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Incompleteness of the geological record in Middle-Upper Pleistocene key sections of the Northern Caspian Lowland

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ABSTRACT

Pleistocene key sections of the Northern Caspian Lowland are characterized by the incompleteness of the geological record, which is presented in depositional breaks, their duration, causes, and types. Depositional breaks occurred in all periods of the Middle and the Late Pleistocene and occupied various time intervals, usually quite continuous – from ~180 ka (Cherny Yar) to 100–110 ka (Alexandrov Gay, Gorky Erik, Kopanovka, Enotaevka), rarely shorter – about 15–40 ka (Seroglazovka, Mergenevo). Period of accumulation in these sections is small (3.5–44 ka) and covers only 1.2–9% (average 3–4%) for presented deposits and less than 10% from all chronological record. The total chronological assessment of the geological record incompleteness in all studied sections estimated as more than 90%. In all studied sections accumulation rates for Holocene, Upper Khvalynian, Lower Khvalynian, Upper Khazarian, Chernoyarian, and Lower Khazarian are lower than the average for this region. Incompleteness is usually characterized by erosion of river waters of the Volga and Ural system, but more often by abrasion of the Khvalynian and the Khazarian transgressive waters. Another cause of incompleteness of the geological record is long continuous periods without significant deposition. This is often observed in subaerial conditions in the vast watershed area.

1. Introduction

Charles Darwin (1859) was one of the first who drew attention to the incompleteness of the geological record in stratigraphic sections, and many geologists focused their research on this subject later (e.g. Barrell, 1917; Schuchert, 1931; Svitoch, 1966, 1974; Rukhin, 1969; van Andel, 1981; Sadler, 1981; Dott, 1983; Sommerfield, 2006). However, this chronological incompleteness sometimes cannot be seen clearly in outcrop and it is possible that it may not be taken into account and average rates of sedimentation can be underestimated. If presented layers of a section are wrongly taken for the entire stratigraphic and geochronological record of the studied object (event), this significantly reduces the reliability of stratigraphic and paleogeographic reconstructions.

In this paper, we try to estimate the volume of actual geological information in the key Pleistocene sections of the Northern Caspian Sea Lowland. The choice of the studied area was determined by a number of reasons: location in the Caspian region with a complex history of geological development; presence of key sections studied by various methods of analysis; relatively young age (Pleistocene) of deposits that are almost unaffected by soil formation and diagenesis, with the rate of accumulation similar to modern; sediment composition with a predominance of well-studied coastal-marine, shallow water and subaerial deposits (Svitoch, 1974).

2. Materials and methods

This stratigraphic analysis of key sections of the Northern Caspian Sea Lowland is based on a huge amount of materials which were collected during a long period of study (since 1966). Seven key sections were studied to identify the incompleteness ratio of the geological record during the Middle and Upper Pleistocene – Cherny Yar, Kopanovka, Enotaevka, Seroglazovka, Gorky Erik, Alexandrov Gay, and Mergenevo (Fig. 1). Lithostratigraphical units were defined based on lithology, grain size, sedimentary structures, bed contacts, thickness, type of index-fossils species and some absolute ages (Figs. 2 and 3). A stratigraphic scheme of the Northern Caspian region in comparison with the international stratigraphical chart, marine isotope stages and paleomagnetic record is presented in Fig. 4, modified according to Svitoch and Yanina (1997) and Svitoch (2014). The approximate duration of the main stages in the Northern Caspian region is based on absolute ages, which were obtained using thermoluminescence (TL), radiocarbon (^{14}C), uranium-thorium (Th/U) and electron spin resonance (ESR) methods (Table 1). Accumulation rates (yr/cm) were

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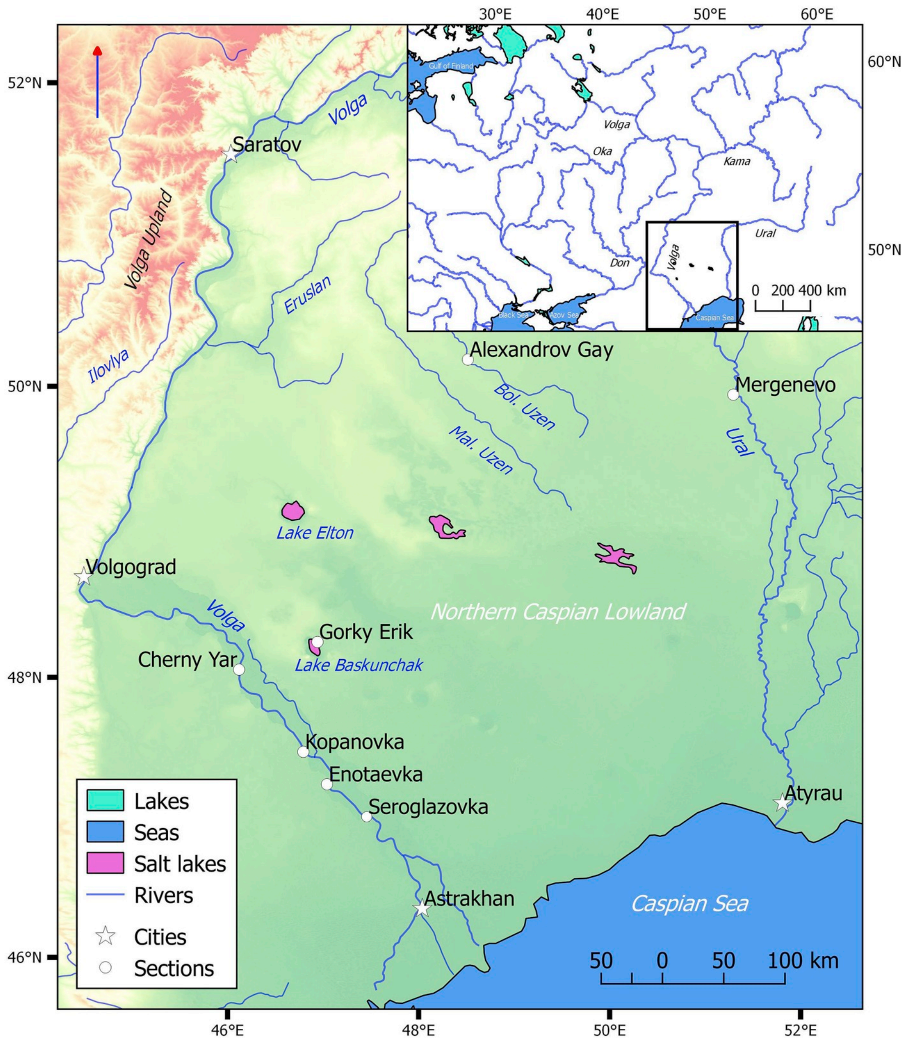

Fig. 1. Location map showing the studied sections in the Northern Caspian Lowland area. The rectangle indicates the location of study region in the East European Plain.

calculated using age-depth modeling software CLAM 2.3 (Blaauw, 2010).

The main method used in this research was a comparative analysis between total duration of all stratigraphic horizons and an estimated duration of sediment deposition for each section (Svitoch, 1974). Duration of sediment deposition was calculated based on approximate accumulation rates for each type of sediment (Table 2) (Rukhin, 1969; Svitoch, 1974). We also used such methods as an indication of section stratigraphic incompleteness by comparative analysis with the data of other key sections, revealing well-marked geological differences between deposits, tracing sediment drop-outs and marks of erosion, and defining the mode of occurrence and geomorphological features of sediments in section.

3. Stratigraphy

In the Northern Caspian Lowland the Middle and Upper Pleistocene and Holocene deposits are divided into horizons (Holocene, Khvalynian, Atelian, Khazarian and Bakunian) and subhorizons (Holocene (Mangyshlakian, Novocaspian)), Upper Khvalynian, Lower Khvalynian, Atelian, Upper Khazarian, Chernoyarian, Lower Khazarian, Singilian and Upper Bakunian) (Svitoch, Yanina, 1997). A stratigraphic scheme of the Northern Caspian region in comparison with the international stratigraphical chart, marine isotope stages and paleomagnetic record is presented in Fig. 3, modified according to Svitoch and Yanina (1997) and Svitoch (2014).

3.1. Holocene

3.1.1. Novocaspian horizon and subhorizon

Novocaspian (Holocene) deposits were described at first as facies of the Caspian Stage (Andrusov, 1889), the Sarinskian (Pravoslavlev, 1908) and the Post Khvalynian (Zhukov, 1945) sediments. The term “Novocaspian” was suggested by Fedorov (1957). Novocaspian deposits consist of marine and continental sediments. In the Northern Caspian Lowland the Novocaspian marine deposits cover the area below −20 m asl (Svitoch, 2014). They are characterized by marine shallow-water facies of silty sand including fresh (*Unio, Dreissena*, *Sphaerium, Pisidium*) and brackish (*Didacna trigonoides, Cerastoderma glaucum*) water molluscs (Yanina, 2012). The timing of marine deposits corresponds to the Novocaspian transgression, which occurred around 6–7 ka (Yanina, 2012). The continental deposits are represented by alluvial, deltaic, lacustrine, aeolian sediments and paleo and modern soils and correspond to Mangyshlakian regression (Svitoch and Yanina, 1997). These deposits occur all over the Northern Caspian Lowland. In the area that was affected by the Novocaspian transgression the continental deposits

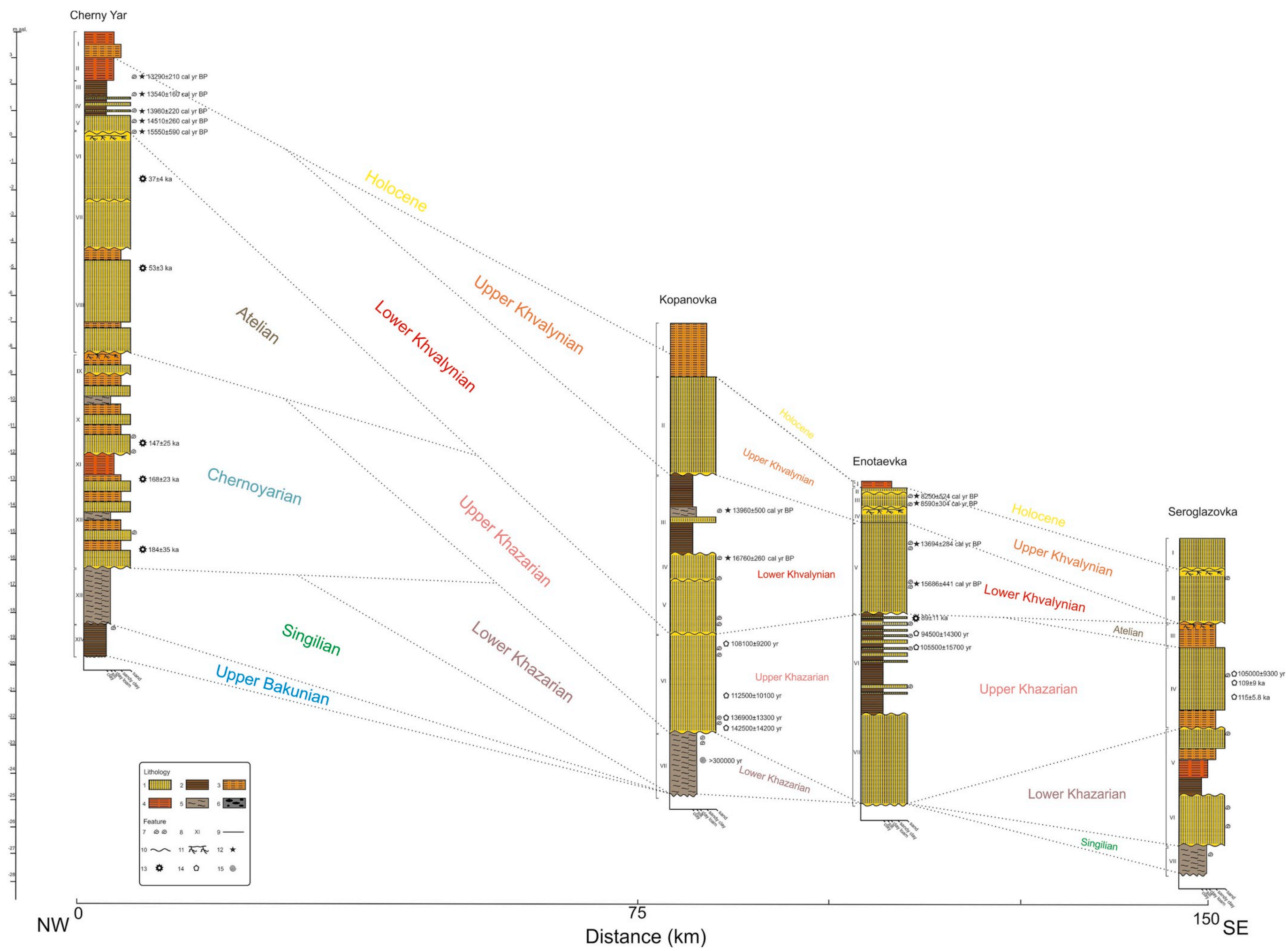

Fig. 2. Stratigraphic columns of studied sections at the Lower Volga region Northern Caspian Lowland. Column legends: 1. Sand; 2. Clay; 3. Sandy clay; 4. Clay loam; 5. Silt; 6. Gravel; 7. Fauna; 8. Unit; Lithological boundaries: 9. Gradual; 10. Sharp; 11. Paleosoil; Absolute dates: 12. Radiocarbon; 13. TL; 14. ESR; 15. Th/U.:

are covered by marine sediments. The age of the Novocaspian deposits corresponds to MIS 1.

3.2. Upper Pleistocene

Upper Pleistocene deposits are represented by the Khvalynian, Atelian and Upper part (Upper Khazarian subhorizon) of Khazarian horizons.

3.2.1. Khvalynian horizon

Khvalynian deposits were defined by Andrusov (Pravoslavlev, 1913). They correspond to the Khvalynian transgression, when sea level reached +50 m asl (Varuschenko et al., 1987; Svitoch, 2014; Yanina, 2012). Khvalynian horizon is divided by Enotaevkian continental layer into the Upper and Lower Khvalynian subhorizons. Deposits of the Enotaevkian layer correspond to regressive phase of the Khvalynian basin and are found only on the left bank of the Volga River valley near the Enotaevka village (Brotskiy and Karandeeva, 1953). Upper and Lower Khvalynian deposits are mostly recognized by geomorphological positions of marine terraces. The Upper and Lower Khvalynian deposits in the Northern Caspian Lowland are found within 0 to −20 and + 50 to 0 m asl respectively.

3.2.1.1. Upper Khvalynian subhorizon. Upper Khvalynian sediments in the Northern Caspian Lowland are developed within 0 to −20 m asl. They were deposited during the short transgressive phase (the Late Khvalynian) of the Khvalynian basin with maximum level to 0 m asl. The deposits are represented by marine sand and silt including mollusc shells *Didacna protracta, D. praetrigonoides Dreissena polymorpha, Monodacna caspia, Hypanis plicatus, etc.* (Yanina, 2012). Upper Khvalynian deposits can be also recognized in Baer Knolls. The accurate age of the Lower Khvalynian deposits is still under debate and estimated between 9 and 14 ka (Svitoch and Yanina, 1997; Rychagov, 1997), 12–14 ka cal BP (Arslanov et al., 2016) and around 15 ka (Krijgsman et al., 2019).

3.2.1.2. Lower Khvalynian subhorizon. Lower Khvalynian deposits in the Northern Caspian Lowland are presented by marine chocolate clay, silty clay and sand. They were deposited during the Early Khvalynian transgression. Within the Volga River valley these deposits are mainly represented by specific facies of chocolate clay, which contain thin sand and silt layers with mollusc shells *Didacna protracta, D. parallella, D. ebersini, Dreissena polymorpha, Monodacna caspia etc.* (Yanina, 2012) In the Volga-Ural interfluve area these deposits consist of interbedded sand and clay with mollusc shells *Didacna ebersini, D. parallella and D. protracta* (Svitoch, Yanina, 1997). Lower Khvalynian deposits in the Ural River valley are represented by laminated clay with silt and sand including mollusc shells *Didacna ebersini, D. subpyramidata, D. parallela, D. protracta, Monodacna caspia, Hypanis plicatus, Dreissena polymorpha,* etc.(Yakhemovich et al., 1986). The age of Lower Khvalynian deposits in the Northern Caspian Lowland is estimated by radiocarbon between 19–13,3 ka cal BP (Kaplin et al., 1972; Arslanov et al., 1988, 2016;

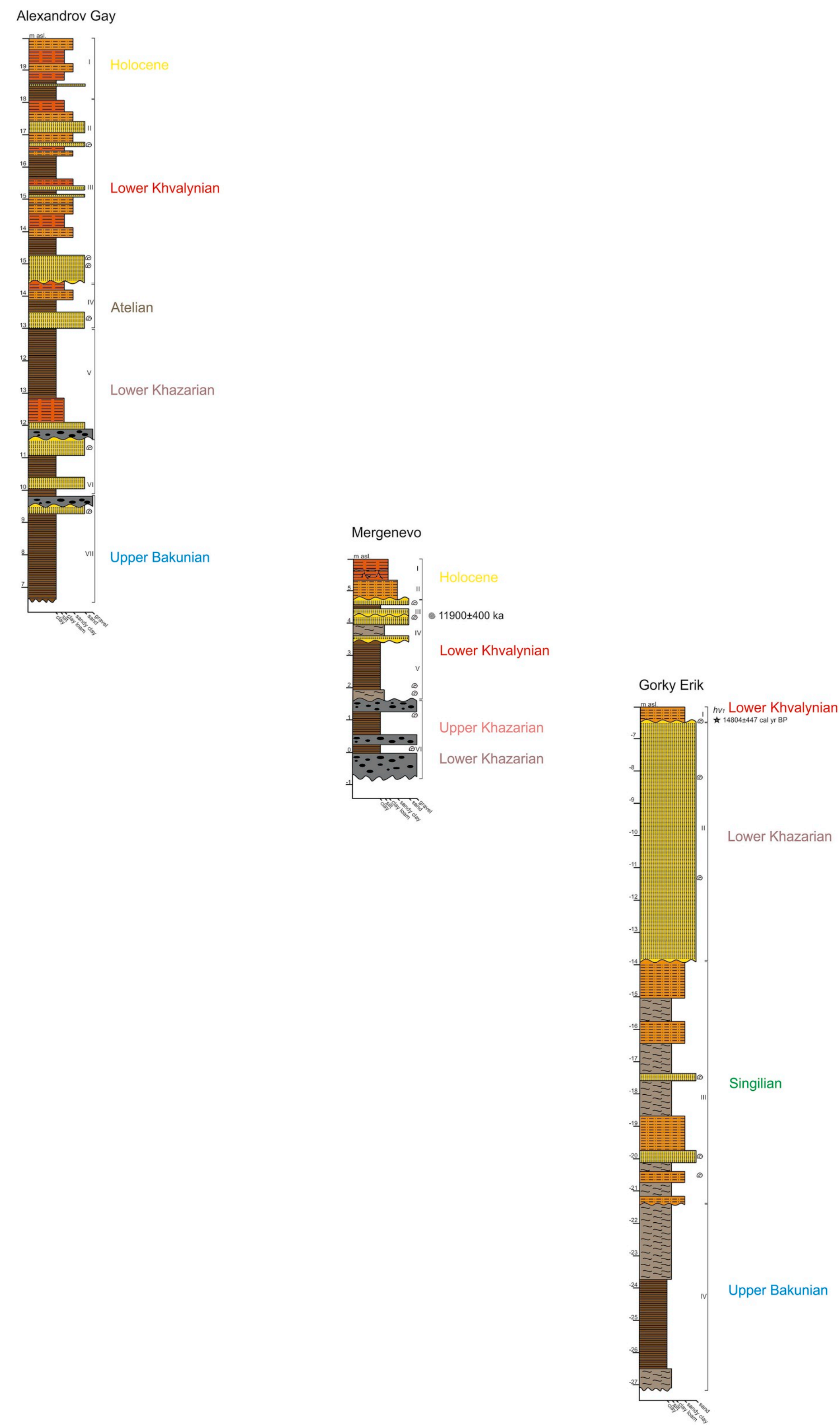

Fig. 3. Stratigraphic columns of the Alexandrov Gay, Gorky Erik and Mergenevo sections. Column legends see Fig. 2

Parunin et al., 1989; Yanina and Svitoch, 1997; Tudryn et al., 2016; Makshaev and Svitoch, 2016). The OSL dating has shown 15–13 ka (Yanina et al., 2017). The results of Th/U dating demonstrate 15,9–11,9 ka (Arslanov et al., 1988).

3.2.2. Atelian horizon

P.I. Pravoslavlev (1908) named this horizon after the ancient name (Atel) of the Volga River. The horizon is represented by loess, paleosoil and alluvial deposits. The Atelian deposits were developed during the deep regression of the Caspian Sea. In the Northern Caspian Lowland the most representative sections with the Atelian deposits are located on the both banks of the Lower Volga River valley. The Atelian deposits were dated by TL at 28–80 ka (Shakhovets, 1987) and OSL at 48 ± 3 ka (Yanina et al., 2017).

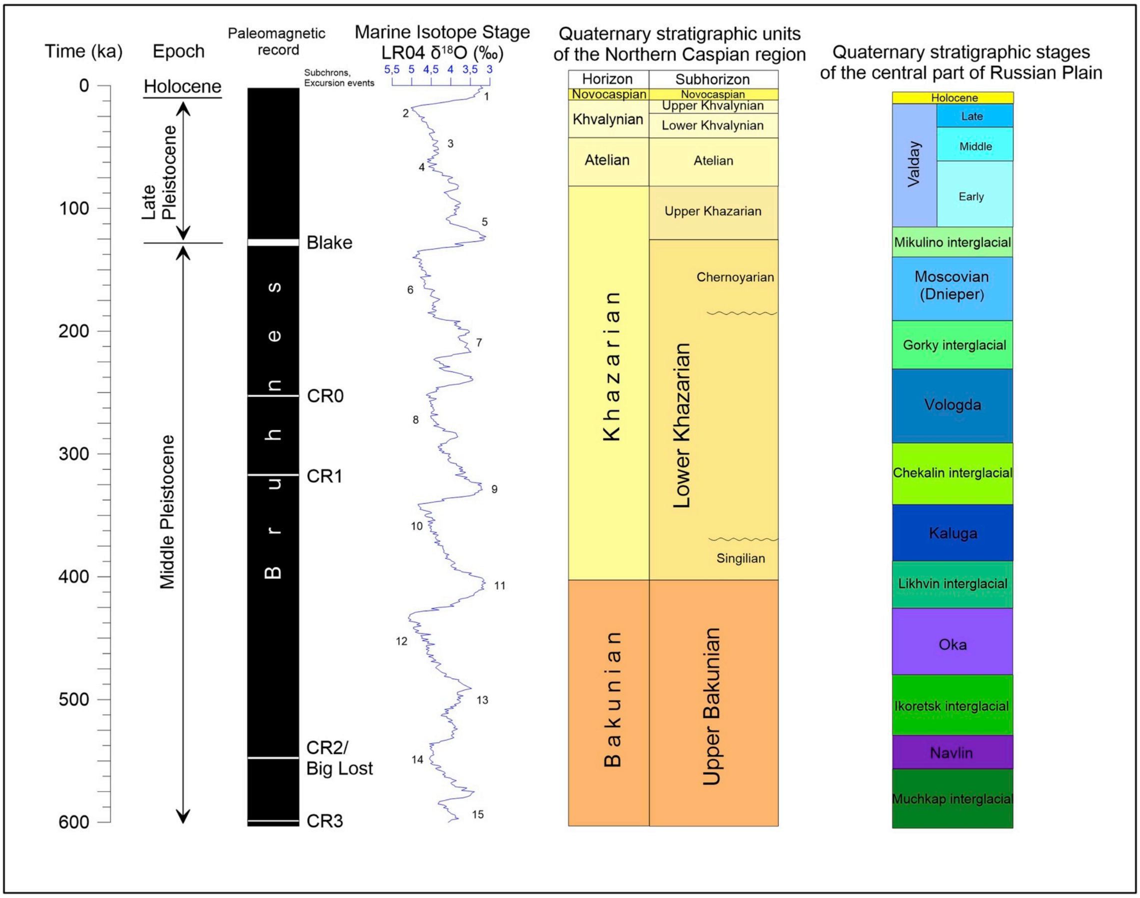

Fig. 4. Stratigraphic scheme for the Northern Caspian region (modified after Svitoch and Yanina, 1997; Svitoch, 2014). The Holocene, Pleistocene (Late, Middle) epochs and paleomagnetic records are taken from Pillans and Gibbard (2012). The Marine Isotope Stages (MIS) follow Lisiecki and Raymo (2005). Quaternary stratigraphic stages of the central part of Russian Plain according to Shick (2014).

Table 1
Thermoluminescence (TL), radiocarbon (^{14}C), uranium-thorium (Th/U), electron spin resonance (ESR) ages of stratigraphical units of the Northern Caspian region.

Stratigraphic unit	Method	Age range ka BP	References
Upper Khvalynian	^{14}C	14–12	Arslanov et al. (2016)
Lower Khvalynian	^{14}C	20–13.5	Arslanov et al. (2016), Yanina et al. (2018)
Atelian	TL	28–80	Shakhovets (1987)
Upper Khazarian	TL	117–91	Rychagov et al. (1997)
	TL	127 (130)-89	Shkatova (2010)
	Th/U	122–87	Shkatova (2010)
	ESR	105–85	Shkatova (2010)
	ESR	75–142	Molodkov and Bolikhovskaya (2002)
Chernoyarian	TL	122–184	Shakhovets (1987)
Lower Khazarian	Th/U	> 250 > 300	Arslanov et al. (1976), Shkatova (2010)
Bakunian	TL	400–480	Kaplin et al. (1977), Svitoch and Yanina (1997)

Table 2
The average accumulation rate of the Caspian region.

Type of deposits	Average accumulation rate (mm/yr)	Reference
Caspian marine	2.0	Bruevich (1949), Klenova and Yastrebov (1956)
Deltaic	2.5	Belevich (1965), Key (1957)
Alluvial	30–40	Lavrushin (1963)
Lagoonal	1.4	Overeem et al. (2003)
Loess	1.5	Nalivkin (1956)
Aeolian	0.15	Fett (1961)

3.2.3. Khazarian horizon

The horizon was firstly described by Andrusov (Pravoslavlev, 1913). Based on the mollusc assemblages of *Didacna* species and lithostratigraphy P.V. Fedorov (1957) Khazarian horizon was divided into Lower and Upper Khazarian subhorizons. Lower Khazarian subhorizon includes the Singilian and the Chernoyarian suites. In the Upper Pleistocene the Khazarian horizon is represented by the Upper Khazarian subhorizon.

3.2.3.1. Upper Khazarian subhorizon. Upper Khazarian deposits correspond to small transgressive stage (the Late Khazarian) of the

Table 3
Stratigraphic descriptions of the units and their ages in the studied key sections of the Northern Caspian Lowland.

Section	Total thickness	Unit	Description	Fauna	Thickness	Boundary type	Stratigraphic Unit	Age	Absolute age	Reference absolute ages
Cherny Yar	23 m	I	Reddish brown clay loam and sandy clay with low humus		1 m	gradual	subaerial deposits	Holocene		
		II	Brownish clay loam with calcareous nodules		0.8 m	gradual	marine	Lower Khvalynian		
		III	Chocolate clays, thin-laminated with lenses of sand and molluscs	*Dreissena polymorpha, Monodacna Caspia, etc.*	0.8 m	gradual	marine	Lower Khvalynian	14C, 13290 ± 210 cal yr BP (LU-7039)	Makshaev and Svitoch, (2016)
		IV	Alternation of gray fine-grained sand and clay with abundant molluscs	*Didacna protracta, D. trigonoides*	0.5 m	sharp (eroded)	marine	Lower Khvalynian	14C, 13540 ± 160 cal yr BP (LU-7040) 14C, 13980 ± 220 cal yr BP (LU-7041)	Makshaev and Svitoch, (2016) Makshaev and Svitoch, (2016)
		V	Gray-yellow sand, well-graded, fine-grained with thin layers of chocolate clay and mollusc shells	*Didacna protracta, D. ebersini, Dreissena polymorpha, Dr. Rostriformis*	0.5 m	sharp (eroded)	marine	Lower Khvalynian	14C, 14510 ± 260 cal yr BP (LU-7042) 14C, 15500 ± 590 cal yr BP (LU-7038)	Makshaev and Svitoch, (2016) Makshaev and Svitoch, (2016)
		VI	Gray-yellow sand, compact-grained with lime (soil remains?) in the upper part		2.5 m	sharp	subaerial deposits	Atelian	TL, 37 ± 4 ka	Shakhovets, (1987)
		VII	Yellow sand, well-graded, fine-grained		2.5 m	sharp	subaerial deposits	Atelian		
		VIII	Yellow and reddish-brown sand clay with calcareous nodules in the upper part and with thin layers of shoe-string sands in the lower part		4 m	sharp (eroded)	subaerial deposits	Atelian	TL, 53 ± 3 ka	Shakhovets, (1987)
		IX	Brownish sand clay and sand, with paleosoil in the upper part		0.3 m	sharp	lacustrine deposits	Chernoyarian		
		X	Gray silt and sand-clay with iron-rich layers of sand	*Unio, Dreissena*	4–5 m	sharp (eroded)	alluvium deposits	Chernoyarian	TL, 147 ± 25 ka	Shakhovets, (1987)
		XI	Brown clay loam with lime, with sand clay and gray sand in the bottom part		0.8 m	gradual	alluvium deposits	Chernoyarian	TL, 168 ± 23 ka	Shakhovets, (1987)
		XII	Brown sand clay and sand in the lower part with yellow sand, fine-grained, ferruginous with small lenses of sand clay and silt. The bottom part of the layer contains fine-grained, cross-bedded sand, with a large amount of redeposited shells of Apsheronian and Khazarian	*Viviparus, Sphaerium, Dreissena* redeposited molluscs *Didacna pallasi, D. subpyramidata, D. paleotrigonoides*	9 m	sharp	alluvium deposits	Chernoyarian	TL, 184 ± 35 ka	Shakhovets, (1987)
		XIII	Brownish-gray micro-laminated silt, sparsely ferruginous, with dark-gray silt in the lower part		up to 9 m	sharp (eroded)	liman and lacustrine deposits	Singilian		
		XIV	Greyish horizontal bedded clay with thin layers of silt and mollusk shells	*Didacna catillus volgensis, Dreissena rostriformis*	>2 m		marine	Upper Bakunian		

(continued on next page)

Table 3 (*continued*)

Section	Total thickness	Unit	Description	Fauna	Thickness	Boundary type	Stratigraphic Unit	Age	Absolute age	Reference absolute ages
Kopanovka	**~18 m**	I	Grayish low humus sand loam, gradually changing to brownish heavy sand loam		2 m	sharp	subaerial and aeolian deposits	Holocene		
		II	Grayish-yellow heavy sand with micro-lamination. Lower sand becomes dark-brown, fine-grained with horizontal micro-lamination		up to 6 m	sharp	marine and aeolian deposits	Upper Khvalynian		
		III	Chocolate clay with lamination of brownish silt and ferruginous sand rich in mollusc shells	*Didacna ebersini, Didacna protracta, D. delenda, Dreissena polymorpha, Dr. Rostriformis distincta*	1.5–8 m	sharp	marine	Lower Khvalynian	14C, 13960 ± 500 cal yr BP (LU-6917) 14C, 16760 ± 260 cal yr BP (LU-8741)	unpublished unpublished
		IV	Grayish medium- and fine-grained cross-bedded sand rich with lamination of Khvalynian mollusc shells	*Didacna protracta, Adacna vitrea, Dreissena polymorpha, Monodacna caspia*	1.3 m	sharp	marine	Lower Khvalynian		
		V	Well-sorted yellow fine sand with horizontal micro-lamination		1.2–3.5 m	sharp	marine	Lower Khvalynian		
		VI	Bright-yellow and light-gray cross-bedded fine sand with clay clasts and abundance of freshwater mollusk shells and brackish-water mollusc shells	*Corbicula fluminalis, Planorbis* sp., *Viviparus* sp., *Sphaerium* sp., *Unio* sp., *Didacna palassi, D. paleotrigonoides, D. subpyramidata, Monodacna caspia, Adacna laeviuscula, Hypanis plicatus, Dreissena rostriformis distincta*	up to 5 m	sharp	marine	Upper Khazarian	ESR, 108100 ± 9200 yr (123–105) ESR, 112500 ± 10100 yr (125–105) ESR, 136900 ± 13300 yr (119-105a) ESR, 142500 ± 14200 yr (120–105)	Molodkov and Bolikhovskaya, (2002) Molodkov and Bolikhovskaya, (2002) Molodkov and Bolikhovskaya, (2002) Molodkov and Bolikhovskaya, (2002)
		VII	Blue-gray clayey silt with horizontal micro-lamination, ferruginous in the upper part and abundant in mollusc shells	*Didacna subpyramidata, D. palassi*	>2 m		marine	Lower Khazarian	Th/U, > 300000	Shkatova, (2010)

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Table 3 (*continued*)

Section	Total thickness	Unit	Description	Fauna	Thickness	Boundary type	Stratigraphic Unit	Age	Absolute age	Reference absolute ages
Enotaevka	**~12 m**	I	Brown clay loam with low humus		0.2 m	gradual	subaerial deposits	Holocene		
		II	Brownish-yellow well-sorted fine sand with subhorizontal micro-lamination		0.2 m	sharp	marine	Upper Khvalynian		
		III	Yellow-brown well-sorted fine sand with horizontal micro-lamination, cross laminated, with mollusc shells		0.6 m	sharp	marine	Upper Khvalynian	14C, 8250 ± 524 cal yr BP (MSU-796) 14C, 8590 ± 304 cal yr BP (MSU-794)	Svitoch and Yanina, (1997) Svitoch and Yanina, (1997)
		IV	Grayish-yellow and brownish well-sorted sand contains traces of soil formation (Enotaevkian layers?) in the upper part and carbonate concretions in the lower part		0.5 m	gradual	marine and deltaic	Upper Khvalynian		
		V	Yellow-brown well-sorted fine sand with horizontal lamination and Khvalynian mollusc shells	*Didacna protracta, D. trigonoides, Dreissena polymorpha*	4.5 m	sharp	marine	Lower Khvalynian	14C, 13694 ± 284 cal yr BP (MSU-793) 14C, 15686 ± 441 cal yr BP (MSU-25)	Parunin et al., (1989) Kaplin et al., (1972)
		VI	Interbedding of brownish-gray clay and grayish fine sand with abundant mollusc shells	*Didacna nalivkini, Dreissena čelekenica*	4 m	sharp	marine	Upper Khazarian	TL, 89 ± 11 ka ESR, 94500 ± 14300 yr	Shkatova, (2010) Molodkov and Bolikhovskaya, (2002)
		VII	Grayish well-sorted fine sand with horizontal and wavy lamination		>4 m		marine	Upper Khazarian	ESR, 105500 ± 15700 yr	Molodkov and Bolikhovskaya, (2002)
Seroglazovka	**12–16 m**	I	Yellow-gray fine sand and sandy silt		up to 3.2 m	sharp	aeolian sediments	Holocene		
		II	Brownish-yellow compacted sand with horizontal micro-lamination included mollusc shells and ostacods and low humus horizon in the upper part	molluscs *Didacna delenda, Dreissena rostriformis*, and ostracods *Cyprideis torosa, Caspiolla gracilis, Aurilla azerbaidjanica, Leptocythere bacuana, Ilyocypris bradyi*	up to 5 m	sharp (eroded)	marine	Upper Khvalynian		
		III	Brownish-gray sandy clay rich in humus in its upper part		up to 1.5 m	gradual	loess deposits	Atelian		
		IV	Polyfacial marine (Upper Khazarian) deposits contain abundant brackish and freshwater mollusc shells	*Didacna ex gr. Trigonoides, D.* cf. *Pontocaspia, D. surachanica, D. nalivkini, D. subcrassa, D. pallasi, Monodacna caspia, Dreissena polymorpha*	4 m	sharp	marine, alluvial-marine and deltaic deposits	Upper Khazarian	ESR, 105000 ± 9300 yr (115-105a) ESR, 109 ± 9, 115 ± 5.8 ka	Molodkov and Bolikhovskaya, (2002) Shkatova, (2010)
		V	Interbedding of brownish-gray clay and loam with grayish sand and sandy silt that contains abundant mollusc shells	*Didacna schuraosenica, D. cristata, D.catillus volgensis, D. subcrassa, D.* cf. *Pontocaspia, D. ex gr. Trigonoides, D. pallasi, Dreissena rostriformis, Monodacna caspia, Hypanis plicatus*	2–3 m	sharp	marine	Lower Khazarian		
		VI	Yellow-gray fine sand with mollusc shells	*Didacna paleotrigonoides*	3–4 m	sharp	marine	Lower Khazarian		
		VII	Grayish compacted silt with various freshwater mollusc shells	*Viviparus* sp., *Sphaerium* sp., *Micromelania caspia, Dreissena polymorpha, Dr. Caspia, Dr. Cf. Pontocaspia*	>1 m		liman and lacustrine deposits			

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Table 3 (*continued*)

Section	Total thickness	Unit	Description	Fauna	Thickness	Boundary type	Stratigraphic Unit	Age	Absolute age	Reference absolute ages
Gorky Erik	**21 m**	I	Grayish-brown sandy clay with humus in the upper part contains mollusc shells	*Didacna protracta, Dreissena rostriformis, Dr. Polymorpha*	0.5 m	sharp	marine	Singilian Lower Khvalynian	14C, 14804 ± 447 cal yr BP (MSU-19)	Kaplin et al., (1972)
		II	Grayish and yellow-gray well-sorted medium to fine sand with horizontal lamination and ferruginous layers in the upper part	*Didacna nalivkini, D. subcatillus, D. trigonoides khazarica*	7.3 m	sharp (eroded)	marine	Lower Khazarian		
		III	Interbedding of dark-brown ferruginous sandy clay and silt and brownish-yellow sand with abundant freshwater molluscs	*Unio* sp., *Dreissena* sp.	7.5 m	sharp (eroded)	deltaic	Singilian		
		IV	Interbedding of grayish, blue-gray and dark-brown silt with gray plastic clay and dark-gray slightly ferruginous sand	*Didacna rudis, Didacna carditoides*	>6 m		marine	Upper Bakunian		
Alexandrov Gay	**~13 m**	I	Grayish and gray-brown sandy clay, clay loam, clay with micro-lamination of sand	up to 2 m	gradual	alluvium deposits	Holocene			
		II	Yellow-brown and grayish-yellow clay loam, sandy clay and sand with mollusc shells, ostracods and thin lamination of brown clay	*Didacna protracta, D. parallella, D. trigonoides khvalynica, Dreissena rostriformis, ostracods Loxoconcha eichwaldi, L. lanta, Leptocythere marpha, L. quinquetuberculata, L. postconcava, L. angusta*	2 m	gradual	marine	Lower Khvalynian		
		III	Brownish clay with horizontal micro-lamination of grayish-yellow ferruginous sand and sandy clay with mollusc shells	*Hypanis plicatus, Monodacna caspia, Didacna trigonoides khvalynica, Dreissena polymorpha*	0.7–1.5 m	sharp	marine	Lower Khvalynian		
		IV	Grayish-yellow and bluish-green sandy clay, clay loam, sand and clay with ferruginous layers, humus, gypsum and calcareous concretions, with abundant freshwater molluscs.	*Unio* sp., *Viviparus* sp.	up to 8 m	sharp	alluvium deposits	Atelian		
		V	Brownish-red clay and clay loam with micro-lamination and thin layers of sand included mollusc shells. In the lower part lamination of sand and gravel can be recognized	*Didacna nalivkini*	3.7 m	sharp	marine	Lower Khazarian		
		VI	Brownish-gray sand and clay with lenses of gravel and mollusc shells	*Dreissena čelekenica, Monodacna caspia, Hypanis plicatus, Adacna laeviuscula*	1.5–2.5 m	sharp	marine	Lower Khazarian		
		VII	Reddish and reddish-brown clay with lenses of fine sand and mollusc shells	*Didacna* sp., *Planorbis*	up to 3 m		marine	Upper Bakunian		

(*continued on next page*)

Table 3 (*continued*)

Section	Total thickness	Unit	Description	Fauna	Thickness	Boundary type	Stratigraphic Unit	Age	Absolute age	Reference absolute ages
Mergenevo	**~7 m**	I	Light-brown clay loam with carbonates (paleosol?)	0.7 m	gradual	subaerial deposits	Holocene			
		II	Yellow-brown sandy clay with carbonates		0.5 m	sharp	subaerial deposits	Holocene		
		III	Grayish-brown medium to fine sand with lamination of reddish-brown clay and abundance of brackish- and freshwater ostracods, with rare mollusc shells	*molluscs Didacna protracta, D. parallella, Hypanis, plicatus, Dreissena rostriformis, Dr. Polymorpha, etc.,ostracods, Caspiolla gracilis, Iliocypris bradyi, I. gibba, I. dosipiens, I. bella, Cyclocypris laevis, C. ovum, Cyprea curvifurcata, Leptycythere arevina, L. quinquetuberculata, L. martha, L. pirsagatica, Loxoconcha gibboida, L. laevis, L. unodensa, etc*	0.5 m	sharp	marine	Lower Khvalynian	Th/U, 11900 ± 400 ka (LU-843)	Arslanov et al., (1988)
		IV	Light-brown fine sand with cross-bedding of silt and coarse sand included mollusc shells	*Didacna protracta, D. parallella, Micromilania caspia, Hypanis plicatus, Dreissena polymorpha, Dr. Rostriformis, Anodonta* sp., *Pisidium amnicum, Lithoglyphus* sp., *Planorbis*	0.8 m	sharp	marine	Lower Khvalynian		
		V	Reddish-brown clay with lamination of silt and gravel		1.6 m	sharp	marine	Lower Khvalynian		
		VI	Clay and gravel with lenses of Khazarian mollusc shells and ostracods	*Didacna subpyramidata, Monodacna caspia, Hypanis plicatus, Dreissena polymorpha, Dr. Rostriformis, Dr. Caspia, Micromelania caspia, ostracods Caspiolla gracilis, Candona neglecta, Candona juv., Iliocyprus bradyi, Leptocythere pirsagatica, L. arevina, Cypreideis littoralis, Paracypreideis naphtatscholana, etc.*	>2 m		marine	Lower and Upper Khazarian		

Caspian Sea, when the sea level reached 0–5 m asl (Svitoch, 2014). These deposits are represented by coastal-marine sand and liman clay with mollusc shells *Didacna surachanica, D. nalivkini, D. pallasi, Dreissena caspia, Dr. Distincta, Dr. Polymorpha, Monodacna caspia and* freshwater molluscs *Unio* sp.*, Sphaerium* sp. (Fedorov, 1978). The age of Upper Khazarian deposits from the Northern Caspian Lowland was obtained by TL and ranges from 127 (130) to89 ka (Shkatova, 2010) and 117 to91 ka (Rychagov, 1997). According to Th/U dating the age is 122–87 ka (Shkatova, 2010), by ESR it is 105–85 ka (Shkatova, 2010) and 142–75 ka (Molodkov and Bolikhovskaya, 2002).

3.3. Middle Pleistocene

In the Northern Caspian Lowland Middle Pleistocene deposits include Chernoyarian and Singilian and Lower Khazarian subhorizons.

3.3.1. Chernoyarian subhorizon

Chernoyarian deposits were named after the Cherny Yar village (Fedorov, 1953). Their accumulation occurred during the Chernoyarian regression of the Caspian Sea within paleoVolga River valley. These deposits are characterized by cross-bedded alluvial sand. Chernoyarian deposits also contain numerous fossil remains of large mammals *Mammuthus trogontherii* cf. *Chosaricus*, *Equus caballus chosaricus, Coelodonta antiquitatis* (Gromov, 1935), freshwater molluscs *Pisidium amnicum, Valvata piscinalis, Viviparus duboisianus, Unio,* etc. And the Apsheronian, Bakunian and Lower Khazarian redeposited brackish water molluscs *Didacna pallasi, D. subpyramidata, D. paleotrigonoides* (Yanina, 2012). The age of deposits was determined by TL dating at 184–122 ka (Shakhovets, 1987).

3.3.2. Lower Khazarian subhorizon

Lower Khazarian deposits were accumulated during the long Early Khazarian transgression (Svitoch, 2014). In the maximal stage of transgression, the sea level reached 40–45 m asl (Nikolaev, 1958). The deposits within the Lower Volga region are represented by shallow marine sand, silty clay with mollusc shells *Didacna schuraosenica, D. paleotrigonoides D.* cf. *Cristata, Dreissena rostriformis,*. The stratotype sections are located near the Kopanovka and Seroglazovka villages (Shkatova, 1973; Sedaikin, 1988; Svitoch and Yanina, 1997). According to Th/U dating Lower Khazarian deposits correspond to > 250 ka (Arslanov et al., 1976) and > 300 (Shkatova, 2010).

3.3.3. Singilian subhorizon

Singilian suite was firstly described by P.A. Pravoslavlev (1932). The stratotype section is located in the south part of Raigorod village. Stratigraphy of Singilian deposits is under discussion. Singilian layers were defined as the upper part of Bakunian sediments (Zhukov, 1945; Goretskiy, 1966). They also were considered to be a part of Lower Khazarian deposits (Pravoslavlev, 1932; Fedorov, 1957; Moskvitin, 1962; Popov, 1983). These deposits are also suggested to be found between Lower and Upper Khazarian sediments (Zastrozhnov et al., 2018a, b). In this paper we consider the Singilian subhorizon as synchronous to the end of the Urundzhikian stage, which correspond to MIS-11 (Svitoch and Yanina, 1997; Yanina, 2012). Singilian deposits are represented by dark-gray clay and silt with freshwater molluscs *Unio pictorum, Sphaerium corneum, Valvata piscinalis, V. pulchella and Pisidium amnicum* (Svitoch and Yanina, 1997). The Singilian deposits are located at the base of the most key sections on the left bank of the Lower Volga River valley.

3.4. Bakunian horizon

The horizon was defined by Sjögren in 1891 near the Baku city. The stratotype section Gora Bakinskogo Yarusa is located on the Apsheron Peninsula (Golubyatnikov, 1904). In the studied sections of the Northern Caspian Lowland this horizon is presented by the Upper Bakunian subhorizon.

3.4.1. Upper Bakunian subhorizon

The Upper Bakunian subhorizon in the Northern Caspian region can be found in Cherny Yar, Alexandrov Gay and Gorky Erik sections. Bakunian deposits in these sections are mostly represented by gray horizontal laminated silty clay with mollusc shells *Didacna rudis*, *D. catillus volgensis*, *Dreissena rostriformis* (Svitoch and Yanina, 1997). These deposits correspond to the stabilization of sea level during the Bakunian transgression. The age of the Bakunian deposits in the Northern Caspian region is based on TL data and corresponds to 400–480 ka (Kaplin, 1977).

4. Results

4.1. Lithological description of the studied sections

Based on the numerous materials, which were collected during the expeditions, stratigraphic descriptions of the Middle, Upper Pleistocene and Holocene deposits are presented. Stratigraphic descriptions of the units and their ages in the studied key sections of the Northern Caspian Lowland are shown in Table 3. The stratigraphic columns of studied sections are presented in Figs. 2 and 3. A simplified conceptual major sequence stratigraphic cross section of the Lower Volga River valley area and fluctuations of the Caspian Sea level during the Middle-Holocene is shown in Fig. 9.

4.1.1. Cherny Yar

Section (Table 3, Fig. 2) is located on the right side of the Volga River valley and was first described by K. Baer (1856). This is one of the most studied key sections of the Lower Volga region (Pravoslavlev, 1908; Zhukov, 1935; Grichuk, 1954; Fedorov, 1957; Vasilyev, 1961; Moskvitin, 1962; Svitoch and Yanina, 1997; Yanina, 2012 and many others). This section is 5 km long and can be divided into two parts – northern (Cherny Yar) and southern (Nizhnee Zaimische). The base of the 23 m thick Cherny Yar section lies at ~4 m asl. This is the area where Cherenoyarian deposits were firstly described (Fedorov, 1953). Holocene, Lower Khvalynian, Atelian, Chernoyarian, Singilian and Bakunian sediments can be found in this section (Fig. 5). Incompleteness of this section is indicated by the absence of Lower Khazarian marine deposits. Traces of Lower Khazarian molluscs are usually found in Chernoyarian alluvium.

4.1.2. Kopanovka

Section was first described by Mushketov (1895) and after that was studied by many researchers (Pravoslavlev, 1908; Zhukov, 1945; Fedorov, 1957; Shkatova, 1973, 2010; Sedaikin, 1988; Svitoch and Yanina, 1997 and many others). This is a long (~5 km) Volga river cliff that starts in the southern part of Kopanovka village. Seven lithostratigraphic units can be recognized in this section (see Table 3, Fig. 2). This is the northern boundary of the Baer Knolls area. In this section Holocene, Upper and Lower Khvalynian, and Upper and Lower Khazarian deposits are represented. Incompleteness of the Kopanovka section is shown by the absence of Atelian deposits.

4.1.3. Enotaevka

Section is the only one on the right bank of Volga River where marine Khvalynian deposits are divided by terrestrial facies – Enotaevkian layers (Karandeeva, 1951; Brotskiy and Karandeeva, 1953). The most representative part of this section is located on the north-end of the Enotaevka village (see Table 3, Fig. 2). The deposits of Units II-IV were formed in the shallow water basin which corresponded to Late Khvalynian stage. There are no Enotaevkian layers between Khvalynian deposits, but a small humus horizon with plant remains in Unit IV can be recognized. Also, incompleteness in this section is reflected in the absence of Atelian deposits.

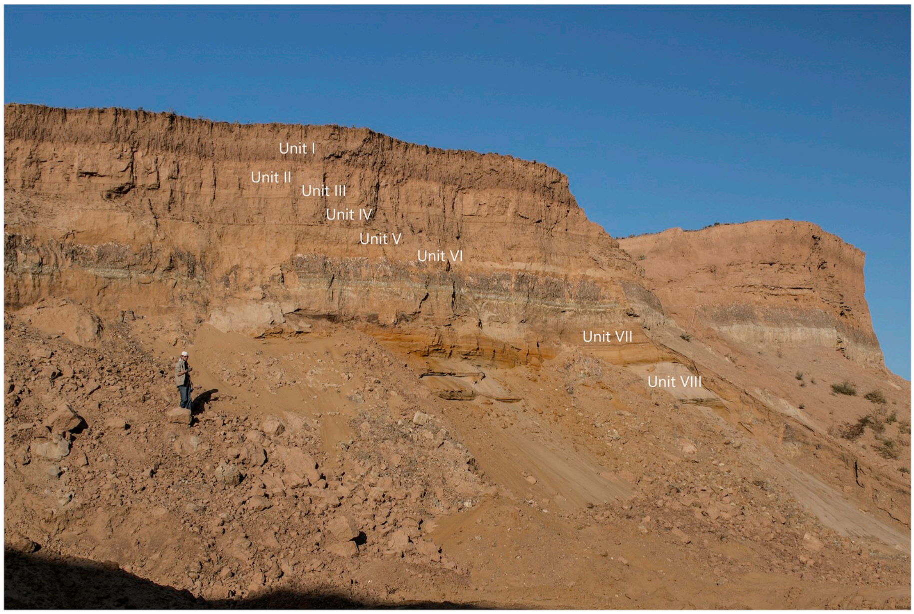

Fig. 5. The Cherny Yar section. Units I-VIII are visible. Talus covers the lower part of the slope (Units IX-XIV).

4.1.4. Seroglazovka

Section was described by many researchers (Sedaikin, 1988; Svitoch, Yanina, 1997; Shkatova, 2010; Yanina, 2012; Zastrozhnov et al., 2018a, b and many others). The section is very long (~2 km) and located on the right bank of the Volga River valley in the north-end of Seroglazovka village. The lithological structure of this section contains multi-layered polyfacial series of marine deposits with various mollusc shells (see Table 3, Fig. 2).

The Holocene, Upper Khvalynian, Atelian, Upper and Lower Khazarian and Singilian deposits are found in this outcrop. The remains of Lower Khvalynian deposits can be found further south from this section and in borehole 5 near Seroglazovka section. There are four cultural layers with coal, and fragments of ceramics etc. Which can be found on the western side of this section in the Unit I. The Blake magnetostratigraphic event was defined in the unit IV by Eremin and Molostovskiy (1981). Incompleteness in this section is shown by the absence of Lower Khvalynian marine deposits eroded during Enotaevka regression and the Late Khvalynian transgression.

4.1.5. Gorky Erik

Section is located on the north-east side of Baskunchak Lake. The area is affected by salt dome structure. This is one of the most complete sections with Upper Khazarian and Singilian deposits in the NW part of the Northern Caspian Lowland area (see Table 3, Fig. 3). Quaternary deposits and mollusc shells in this section were first described by P.A. Pravoslavlev (1939). Lower Khvalynian, Upper Khazarian, Singilian and Bakunian sediments can be found in this outcrop. Forty-five species of molluscs were identified by P.A. Pravoslavlev (1939) in this section. Subsequent research of these mollusc shells showed that this entire Unit IV complex contains a large number of *Didacna* species. Incompleteness in this section is shown by the absence of the marine Upper Khazarian deposits, which were eroded during the Early Khvalynian transgression. There is also a thin sediment record of Upper Khvalynian deposits and the absence of Atelian and Holocene sediments.

4.1.6. Alexandrov Gay

Section is located on the north of the Northern Caspian Lowland in the Bolshoy Uzen' River valley. The section was first described by N.N. Tikhonovich and wasstudied by many researchers (Neustruev and Bessonov, 1909; Pravoslavlev, 1918; Zhukov, 1945; Vasiliev, 1961). This section is represented by a series of outcrops eroded by the Bolshoy Uzen' River (see Table 3, Fig. 3). The elevation of this section is ~20 m asl. Holocene, Lower Khvalynian, Atelian, Lower Khazarian and Bakunian sediments can be found in this area. Incompleteness in this section is evident by the absence of the Singilian deposits.

4.1.7. Mergenevo

Section is located on the right bank of Ural River valley (see Table 3, Fig. 3). The section was described by many researchers (e.g. Pravoslavlev, 1913; Zhukov, 1945; Shkatova, 1975; Yakhemovich et al., 1986). The elevation of this section is about 6 m asl. Holocene, Lower Khvalynian, Upper and Lower Khazarian deposits can be recognized in this section. According to Yakhemovich et al. (1986) the deposits of Unit V and VI are Upper Khazarian, but molluscs and ostracods correspond to the Upper and Lower Khazarian sediments. Incompleteness in this section is shown by the absence of Atelian deposits, that were eroded by waters of the Early Khvalynian transgression or had been deflated. No remains of the Atelian deposits can be found within Ural River valley.

4.2. Comparative analysis between total duration of all stratigraphic horizons and estimate duration of sediment deposition

The results of chronological data analysis showed uneven completeness of the geological record in studied sections (Table 4). We used the reference data on duration of major events in the Caspian Sea history compared to marine isotope stages (MIS) (Yanina, 2012). Sediment accumulation rates for different types of deposits of the Caspian Sea also have been used (Svitoch, 1974). We also compared these results with an age-model data using CLAM 2.3 software (Blaauw, 2010). The quantitative data which was used to evaluate the completeness of the geological record of the section is approximate. The results show only general idea of chronological representivity and completeness of sections. In all studied sections the accumulation rates for Holocene, Upper Khvalynian, Lower Khvalynian, Upper Khazarian, Chernoyarian and Lower Khazarian are lower than the average for this region.

According to the average depositional rate for the Caspian region, the chronological completeness of sections (i.e. the total amount of time represented) is evaluated as between 300 and 480 ka. The largest time interval was interpreted in the Cherny Yar, Gorky Erik and Alexandrov Gay sections and the smallest was in the Kopanovka, Enotaevka and Mergenevo sections (Table 4). Periods of accumulation in these latter

Table 4
Incompleteness of the geological record in key sections of the Northern Caspian Lowland.

Section	Chronological completeness presented in section (ka)	Period of accumulation presented in section (ka)	Chronological volume presented in section (%)	Duration of deep erosion		Total chronological incompleteness (%)
				ka	%	
Cherny Yar	~480	13	2.7	180	37.5	97.3
Kopanovka	~300	14	4.7	88	29.3	95.4
Enotaevka	~300	7.5	2.5	70	23.3	97.5
Seroglazovka	427	15	3.3	15	4	96.7
Gorky Erik	500	44	9	100	20	91.0
Alexandrov Gay	500	15	3	110	22	97.0
Mergenevo	~300	3.5	1.2	40	11	98.8

sections are small (3.5–44 ka) and cover only 1.2–9% (average 3–4%) of the total deposits and less than 10% of the chronological record. The longest period of deposition is observed in the Gorky Erik section (44 ka), and the shortest in the Mergenevo section (3.5 ka). The duration of long (deep) erosional events in studied key sections is estimated at 15–180 ka, which is 4–37.5% of the entire time interval. The longest period of erosion is found in the Cherny Yar section, where there are no Lower Khazarian depositions. The total chronological assessment of the geological record incompleteness in all studied sections is estimated as more than 90%.

4.3. Sedimentary environments and accumulation rates

4.3.1. Holocene deposits

In studied key sections Holocene deposits consist of marine and continental sediments. The Cherny Yar section is comprised of continental deposits (aeolian), which have an average depositional rate of 0,15 mm/yr. According to the age-model, the average accumulation rate is 88,6 yr/cm, which is slightly lower than the average depositional rate for this region (Fig. 6, Table 6). In the Seroglazovka, Enotaevka, Kopanovka sections Holocene deposits are mainly represented by redeposited sand and silty clay of the Upper Khvalynian sediments

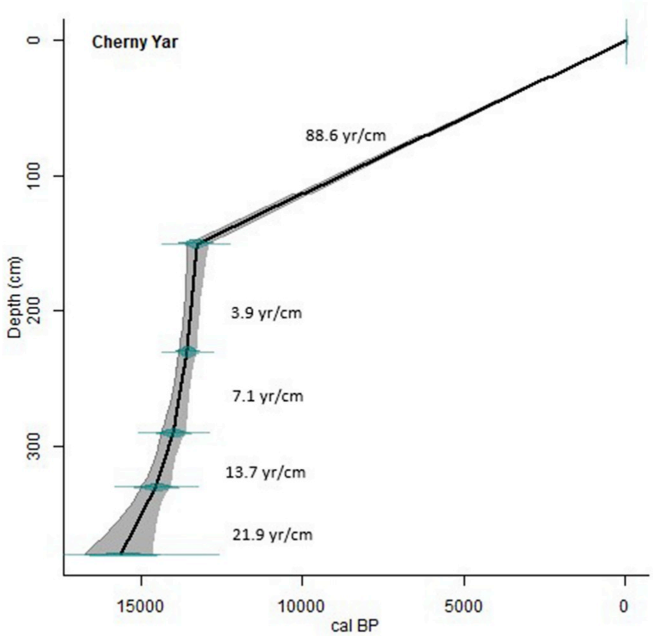

Fig. 6. Age-depth models and average accumulation rate for Cherny Yar section according to radiocarbon dating. The green blocks show the ^{14}C dates with 95% hpd (highest posterior density) and the greyscale shows 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

affected by aeolian processes. The deposition in the Baer Knolls area is affected by their morphology. The Baer knolls are separate hills or ridges, which are in average 2–4 km long, 10–12 m high, located across wide terrains and have southwest orientation (Badyukova, 2017). In the Enotaevka section Holocene deposits are presented by a thin layer (only 20 cm thick) and accumulation rate of around 161,5 yr/cm (Fig. 8, Table 6). The reason of lower sediment accumulation rate can be significant deflation of the upper slope of the Baer knoll. Conversely, sections Seroglazovka and Kopanovka have higher accumulation rate - around 36 and 58 yr/cm (Table 6) respectively. These accumulation rates are common to closed depressions between the Baer knolls. In the outcrops that were not affected by the Late Khvalynian transgression accumulation of sediments occurred in the continental regime. Holocene sediments of the Alexandrov Gay section are comprised of alluvial sand of the second terrace of the Bolshoy Uzen River. According to Lavrushin (1963), an average depositional rate in the Northern Caspian Lowland is up to 40 mm/yr. The accumulation rate in the Alexandrov Gay section during the Holocene is estimated around 58 yr/cm (Table 6). According to one radiocarbon data (Kaplin et al., 1972) the average accumulation rate for Gorky Erik section since 14.8 ka is 296.8 yr/cm (Table 6). Holocene deposits in the Mergenevo section are represented by redeposited sandy clay and sandy loam of the Lower Khvalynian deposits affected by Aeolian processes. The average accumulation rate since 11.9 ka is 92 yr/cm (Table 6).

4.3.2. Upper Khvalynian deposits

The Upper Khvalynian marine facies can be found in the Kopanovka, Enotaevka and Seroglazovka sections. They are represented by sand and silty clay with mollusc shells. In these sections Upper Khvalynian marine deposits form the Baer knolls. The Baer knolls are generally composed of three layers. Upper horizon consists of an alternation of cross-bedded sand and silt with lenses of detritus and mollusc shells of *Didacna protracta, Dreissena polymorpha.* The lower horizon is represented by diagonal crisscross lamination of clay and silt containing detritus. This horizon is mainly composed of redeposited chocolate clay. The lower part of the horizon contains cross-bedded sand and clay layer. The core of the Baer Knolls consists of chocolate clay. The accumulation of the Baer knolls deposits occurred during the Late Khvalynian stage in the relatively shallow environments (Badyukova, 2017). The multidirectional cross-bedding structure of the Baer knolls can potentially correspond to fluctuations of the water flow. The mollusc shells in the Baer knolls are represented only in the lower horizon, in contact with chocolate clay. The cross-bedded sand contains thin (2–3 mm) layers of detritus of Khvalynian molluscs. This type of structure can be found in Kopanovka, Enotaevka and Seroglazovka sections. According to radiocarbon dating, the age of Baer Knolls is around 11,6–9,6 cal ka BP (Svitoch and Klyuvitkina, 2006). The accumulation rate depends on the morphology of the section. In the Kopanovka and Seroglazovka sections the average accumulation rates of Upper Khvalynian deposits are 5 yr/cm (Table 6). In the meantime in the Enotaevka section average accumulation rate is 32 yr/cm (Fig. 8, Table 6).

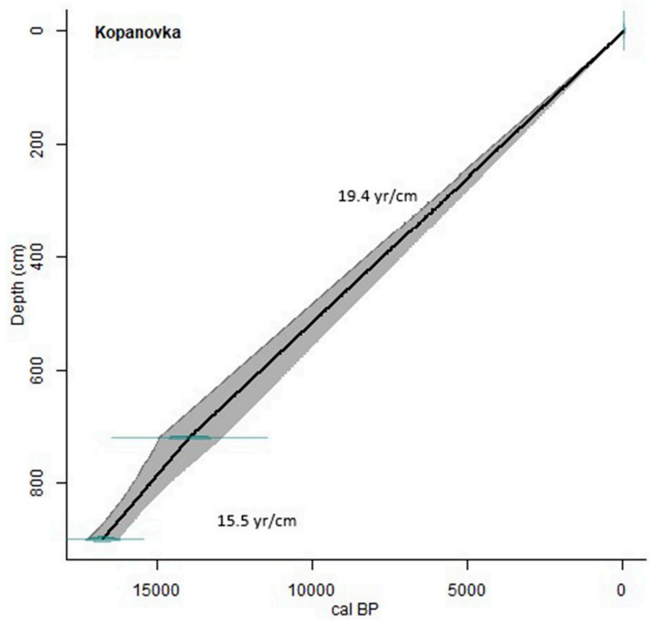

Fig. 7. Age-depth models and average accumulation rate for Kopanovka section according to radiocarbon dating. The green blocks show the ^{14}C dates with 95% hpd (highest posterior density) and the greyscale shows 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

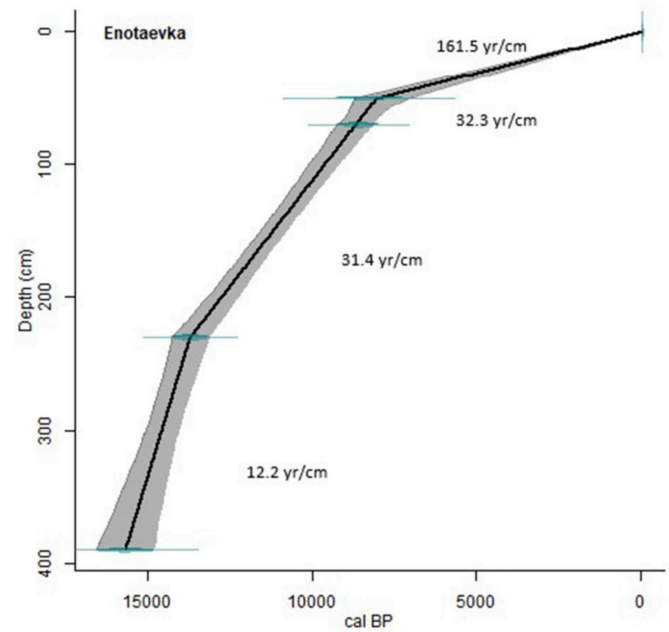

Fig. 8. Age-depth models and average accumulation rate for Enotaevka section according to radiocarbon dating. The green blocks show the ^{14}C dates with 95% hpd (highest posterior density) and the greyscale shows 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.3.3. Lower Khvalynian deposits

Lower Khvalynian deposits in the studied sections are mainly represented by chocolate clay with thin lenses of sand and silt. The accumulation of chocolate clay depends on paleogeomorphology. The chocolate clay is confined to Pre-Khvalynian depressions of various origins. In the Lower Volga region chocolate clay infills the estuary of the Pre-Khvalynian surface. Their thickness varies between 2 and 4 m, although it may reach more than 10 m (Makshaev, Svitoch, 2016). Only in the Kopanovka section the thickness of chocolate clay is more than 5 m. The absence or incompleteness of the chocolate clay horizon in the southern sections related to the Late Khvalynian transgression. The upper part of chocolate clay during the Late Khvalynian transgression was redeposited and formed the lower horizon of the Baer knolls. According to radiocarbon dating, chocolate clay in the Cherny Yar section was deposited between 15,5 and 13,3 cal ka BP (Makshaev, Svitoch, 2016). Accumulation rate of chocolate clay in this section is around 11.6 yr/cm (Fig. 6, Table 6). The highest accumulation rate corresponds to the upper part of chocolate clay. The accumulation rate in the Kopanovka section is estimated around 15.5 yr/cm according to the age-model (Fig. 7, Table 6). In the Enotaevka section accumulation rate of Lower Khvalynian sediments is estimated at 12,2 yr/cm (Fig. 8, Table 6). The Lower Khvalynian deposits in the Seroglazovka section is lacking and can be found only on the edges of the long outcrop. Their thickness is less than 10 cm. The chocolate clay in this section was redeposited and washed out during the Late Khvalynian transgression. The mollusc shells in the Lower Volga section were developed only in the sand and silt layers. Their abundance took place during the cold events (Oldest, Older and Younger Dryas) of the Late Pleistocene according to radiocarbon dating (Yanina et al., 2017). Conversely, the warm periods are characterized by the deposition of chocolate clay, especially during the Bølling warming, when the huge amount of fine-grained material was accumulated within the NW part of the Northern Caspian Lowland. In the Gorky Erik section which is located on the NW flank of the Baskunchak lake, Lower Khvalynian sediments are thin. The reason for the small amount of Lower Khvalynian sediments is salt dome structure and neotectonic activity. Due to vertical movements these sediments are deflated. In the depression of the central part of the Baskunchak area the thickness of the chocolate clay horizon is more than 20 m (Brytsyna, 1954). In the Alexandrov Gay section Lower Khvalynian deposits were accumulated under the estuary and marine conditions. Their average accumulation rate generally depends on the Early Khvalynian stages. In the northern part of the Northern Caspian Lowland the deposition was influenced by Bolshoy Uzen River. During the maximal stage (+50 m asl) of the Early Khvalynian transgression this area was predominated by shallow marine environment, where brownish clay and sand were deposited. Influence of the Bolshoy Uzen River was the most significant during the second phase (+22–25 m asl) of the Early Khvalynian transgression. During this period this area was under estuary regime and clay loam and sandy clay were deposited. The mollusc shells and ostracods in the sandy clay indicate good environmental conditions. Their accumulation rate depends on environments and is estimated at 2.0 mm/yr for marine and up to 10 mm/yr for estuary. Lower Khvalynian deposits of Mergenevo section are comprised mainly of marine deposits, which have an average deposition rate of 2.0 mm/yr.

4.3.4. Atel deposits

In studied sections Atelian deposits can be found only in Seroglazovka, Cherny Yar and Alexandrov Gay sections. They are represented by loess deposits which were formed during the deep Atelian regression of the Caspian Sea. The material was transported by wind from a huge area during the cold phase (MIS 4). In many outcrops of the Northern Caspian Lowland ice-wedges penetrating the underlying sediments can be recognized in the bottom part of Atelian horizon (Fedorov, 1957; Moskvitin, 1962; Yanina, Svitoch, 1997; Yanina et al., 2017; Zastrozhnov et al., 2018a, b). The average accumulation rate for loess deposits is 1,5 mm/yr. The absence of the Atelian deposits in the other sections can be potentially related to the past environments during the Early Khvalynian transgression. Atelian deposits were eroded by intensive runoff with a huge amount of fine material of the Volga and Ural Rivers in the early phase of the Early Khvalynian transgression. According to TL dating in the Cherny Yar section the

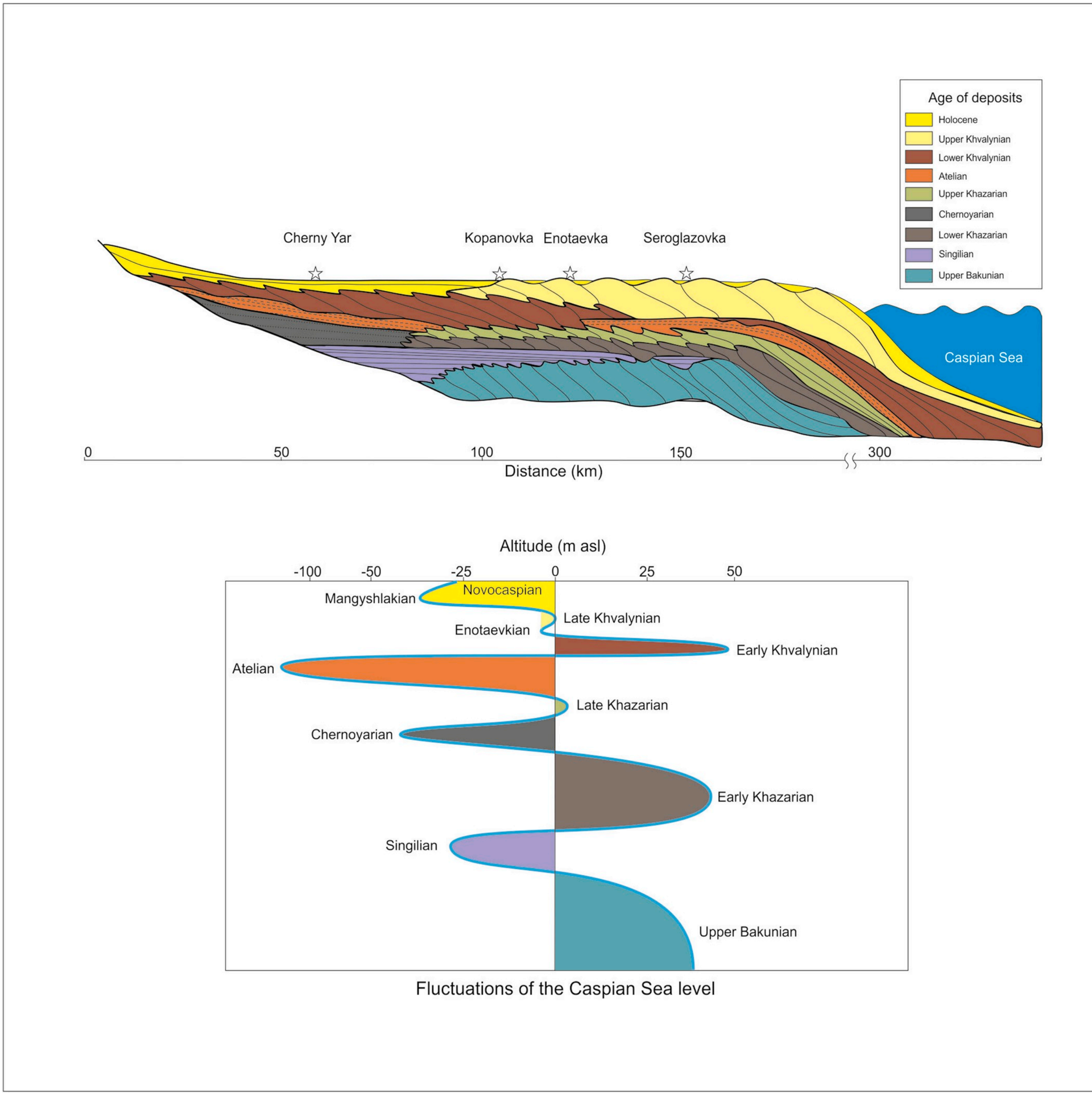

Fig. 9. A simplified conceptual major sequence stratigraphic cross section of the Lower Volga River valley area and fluctuations of the Caspian Sea level during the Middle and Upper Pleistocene and Holocene (Svitoch, 2014).

accumulation rate is estimated around 47 yr/cm or 0.021 cm/yr (Table 6).

4.3.5. *Upper Khazarian deposits*

Upper Khazarian deposits consist of marine sand with thin layers of clay with an abundance of mollusc shells. The deposits are represented in the Kopanovka and Seroglazovka sections. According to ESR dating and the age-model (Molodkov and Bolikhovskaya, 2002), the accumulation rate of the Upper Khazarian sediments in the Kopanovka section in the upper part is 24 yr/cm and in the lower part is around 328-213 yr/cm (Table 6). The accumulation rate of the upper part of the Enotaevka section according to ESR and TL dating varies between 98 and 211 yr/cm (Table 6). In the Seroglazovka section the average accumulation rate of the middle part is around 119-107 yr/cm (Table 6).

According to lithological structure and mollusc assemblages of the Upper Khazarian deposits in the Seroglazovka section their accumulation occurred in three stages that were separated by erosion periods. The first stage is developing deposits of buried terrace (marine, estuary-liman and lacustrine sediments). The second stage of deposition of the deltaic, shallow and coastal marine deposits occurred after channeling. The third stage is characterized by repeated channeling and filling by alluvial and deltaic sediments (Svitoch and Yanina, 1997).

4.3.6. *Chernoyarian deposits*

Chernoyarian deposits are presented in the Cherny Yar section, but

Table 5
Causes of the incompleteness of the geological record in key sections of the Northern Caspian Lowland.

	Section	Type of incompleteness	Period of incompleteness	Stratigraphic period	Main causes
1	Cherny Yar	Deep erosion	The end of the Middle Pleistocene	Lower Khazarian horizon	paleoVolga River erosion
2	Kopanovka	Deep erosion	the beginning of the Late Pleistocene	Atelian horizons	Abrasion of the Early Khvalynian sea
3	Enotaevka	Deep erosion; Absence of subaerial accumulation.	The beginning of the Late Pleistocene; The end of the Late Pleistocene.	Atelian horizons; Enotaevkian layers?	Abrasion of Early and Late Khvalynian sea;
4	Seroglazovka	Erosion	The end of the Late Pleistocene	Lower Khvalynian horizon	Abrasion of the Late Khvalynian sea
5	Gorky Erik	Deep erosion; Absence of subaerial accumulation.	The end of the Middle Pleistocene – the beginning of the Late Pleistocene; The Holocene.	Upper Khazarian and Atelian horizons; Post-Khvalynian subaerial layers.	Abrasion of the Early Khvalynian sea
6	Alexandrov Gay	Deep erosion	The beginning of the Middle Pleistocene	Singilian horizon	Abrasion of the Early Khazarian sea
7	Mergenevo	Deep erosion	The beginning of the Late Pleistocene	Atelian horizon	Abrasion of the Early Khvalynian sea

they also could be found in the outcrops on the left bank of the Volga River between Raigorod and Nikolskoe villages. These sediments are represented by alluvial cross-bedded sand with an abundance of re-deposited mammal fossils and the Apsheronian, Bakunian and Lower Khazarian mollusc shells. The deposition of the Chernoyarian sediments occurred in the paleoVolga River valley with an average run-off similar to recent time (Svitoch and Yanina, 1997). According to TL dating accumulation rate is around 152-78 yr/cm (Table 6).

4.3.7. Lower Khazarian deposits

These sediments are found in the Kopanovka, Seroglazovka, Gorky Erik, Alexandrov Gay and Mergenevo sections and represented by marine sand and clay. In most sections thin laminated clay can be found above sand layer. Their deposition occurred in shallow marine and lagoonal environments. According to Fedorov (1978), the paleoVolga River valley incised into Bakunian deposits in the early stage of the Early Khazarian transgression. The thickness and mollusc assemblages of the Lower Khazarian deposits could potentially indicate a long period of accumulation in the shallow marine environments. According to few Th/U dates Lower Khazarian sediments show an average accumulation rate of 70–80 yr/cm (Table 6). In the northern sections within the Lower Volga River valley the Lower Khazarian deposits were eroded by paleoVolga River during the Chernoyarian regression.

4.3.8. Singilian deposits

Singilian deposits can be found in Cherny Yar, Seroglazovka and Gorky Erik sections. These deposits are generally presented by micro-layered gray silt with an abundance of freshwater molluscs. They were deposited in the liman, lacustrine and deltaic environments. The average accumulation rate of lagoonal deposits in the Lower Volga region according to (Overeem et al., 2003) is 1,4–2,5 mm/yr. According to Dorofeev (1950) and Grichuk (1954) during this time the boreal forests were developed within this area.

4.3.9. Upper Bakunian deposits

Upper Bakunian deposits are found at the Cherny Yar, Gorky Erik and Alexandrov Gay sections. These deposits are generally represented by gray horizontal laminated silt and clay with mollusc shells. During this time shallow marine environments with an abundance of molluscs *Didacna rudis* and *D. catillus volgensis* prevailed (Yanina, 2012; Svitoch, 2014). These deposits are mainly accumulated in marine conditions and have an average accumulation rate of 2,0 mm/yr in the Northern Caspian region. According to TL dating the age of the Upper Bakunian deposits in the Northern Caspian Lowland region is 400–480 ka (Kaplin et al., 1977; Svitoch and Yanina, 1997).

5. Discussion

The results show that all studied key sections (Figs. 2 and 3) of the Northern Caspian Sea Lowland show evidence of depositional intervals. The extent of stratigraphic incompleteness intervals, their duration, depth and causes are different for each section (Table 5). Comparison of the average accumulation rate for the Caspian region with data from the CLAM 2.3 age model demonstrates the incompleteness of studied sections. It is proved by the average accumulation rate, which is lower for all studied sections.

Stratigraphically, depositional breaks are observed in all sub-horizons of the Middle Pleistocene and the Holocene, from the Singilian deposits (Alexandrov Gay section) to the late Holocene (Gorky Erik section). There are no Upper Khazarian and Atelian horizons in the Northern Caspian Sea Lowland due to erosion (e.g. in the Kopanovka, Gorky Erik, Mergenevo sections). Incomplete deposition of the geological record occurred even after Khvalynian epoch: Khvalynian deposits are often covered by thin subaerial Holocene formations.

Depositional breaks mostly happened in the Late Middle – beginning of the Late Pleistocene (e.g. Seroglazovka). Duration of these

Table 6
The average accumulation rate (yr/cm) for studied section using CLAM 2.3 age-depth model software (Blaauw, 2010).

	Cherny Yar	Kopanovka	Enotaevka	Seroglazovka	Alexandrov Gay	Gorky Erik	Mergenevo
Holocene	88.6	58	161.5	36	58	296.9	92
Upper Khvalynian		5	32	5			
Lower Khvalynian	11.6	15.5	12.2				
Atelian	47						
Upper Khazarian		24-upper part 328-213-lower part	98-211-upper part	119-107 middle part			
Chernoyarian	152–78						
Lower Khazarian		70–80					

breaks occupies various time intervals, usually quite continuous – from ~180 ka (Cherny Yar) to 100–110 ka (Alexandrov Gay, Gorky Erik, Kopanovka, Enotaevka), rarely shorter – about 15–40 ka (Seroglazovka, Mergenevo) (Table 4).

There are several types of lithological boundaries in the studied region. Sometimes it is a sharp boundary, usually due to erosion by river waters of the Volga and Ural system, but more often it is due to abrasion by Khvalynian and Khazarian transgressive waters.

The main reason for the incompleteness of the geological record in the studied sections is erosion. Deep erosion leads to long breaks in sedimentation and the complete disappearance of section record, although some remains of sediments can be preserved. For example, there are numerous redeposited Khazarian and Apsheronian mollusc shells that are found in Chernoyarian alluvium, and in the Mergenevo section, Khvalynian deposits contain redeposited Akchagylian and Cretaceous ostracods. Less deep erosion affects only some parts of the section and usually leads to a reduced thickness of deposits and the loss of some of geological record. Traces of such erosion are usually found in alluvial and marine deposits of the Northern Caspian Lowland sections. Another specific type of erosion corresponds to the accumulation of a series of alluvial and coastal-marine deposits. These types of deposits are usually separated by surface erosion. Accumulation and the following period of erosion are often close in duration.

The second main reason for the incompleteness of the geological record is long continuous periods without significant deposition. This is often observed in subaerial conditions in the vast watershed area. For instance, The Volga-Ural interstream areas with heights between 0 and 35 m asl. Are covered by Lower Khvalynian clay loam with a thin layer of amorphous soil. After the Early Khvalynian regression, this area was characterized by very low accumulation rate or even no sedimentation at all. These conditions can be found in Gorky Erik section, where supra-Khvalynian deposition is absent.

The eroded deposits from the Northern Caspian Lowland were transported and accumulated in the shore and littoral zones of the Caspian Sea. According to drilling data and seismoacoustic profile the deposits are characterized by large thicknesses, especially Lower Khvalynian and Upper Khazarian horizons (Yanina et al., 2018; Bezrodnykh et al., 2015, 2004).

The evolution of the Caspian Sea and paleoclimatic events of the East European Plain during the Pleistocene are correlated by Yanina (2012). For example, the beginning of the Bakunian transgression coincides with the Don glaciation and with the end of the Oka glaciation. The Early Khazarian transgression basically corresponded to the Kaluga, Vologda and Moscovian (Dnieper) glaciations and the Early Khvalynian transgression to the Late Valdai glaciation. There were “warm” transgressions of Urundzhik, Late Khazarian and Novocaspian, which coincided with interglacial periods of the East European Plain (Fig. 4). The longest depositional breaks correspond to different hydroclimatic conditions (Table 5) due to geomorphologic settings of sections, which influenced the depth of erosion. For instance, the Novobogatinskaya trough, which is located near the Atyrau city bounded to the salt-dome structure is the most complete example of Bakunian deposits (Svitoch and Yanina, 1997). At the same time in Cherny Yar section completeness of Bakunian sediments is minimal due to continuous erosion or non-deposition.

The main reason of incompleteness is not deep erosion but the specificity of deposition in water conditions during the fluctuations of the Caspian Sea level. Sections with complete chronological record are rare in the Northern Caspian Lowland. The thickness of the Bakunian clay in the Novobogatinskaya trough reaches 400 m and its deposition continued for no less than 200–300 ka (Svitoch, 1974). The high rate of the geological record completeness of Lower Khvalynian deposits (with 30 m of thickness) also occurs in the Saykhin-Botkul depression between Elton and Baskunchak lakes, (Britsyna, 1954).

6. Conclusion

Key Pleistocene sections of the Northern Caspian Sea Lowland are characterized by different completeness of the geological record.

The incompleteness is generally connected with geomorphological positions of the studied sections and fluctuations of the Caspian Sea level during the Middle to Holocene periods. The deep erosion processes influenced only river valleys and occurred during the long periods of regressive stages (e.g. Chernoyarian, Atelian). Meanwhile, during the intensive transgressive stages (e.g. the Early Khvalynian) a huge amount of deposits (Atelian) all over the Northern Caspian Lowland were eroded.

Assessment of incompleteness of the geological record in studied key sections indicates low depositional representation. No more than 10–11% of the record is presented for each stratigraphic unit. For accurate stratigraphic and paleogeographic reconstructions we need to utilize comprehensively studied sections with the maximum thicknesses of deposits, and with good chronological assessment of each unit.

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