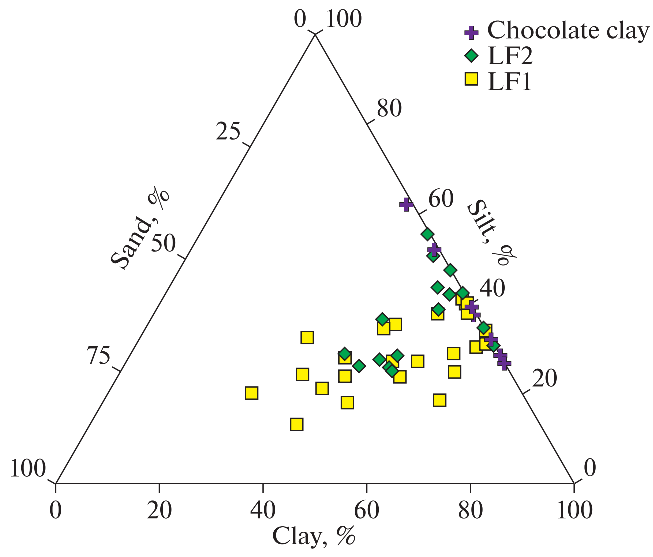

Fig. 4. Ternary diagram of sand, silt, and clay concentration in Baer knolls sediments (Yaksatovo, Troitsky, Mirnii, and Nartovo knolls).
Рис. 4. Треугольная диаграмма гранулометрического состава (песок, алеврит, глина) бугровых отложений из бугров Яксатово, Мирный, Нартово и Троицкий.

Table 3. The geochemical composition of Baer knoll deposits
Таблица 3. Геохимический состав бугровых толщ

Lab. No.	Site	Lithofacies	MgO	Al_2O_3	K_2O	CaO	TiO_2	Fe_2O_3	SiO_2
			(%)						
L 16-1	Yaksatovo	LF1	1.38	8.09	1.72	3.53	0.35	3.25	80.43
L 16-2	Yaksatovo	LF1	1.26	7.68	1.67	2.86	0.33	2.95	81.98
L 16-3	Yaksatovo	LF1	1.25	7.78	1.74	3.03	0.32	2.93	81.81
L 16-4	Yaksatovo	LF1	1.40	8.46	1.78	3.70	0.38	3.41	79.77
L 16-5	Yaksatovo	LF1	1.24	8.24	1.78	3.51	0.38	3.08	80.79
L 16-6	Yaksatovo	LF1	1.17	8.37	1.84	3.36	0.35	3.06	80.90
L 16-7	Yaksatovo	LF1	1.23	8.19	1.78	3.62	0.35	2.97	80.87
L 16-8	Yaksatovo	LF2	2.09	11.70	2.20	5.43	0.57	5.14	70.92
L 15-1	Troitsky	LF2	1.98	13.30	2.57	3.79	0.61	5.66	70.65
L 15-2	Troitsky	LF2	1.99	13.60	2.58	3.80	0.65	5.79	70.21
L 15-3	Troitsky	LF2	1.99	13.10	2.63	3.23	0.64	5.63	71.12
L 13-1	Troitsky	LF1	1.55	9.83	1.89	2.80	0.46	4.03	78.02
L 13-2	Troitsky	LF1	1.59	10.40	2.09	2.88	0.48	4.24	76.89
L 13-3	Troitsky	LF1	1.29	7.99	1.70	2.65	0.33	3.20	81.42
L 13-4	Troitsky	LF1	1.77	9.25	1.89	3.66	0.44	4.12	76.59
L 13-5	Troitsky	LF1	1.49	7.62	1.63	5.67	0.38	3.35	78.22
L 13-8	Troitsky	LF1	1.85	9.32	1.77	3.79	0.42	5.02	76.71
CC-40	Yaksatovo	LF3	3.12	11.80	2.42	4.82	0.58	6.74	69.37
CC-70	Yaksatovo	LF3	2.25	12.80	2.38	4.41	0.58	6.04	70.12
CC-150	Yaksatovo	LF3	2.18	15.70	2.92	3.56	0.64	6.52	66.85

the particles, rolling up and falling out in the form of flakes simultaneously with coarse silt and sand fractions. Sand accumulation co-occurred with shell redeposition on the background of deposition of clay particles. The mechanism of BK formation is described more narrowly by Badyukova (2018). We consider that the Baer knolls are analogues of river bedforms like ripples and large dunes, which were formed as a result of a slow stream.

Chronology. We used mollusk shells to determine the radiocarbon age of the Baer knoll (tabl. 2). The obtained dates show the age of the strata contacts. It makes it possible to verify the upper age of BK formation that correlates with the main events of the Late Pleistocene and Early Holocene.

The dates obtained for LF3 correspond to the interval 16.3–15.2 cal ka B.P. They correlate with the onset of the Oldest Dryas cold stage (Stefensen et al., 2008). Dates for LF2 are varying between 14.2 and 13.8 cal ka B.P. Dates of 13.4–11 cal ka B.P. derived from LF2 and LF1 were reported for BK sediments in the Volga Delta (Svitoch, Kluivitkina, 2006). It correlates with the beginning of the Younger Dryas cold event. That means that Baer knoll's lithofacies are not younger than 11 cal ka B.P.

Radiocarbon ages for BK deposits correspond well to OSL dates obtained for the Kosika section Lower Volga: 14.8 ka for LF1 and 18–16.7 ka for LF2 (Zastrozhnov et al., 2020). Thus, deposits of BK refer to an interval from 18 to 11 cal ka B.P. These dates refer to the redeposited shells, not to the age of knolls formation. The LF2 is dated younger than LF1, meaning that the strata accumulated successively due to erosion of underlying sediments. Chocolate clays and Volga alluvium were the significant sources of material for LF1 and LF2, as the bottom of the Late Khvalynian lagoon was eroding. Nonetheless, for LF1, it was also sandy material lying below the CC. We propose that Baer knolls could have been formed during the Late Khvalynian and Early Holocene transition.

Fig. 5. Mollusk shells: (a) – from the contact between chocolate clay and lithofacies 2 from Yaksatovo knoll, (b) – from the contact between lithofacies 1 and lithofacies 2 from Mirnii knoll.

Рис. 5. Образцы раковин: (a) – с контакта между шоколадными глинами и ЛФ2 бугра Яксатово, (b) – с эрозионного контакта между ЛФ2 и ЛФ1 бугра Мирный.

The possible analogues of Baer knolls in the World. Similar to BK landforms are widely distributed around the World. The closest analogues of BK are the so-called "grivy" in the south of Western Siberia (Vel'mina, 1964; Pil'nevich, 1974). This territory has a hilly-ridge landscape, where the ridges are more representative near the shores of Lake Chany. "*Grivy*" vary in spatial shape and length. There is a regular decrease in the absolute height of the ridges closer to the Turgai trough (Lavrov, 1948; Gorodetskaya, 1966). The ridges gradually decrease, spread out and disappear towards the edges of the lowland (Petrov, 1948). They compose mainly of loess-like loams; fine sandy, silty, and clayey fractions. As well as for BK, ridges of the south of Western Siberia (Barabinskaya lowland) have several hypotheses of their origin: aeolian (Volkov, 1961), fluvial (Pil'nevich, 1974; Lavrov, 1948, Velmina, 1964), erosional (Gorodetskaya, 1996), deltaic (Petrov, 1948).

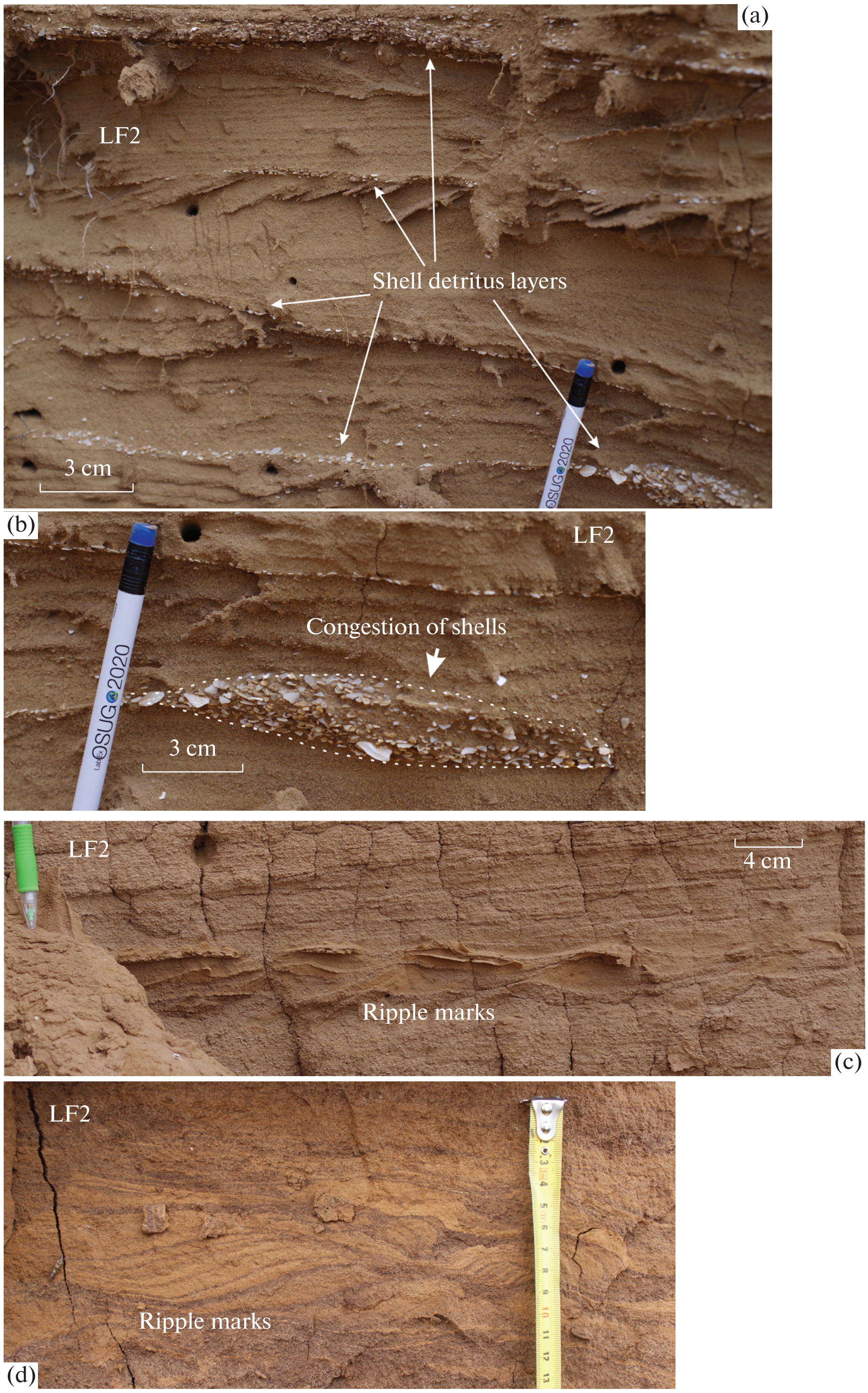

Fig. 6. Sedimentary features of Baer knoll's lithofacies 2 (LF2): (a) – Nartovo knoll's a lower formation with thin shell layers; (b) – Thin shell layers and congestion of shells in Nartovo knoll; (c) – Small ripple marks in Trotisky knoll; (d) – The same in another part of Troitsky knoll.

Рис. 6. Особенности залегания ЛФ2. Бугор Нартово: (a) – тонкие наклонные прослои детрита между пачками песка и глины с косой слоистостью; (b) – скопление раковинного детрита в виде линзы мощностью 4 см. Бугор Троицкий: (c) – небольшие знаки ряби высотой 3–4 см; (d) – знаки ряби до 5 см высотой с прослоями светлого песка и шоколадных глин.

There are different opinions about the input of water from the lakes of Western Siberia to the Aral Sea and then to the Caspian Sea through the Turgai trough. There were two periods when the flow to the south took place (Mangerud et al., 2004; Panin et al., 2020). The ridges could have formed at the bottom of this stream (Middendorf, 1877; Lavrov, 1948; Badyukova, 2018). By now the Turgai trough is filled with a thick stratum of alluvial-lacustrine, slope and aeolian deposits.

We consider limnokames as the next example of possible analogues of BK. The type of formation draws an analogy. Both BK and limnokames were formed at the bottom of streams during the discharge of lakes. Kames are formed in the cracks of dead ice, and due to the massive meltwater influx to its margins; as a result, the ridge-hilly landscape appears. The morphology and internal structure differ. It depends on the incoming material and flow's hydrodynamics (Basalikas, 1969; Badyukova, 2007).

Other possible analogues of the BK are giant gravel dunes on the terrace of the Katun' River in the foothills of Altai mountains near the village of Platovo. The Platovo dunes are the result of the breakthrough of glacial dams during the Neopleistocene period and catastrophic discharge of vast masses of water from glacial dammed lakes (Rudoy, 1993; Baryshnikov, Panin, 2013). Other controversial geomorphological objects are the fields of giant ripples, distributed within the Kurai depression, south-eastern Russian Altai mountains. Most researchers interpret these forms as giant ripples in the current, formed during the breakthrough of glacial dams and the descent of dammed lakes (Carling, 1996; Rudoy, 2005; Herget, 2005; Bricheva et al., 2022). Similar dune fields are noted in the area of the city of Kyzyl, mainly along the right bank of the river Small Yenisei (Shpansky et al., 2020). These "giant current ripples", or "gravel dunes" (Carling, 1996), or "diluvial dunes and antidunes" by (Rudoy, 1993) are composed mainly of gravel and pebbles, sometimes boulders. They are distinguished by researchers as indicators of catastrophic floods (Komatsu et al., 2009).

The Channeled Scabland landscapes are located in the eastern part of Washington State (USA) (Baker, 1973; Benito, 2003), and the so-called "giant current ripples" or GCR are part of a complex scabland landscape (Pardee, 1942; Bretz et al., 1956; Baker, 1973). They were formed at a stream bottom like BK. The giant ripples have a different orientation in space, as well as different heights, like the BK. Stream parameters of scablands incommensurable with those that formed BK. Gravel, pebbles and boulders represent the internal structure of the dunes. Analysis of the literature revealed that GCR are a type of large-scale asymmetric dunes (Allen, 1963). The Froude numbers associated with these shapes were less than 1, but other hydraulic parameters such as speed and depth were more significant than those for shallow ripples (Allen, 1963). According to the authors' observations, it tends to decrease with distance from the region of high-velocity water flow (Harms and Fahnestock, 1960).

CONCLUSIONS

On the base of general sedimentological analysis and several dating methods, we may confirm the following statements about Baer knolls in the Caspian lowland.

The nature of layering in the knolls is most common for the underwater deltaic or lacustrine facies. In general, each stratum was inherited from the underlying one due to the successive redeposition. Chocolate clays (LF3) and Volga alluvium were the main sources of material for LF1 and LF2, as the bottom of the Late Khvalynian lagoon was eroding.

Baer knolls cannot be attributed to aeolian landforms based on bedding types, granulometric and geochemical content. We consider that the Baer knolls analogues are river bedforms that appear as the result of turbulent flow, like ripples and large dunes.

Knolls were formed in brackish water in a shallow lagoon-marine environment during the transition of Late Khvalynian and Early Holocene time (from the second half of MIS-2 to the beginning of MIS-1) that correlates with the Younger Dryas cold event. In our opinion, this event occurred due to the decline of lagoon water level during the water flow through the Manych strait to the Black Sea.

ACKNOWLEDGEMENTS

We are grateful to the scientific group of the VSEGEI Quaternary Geology Department and represented by A.S. Zastrozhnov, D.A. Zastrozhnov. We are thankful to Kh.A. Arslanov and his colleagues from the geochronological laboratory of the Saint Petersburg State University for performing radiocarbon dating of mollusk shells. We are thankful to Doctor of Geographical Sciences, professor T.A. Yanina for identification and classification of mollusk shells.

This work was financially supported by the Laboratory of recent sediments and palaeogeography of the Pleistocene at the Moscow State University and the Russian Science Foundation (project No. 20-77-00068).

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ЛИТОФАЦИАЛЬНОЕ СТРОЕНИЕ И УСЛОВИЯ НАКОПЛЕНИЯ ОТЛОЖЕНИЙ БЭРОВСКИХ БУГРОВ СЕВЕРНОГО ПРИКАСПИЯ[1]

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Бэровские бугры – это, как правило, вытянутые гряды, ориентированные чаще всего близко к субширотному направлению, получившие широкое распространение на территории Северного Прикаспия ниже отметки 0 м абс. Механизм образования этих форм рельефа дискутируется вот уже почти столетие. Данная работа ставит своей целью определение генезиса бэровских бугров на основе структурно-литологических исследований и датирования слагающего их материала. Проведенные исследования позволили заключить, что гряды были сформированы в конце позднехвалынского времени – начале голоцена. Отложения бэровских бугров состоят из трех условно выделяемых литофаций. Основными источниками материала, из которого формировались бугры, являлись шоколадные глины, подстилающие их морские отложения регрессивной террасы и аллювий рек, впадавших в хвалынский бассейн. Данные литологических, фаунистических и геохимических исследований не позволяют считать описываемые формы результатом эолового процесса. Бэровские бугры были образованы на дне лагуны, где существовали течения, обусловленные спуском вод позднехвалынского бассейна через Манычский пролив. Гряды являются аналогами речных дюн, образуемых на дне турбулентного потока, где параллельно с накоплением песчаного материала и детрита шло осаждение глинистых частиц в условиях смешения солоноватых вод лагуны и пресных вод рек, впадающих в нее.

Ключевые слова: поздний плейстоцен, Каспийское море, морская седиментология, хвалынский этап, стратиграфия, дельта Волги

[1] *Ссылка для цитирования*: Лобачева Д.М., Бадюкова Е.Н., Макшаев Р.Р. (2023). Литофациальное строение и условия накопления отложений бэровских бугров Северного Прикаспия // Геоморфология и палеогеография. Т. 54. № 3. С. 67–80. (на англ. яз.). https://doi.org/10.31857/S2949178923030052; https://elibrary.ru/WDAEYY