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Late Pleistocene cryogenesis features of a loess-paleosol sequence in the Srednyaya Akhtuba reference section, Lower Volga river valley, Russia

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ABSTRACT

Permafrost is considered to be one of the important sources of additional water for the vast Late Quaternary Caspian Sea transgressions. The insufficiency of proxy evidence on landscape and climate dynamics during the long Atelian regression (MIS 4 – MIS 3) complicates the analysis of changes in the Caspian water balance. Traces of Late Pleistocene cryogenesis structures were catalogued in the alluvial and loess-soil deposits of the Srednyaya Akhtuba reference section. Four stages of permafrost development were described for the first time in the Lower Volga region. Under conditions of seasonal and longer-term freezing in the Late Pleistocene, cryogenic transformation of the deposits took place; this determined the composition, structure and properties of the loess-paleosol complex at the site. Cryolithological, micromorphological analyzes and particle size distribution of mineral matter were carried out for each horizon, and traces of cryogenic processes were described in order to evaluate the regional paleoclimatic conditions that prevailed during their formation. Optically stimulated luminescence dating was used to establish a chronological framework for the main phases of the development of cryogenic modification in the Lower Volga region. The fourth stage of formation involved deep cracking of the substrate, which occurred during freezing in MIS 4, coincident with the Atelian regression of the Caspian Sea. The third stage is expressed as large wedge-shaped structures (pseudomorphs) on the border of loess and alluvial packages, with their formation known to be associated with the degradation of ice wedges. During the second and first stages of freezing, plastic deformation of deposits occurred.

1. Introduction

Understanding of the causes of the Caspian Sea level fluctuation during the Pleistocene requires detailed reconstruction of landscape dynamics, and the prevailing paleoclimatic regime in the catchment of the basin's main source of water - the Volga River. In order to adequately quantify this, two main issues must be addressed: Firstly, the absence of reliable data on the terrestrial palaeogeography of the regressive eras of the Caspian Sea. Second, the lack of reliable data on Caspian sea-level dynamics during the Late Pleistocene.

The insufficiency of proxy evidence on landscape and climate dynamics during the long Atelian regression complicates the analysis of changes in the Caspian water balance. Their shortage relates to the lack of sufficiently described sections. Historically, sections containing continental sub-aerial deposits were largely ignored, with the main focus of the region's Quaternary researchers being directed towards detailed description of the various marine deposits of transgressive stages.

In terms of Quaternary stratigraphy and palaeogeography, the catchment of the Lower Volga is the most studied region of the Caspian coast. Extensive reaches of the Lower Volga preserve sections that uniquely archive in great detail the Quaternary history of Caspian sea-level fluctuation; these archives take the form of alternating series of marine, alluvial and subaerial (broadly identified as loess-like) sediments that often display extensive lateral continuity.

Of the seminal works outlining the stratigraphy of the region (Pravoslavlev, 1908, 1926; Zhukov, 1945; Fedorov, 1957; Vasiliev, 1961; Moskvitin, 1962; Goretsky, 1966; Shkatova, 1975; Popov, 1983; Svitoch

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and Yanina, 1997), the majority contain only fragmentary descriptions of the cryogenic structures and cryoturbation present in the subaerial loess of the Lower Volga region – permafrost wedges and involutions. Even though a broad consensus appears to exist largely attributing deposition of these modified subaerial sediments to the Atelian regressive episode, these works contain different views on the genesis of the loess and the deformation present within individual horizons.

Some of the research appears to downplay the significance of cryogenesis and considers some of the loess attributed to the Atelian regressive episode to be deluvial, proluvial-alluvial in origin (Moskvitin, 1962), as colluvial deposits (Lavrushin et al., 2014), or as floodplain facies of Volga River alluvium (Fedorov, 1957; Sedaykin, 1988); other research does appear to acknowledge the role of periglacial modification (Kolomiytsev, 1985). While an informative opinion on their polyfacial genesis was expressed by Svitoch and Yanina (1997), the precise mechanism of formation for the traces of cryogenesis in the loess has remained open for reinterpretation.

Despite the recently obtained, evidencing aeolian genesis of the Atelian loess in the Lower Volga region (Költringer et al., 2020; Lebedeva et al., 2018), the sedimentation mechanism of these deposits are still actively discussed, especially in the Russian geological community and caused a wide dispute at the All-Russian Quaternary Meeting of 2018. The absence of a detailed lithological characterisation does not allow us to draw broad conclusions about the genetic properties of the loess, which are widespread in the northern part of the Lower Volga region, and as a result it has not been possible to perform reliable paleogeographic reconstructions for a significant length of the Atelian regressive stage. In this study we have attempted to address this issue by identifying the genetic features of the sediments that built up the terrestrial stratum between the deposits of the Caspian Khvalynian transgression and the underlying estuary sediments of the Khazarian transgressive stage.

1.1. Rationale

The question of which paleoclimatic regime, depositional environment and sedimentary processes prevailed during the accumulation of the Atelian deposits has formed the basis of century of research. Early research (Pravoslavlev, 1926, 1932; Zhukov, 1945) explored the premise that the Atelian sediments were deposited by processes operating in a hot desert climatic regime. The wedges and cracking at the base of the sequence were seen as evidence of regional-scale aridity. Decades later Moskvitin (1962) proposed that it was in fact the severe glacial climatic regime during the Atelian chron, and the subsequent development of permafrost resulted in cracks and wedges forming at the base of the stratum; the products of cyogenesis. Gradually, this became the prevailing view with most researchers assigning Atelian sediments to either the Kalinino (MIS 4) or the Ostashkovo (MIS 2) stages of Valdai glacial epoch (Fedorov, 1978). Despite the long history of research, the pollen record for Atelian sediments and Lower Volga deposits in general are extremely scarce. Broad interpretations as forest-steppe (Grichuk, 1954), tundra-steppe and taiga, are not specific enough to produce a reliable paleogeographic reconstruction of prevailing conditions during the Atelian chron.

There is a genuine dearth of additional interpretative data on paleoclimatic conditions for the region and what does exist is unsatisfactory due to its perfunctory nature. The purpose of this study is to address one of the most problematic Late Pleistocene palaeogeographic issues in the Lower Volga Region – the identification/characterisation of cryogenic processes and their products, in sediments of the Atelian chron. Potentially, these significant data will in turn also contribute towards solutions to a range of other problems of palaeogeography in the region.

2. Regional setting

The presence of pseudomorphs, soil wedges and involutions has long been noted in the loessic sediments that blanket the East European Plain. The role of frost weathering in the origin of these loess-like deposits was first recorded in the 1880s by Wood (according to Krieger, 1965). Wood postulated that these deformed sediments formed away from continental glacial fronts in areas subjected to permafrost, during seasonal thawing, creeping and sliding that took place in the active layer of loessic gelisols. Subsequently confirmed by experimental observations, this served as the foundation for ideas of the cryoeluvial nature of deformed loess-like sediments and their properties (Sergeev and Minervin, 1960; Popov, 1967; Lessovye porody and Tom, 1986).

Identification of features associated with cryoturbation preserved within such loessic deposits has proved a useful tool in the study of paleoclimatic regimes associated with cryochrons – cold stages of the Quaternary; establishing reliable associations between cryogenic formations and regional scale paleoclimate reconstructions. A wide variety of cryoturbation features have been documented on the plains of Eastern Europe (Vandenberghe et al., 2014): soil wedges are commonly described in sections from the central part of the East European Plain, in the Middle Volga region, in the basins of the Desna and Don rivers, and from the middle part of the Urals (Matoshko, 2004; Agadjanian and Kondrashov, 2011; Kosintsev et al., 2013; Kurbanov et al., 2018). Similar traces of cryogenic processes – pseudomorphs, sand/soil wedges, involutions and cryoturbations in the relict active layer – are also described in southern Scandinavia (Serebryannyy, 1960) and the other parts of European Russia (Rozenbaum, 1985; Antonov et al., 1992; Sycheva, 2012; Streletskaya, 2017; Naugolnykh, 2018). A “Map of traces of permafrost rocks on the territory of the East European Plain” detailing the distribution of periglacial features across superficial deposits of the region was compiled on a scale of 1:10 000 000, by Novoselskaya, 1961. Additional research undertaken since then has identified relict polygonal relief features, distributed across almost all geomorphological levels of the former periglacial zones, on the plains of Europe (Bernikov, 1976; Popov, 2013; Andrieux et al., 2016), and in the European part of Russia (Alifanov et al., 2010). These features are the surface expression of sand/soil wedges that represent the development of quite significant ground ice bodies during the Pleistocene.

Velichko (Izmeneniye Klimata I, 1999) describes a horizon of polygonal structures called the “Yaroslavl cryogenic horizon” in the area of the village of Kuchino (Vologodsky District, north-west Russia). The vertical dimensions of sand/soil wedges reached 4–5 m; the width along the top being 2.5–3.0 m, with the size of the polygons extending to $15 \times 20\ m^2$. The enlarged, sometimes deformed upper parts of the structures correspond to the relict active layer, and the wedge-shaped lower parts are pseudomorphs replacing the former wedge ice. Signs of two layers in the structure of fossil wedges make it possible to determine with a high degree of reliability the presence of permafrost, as well as the depth of the active layer in the past (Popov, 2013). Relict permafrost forms have modern analogues in the permafrost zone. Sand/soil wedges are widespread in the areas formerly associated with deep freezing and widespread discontinuous permafrost development (Black, 1976; French, 1999). Ice-ground wedges are today distributed throughout the permafrost zone, and there is a direct correlation between their size and the intensity permafrost conditions (Yang et al., 2015).

More quantitative approaches to climatic reconstructions for the East European Plain over the past 450 ka have also been attempted. Velichko et al. (2004) was able to demonstrate a close correlation between results derived from the different proxy methods employed; paleoclimatic fluctuations and paleotemperature reconstructions inferred from deep ocean sediment and ice core oxygen isotopes appears to be in good agreement with paleocryolithological proxy data from the East European Plain itself.

The Russian portion of the Eastern European Plain is replete with paleocryolithological evidence supporting the existence of sustained periglacial climatic episodes during the Middle Pleistocene; the Stupino cryogenic horizon containing wedge-shaped structures of 1–2 m in size (Velichko et al., 2006); cryogenic deformation of sediments assigned to the Dnieper and Moscow cold stages commonly displaying wedge-shaped structures of 2–3 m in size. For the Late Pleistocene sediments from the Smolensk cryogenic horizon (assigned to MIS 4) are characterized by involutions, soil wedges and wedge-shaped structures up to 3 m in size (Velichko et al., 2006). Uppermost parts of the Bryansk fossil soil (MIS 3) are deformed by wedge-shaped structures larger than 3 m in the Vladimir cryogenic horizon. The period of maximum development of the Valdai ice sheet (MIS 2) corresponds to the Yaroslavl' cryogenic horizon, which contains pseudomorphs and ice-wedge polygons with numerous involutions, cryoturbations and traces of gelifluction (Velichko and Nechayev, 1995; Morozova and Nechaev, 1997).

Located within the Caspian lowland, the Lower Volga Region extends from Obshchiy Syrt in the north to the seaboard of the Caspian Sea in the south. Absolute altitudes within the lowlands vary from minus 28 m on the Caspian coast to 50 m in the northern part of the Caspian lowland. The main type of lowland relief is the marine accumulative plain, subsequently complicated by erosive leakage and aeolian landforms. Two regions clearly stand out on the plain: the northern region, where the Lower Khvalynian Chocolate Clay facies are widespread, and the southern region, where sands and sandy loam formed in the Late Khvalynian stage prevail. The Volga River itself is situated within a wide well-developed floodplain, which in turn is constrained within a wide valley that is box-shaped in transverse profile. Its origins are believed to extend as far back as 600–700 ka, to the earliest part of the Late Pleistocene (Korotaev et al., 2001). Structurally the Volga-Akhtuba valley is located within the Great Volgograd fault and the Volga-Akhtuba structural block, which determine the tectonic orientation of many parts of the valley (Goretsky, 1966). A sharp turn in the Volga in the northern part of the lower region is a consequence of the intersection of transform faults set within this structural block (Landshafty, 1985).

The Lower Volga Valley, with respect to the representativeness of the sections of the Quaternary sediments, their completeness, the conditions of occurrence and exposure, and the abundance of paleontological material, offers a unique opportunities for understanding the history of the Caspian Sea development; these proxies also furnish us with the opportunity to discern the causal relationship of its transgressions and regressions with glacial and interglacial events evidenced on the East European Plain.

Marine and alluvial-marine Lower Khazarian sediments form the basis of the Srednyaya Akhtuba section. The sequence displays a three-membered structure, reflecting the staged development of the Early Khazarian transgression. Next in the sequence are shallow water facies that have been assigned to the Upper Khazarian Caspian transgression. Believed to have been deposited at the beginning of the Late Pleistocene, they are mainly represented by shallow water facies, are of limited extent and consequently are only exposed in the Volga valley below an altitude of −10 m (during MIS 6 on into the first part of MIS 5; Tudryn et al., 2013). A third transgressive sequence is represented in the form of a series of thinly laminated clays intercalated with silts and sand.

Around the Middle of the Late Pleistocene the character of sedimentation shifts to reflect a regressive stage of the Caspian – the Atelian. Since our studies are concentrated mainly on the continental series of the Late Pleistocene formed in the Atelian regressive event of the development of the Caspian Sea, it has been necessary to place some the issues associated with this paleogeographic chronozone in a broader context. The Atelian sedimentary suite was first described by Pravoslavlev (1926), in the Lower Volga region (the name relates to the ancient epithet of the Volga River). It is typified by mainly continental facies with a maximum thickness up to 20 m; sediments are typically loess-like loams, sandy loams and sand, that frequently displays signs of pedogenic modification to automorphic and hydromorphic soils (Bezrodnykh et al., 2015).

The genesis of Atelian sediments has proved to be a source of some debate among researchers in the region. In Russian literature, the terms "loess-like" loams and sandy loams are commonly used (Lavrushin et al., 2014; Konstantinov and Yeremenko, 2012; Kurbanov et al., 2018; Yanina et al., 2017), which implies a polygenetic origin (alluvial facies and colluvial/slope deposits). The use of the term "loess" implies the assumption of undoubted aeolian mechanism of sedimentation, and rarely employed. Recent research of the Atelian sediments (Költringer et al., 2020) based on the detailed rock magnetic analyses of three sections in the northern part of the Lower Volga river valley allowed authors to attain an important assumption: "The material characteristics obtained from the magnetic investigations support those from field observations, showing that the loess-like material can be defined as true aeolian loess, in the sense of a primary air fall terrestrial dust deposit". Micromorphological description and clay mineralogy analysis of the modern Kastanazem at Srednyaya Akhtuba site revealed mixing of two sources forming the composition of the soil, main part coming from the marine Chocolate clays (Early Khvalynian stage) with high input of the aeolian silt, confirming view of atmospheric accumulation as an important factor in formation of the Late Khvalynian loess with a local source (Lebedeva et al., 2018).

Atelian sediments are extensively exposed in many sections, forming vertical walls that delineate the valley sides of the Volga and Akhtuba rivers. Almost always, the lower boundary of the stratum is disrupted by frost-cracking and wedges along which Atelian sediments penetrate deeply into the underlying sediments.

The youngest part of Late Pleistocene sections of the Lower Volga region are completed by Khvalynian chronozone deposits. They are characterized by a complex of open marine, coastal, estuary and estuary-river facies that occur throughout the valley. Stratigraphically, they are divided into Lower and Upper Khvalynian sediments, representing stages of the Khvalynian transgression of the Caspian Sea. The Lower Khvalynian stratum extend to 45–50 m a.s.l., and are epitomised by a characteristic facies – the Chocolate Clays (Fedorov, 1978). These clay-rich silty mudrocks include intercalations of fine sands with different frequencies depending on the locality; sometimes the sandy layers lie only at the base of the sequence (Kurbanov et al., 2020). The Chocolate Clays typically contain horizons rich in marine shells of species endemic to the Caspian Basin, such as *Didacna parallella, Didacna protracta, and Didacna ebersini* (Svitoch and Yanina, 1997).

Below a level of minus 20 m and up to the coastal-line of the modern Caspian Sea, Novocaspian chronozone deposits are widespread. These represent sediments of the Holocene transgression of the Caspian Sea, and contain a malacofaunistic complex (*Didacna trigonoides, Cerastoderma glaucum)*. Fig. 1 demonstrates correlation between regional stratigraphy and global MIS stages.

2.1. Site selection and study area

Information on cryogenesis is fragmentary for the southern regions of the East European Plain. While reference to the presence of cryostructures in various sections of the Lower Volga region does exist (Fedorov, 1957; Vasiliev, 1961; Moskvitin, 1962; Svitoch and Yanina, 1997), there are no published data that specifically evidence the existence of permafrost during the Late Pleistocene in this territory.

Pertaining to this issue, the authors searched for palaeogeographic archives in the Lower Volga region that contained the most complete series of subaerial deposits and include elements that indicated the existence of Late Pleistocene permafrost in the region. During the reconnaissance work in the Volga Valley, the Srednyaya Akhtuba section was recognized as the most characteristic (Figs. 2–3). Exposures at this location typically contained a complex of alluvial and loess-soil sediments, with a total thickness in excess of 10 m. Together these represent a significant cache of information on the evolution of the natural environment during the Atelian regression of the Caspian Sea. A unique feature of the section at Srednyaya Akhtuba was the presence of a series of horizons affected by cryogenic processes. Based on the study of this section, we first described the forms of the cryogenic relief and reconstructed the stages of the development of cryogenesis in the Lower Volga during the Late Pleistocene.

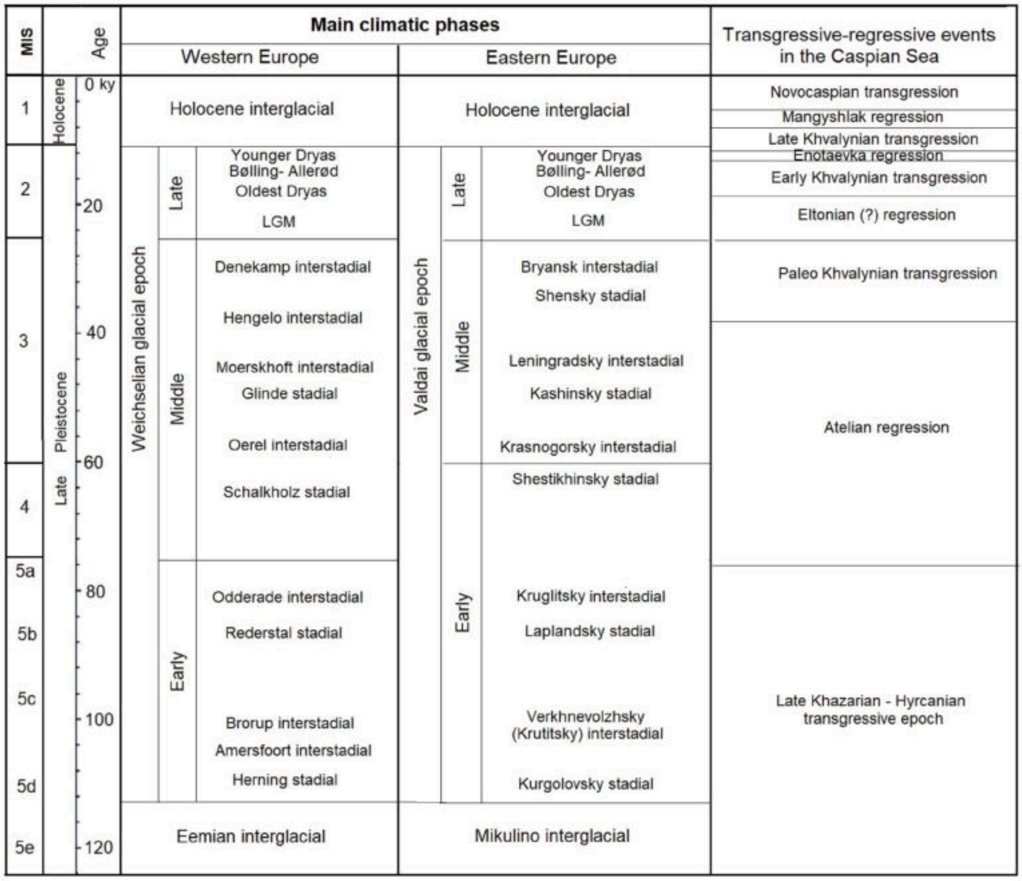

Fig. 1. Correlation table (from Yanina, 2014; Novenko, 2016; with additions).

Field studies were conducted between 2015 and 2019 in the Lower Volga region, which made it possible to identify postcryogenic structures (pseudomorphs, cryoturbation, soil wedges, etc.) of different ages – traces of relict seasonal and long-term freezing. Reconstructing the history of cryogenic phenomena in the Lower Volga region is an important scientific task in understanding the paleogeographic conditions of this region and the causes of fluctuations in the level of the Caspian Sea, since the regressive stages are the least studied. The first results of reconnaissance work on the Srednyaya Akhtuba section were published by Yanina et al. (2017).

3. Material and methods

3.1. Field studies

The work presented here is based on the results of a comprehensive study undertaken at the Srednyaya Akhtuba section (N 48°42′01.3"; E 44°53′37.1″), located on the northern side of the Volga-Akhtuba valley, 3 km south of the village of Srednyaya Akhtuba. Field work included reconnaissance studies, characterisation of the sediments and cryostructures (and their detailed description) in the section wall, sampling for laboratory analysis and age determination, level surveying with determination of horizon boundaries.

The 18.5 m section (illustrated by Fig. 3) reveals the fundamental units of the Lower Khvalynian plain of the Northern Caspian: the reference horizon for the Chocolate Clays of the Khvalynian transgression, alluvial strata, a formation of thick continental sediments, and a complex of deposits from the Khazarian transgressive-regressive stage of the Caspian, containing at least three clearly defined paleosol horizons.

3.2. Lithology (particle size distribution, micromorphology)

A comprehensive laboratory examination of deposits was undertaken in the Cryotrace laboratory at the Earth Cryosphere Institute, Tyumen Scientific Center, SB RAS. Analyses included determination of particle size distribution, mineralogical, micromorphological analyzes, and calculation of coefficient of cryogenic contrast (CCC).

The analysis of particle size distribution was undertaken to identify genetic traits necessary for paleogeographic reconstructions. It was performed using Mastersizer 3000 (Malvern) laser granulometer with dispersion in an aqueous medium. The micromorphology of sediments was studied in order to determine their microstructure (monoliths), and the morphology of the sand-sized particles. The microstructure of loess and the morphology of particles were studied using cohesive blocks and dispersed states, with a Hitachi TM 3000 SEM in combination with a Swift 3000 energy-dispersive spectrometer according to the standard method (Rogov, 2000). Special attention was paid to the shape, the surface morphology, the presence of chips, aggregation, organic and mineral inclusions (plant debris and authigenic formations). A study of clay aggregates was undertaken by spraying a sample onto a carbon patch placed on an objective table. More than 500 images were recorded.

3.3. Mineralogy and coefficient of cryogenic contrast

Studying the composition of silty sediments within the modern cryolithozone (cover loams of the Bolshezemelskaya tundra, the ice complex of northern and central Yakutia) revealed the leading role of cryogenesis in their formation (Konishchev, 1981). This work very effectively demonstrated the close relationship between the particle size distribution and mineralogical composition of cryogenic formations.

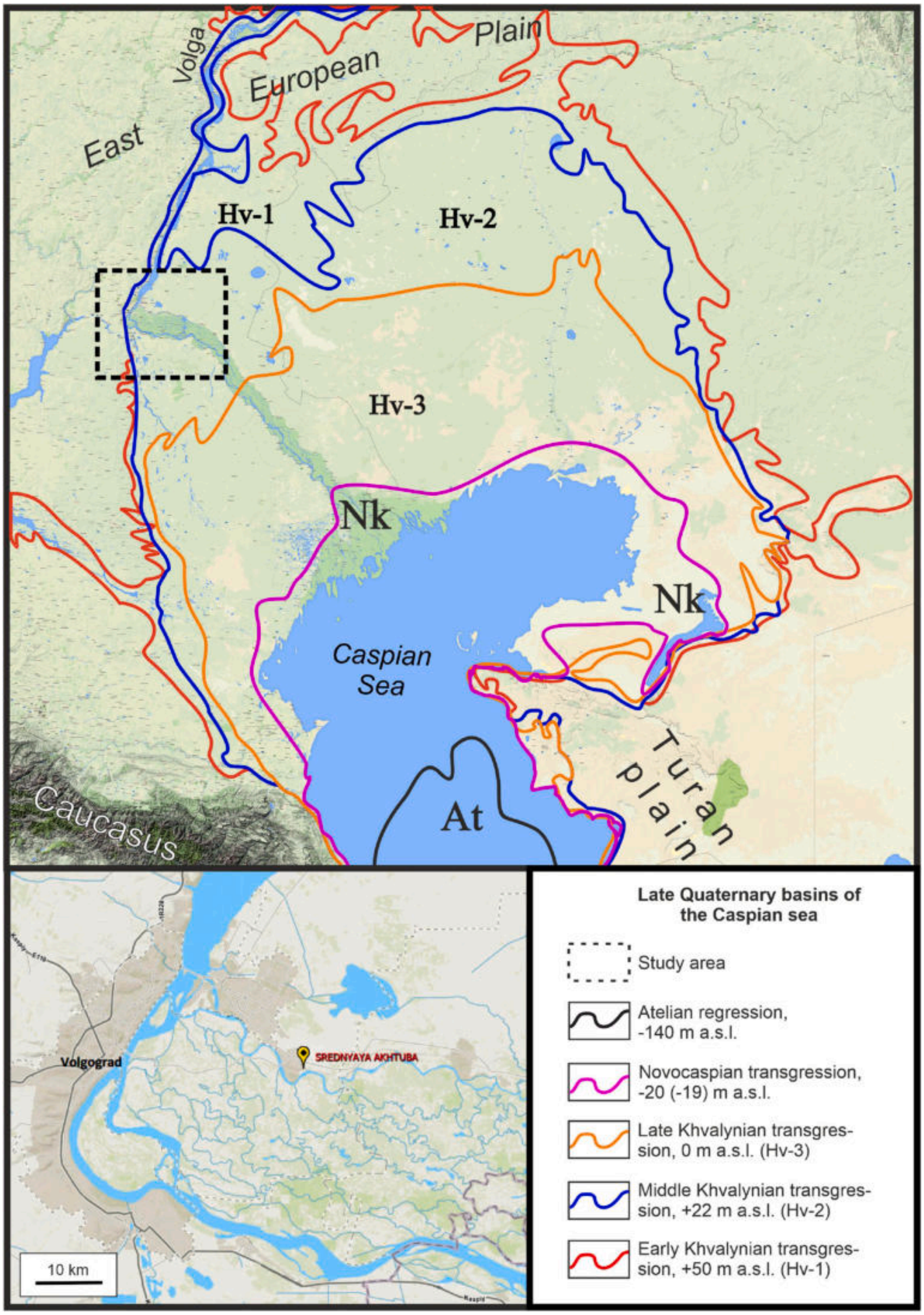

Fig. 2. The regional setting of the Srednyaya Akhtuba reference section with Late Quaternary basins of the Caspian Sea (*source: Google*).

The size of the particles generated is the result of various lithogenic processes (primarily hypergenesis) that affect the course of destruction of the minerals composing the grains over time (Kurchatova and Rogov, 2014). Strakhov (1963) proposed a pattern for sedimentogenesis in humid and arid territories, which was subsequently supplemented by Konishchev (1981) and Konishchev et al. (2005) in order to facilitate its application in regions subjected cryogenesis (both modern and paleo). Based on this supplement, a concept for the transformation of dispersed material in the zone of cyclic cryolithogenesis was formulated (Konishchev et al., 2005). Utilising the specifics of cryogenic stability of the main rock-forming minerals, in combination with a differentiated analysis of the mineral composition of individual particle size fractions, it is now possible to separate the products of cryogenic transformation from other types of hypergenesis and sedimentation processes (Konishchev et al., 2005).

To justify a clear criterion for assessing the influence of periglacial conditions on loess formation (seasonal and long-term freezing), a specific indicator was proposed. It characterizes the distribution and sets maximum values for the main rock-forming minerals (quartz and feldspar) present in the coarse silt and fine sand fractions that accumulate

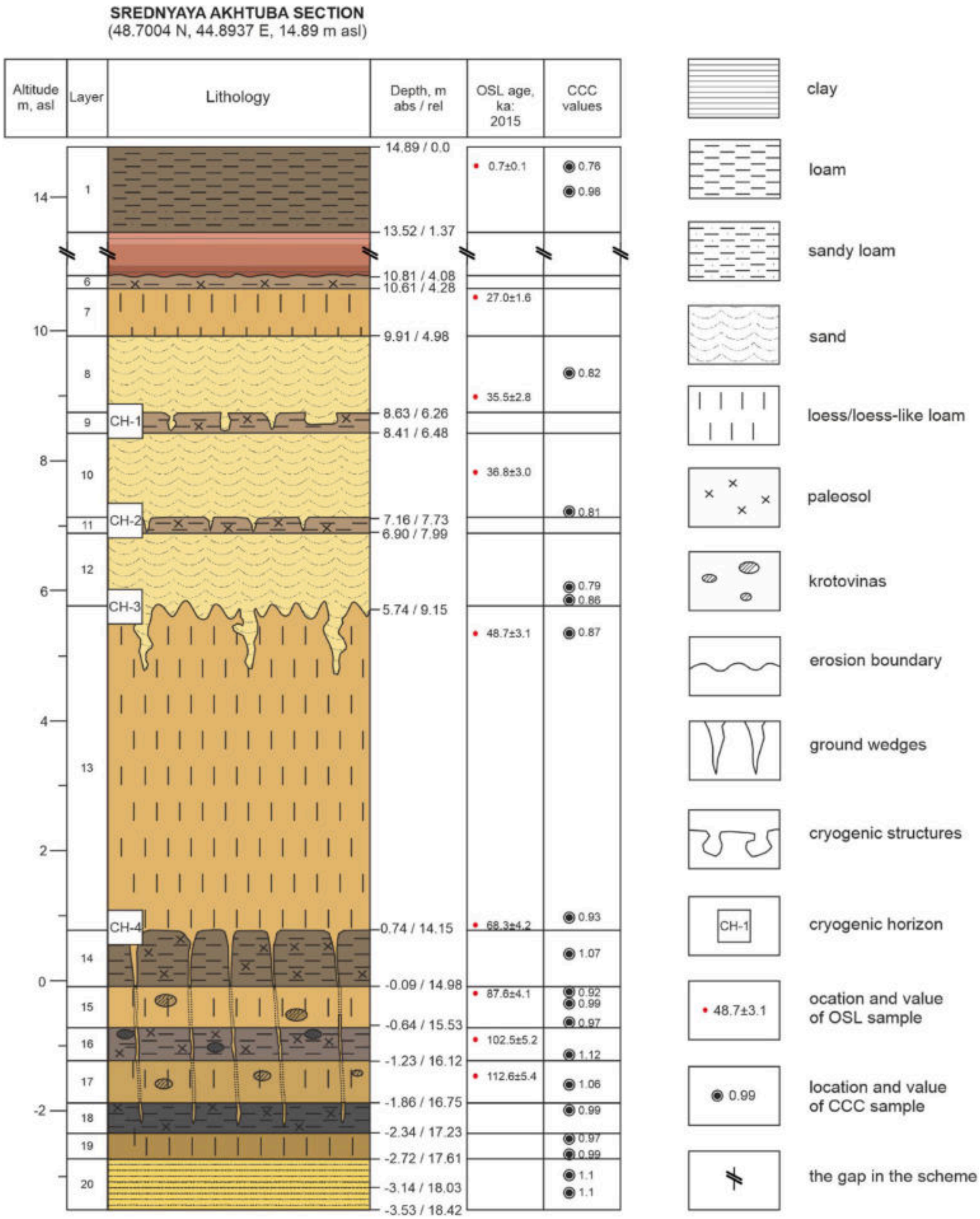

Fig. 3. Schematic representation of the Srednyaya Akhtuba section summarising lithostratigraphic context of the luminescence ages, sample locations, elevation, sedimentary structures and layer numbers for each unit and described cryogenic horizons. Marine facies (layers 2–5) are reduced.

during cryogenesis (Konishchev and Rogov, 1994). This indicator was called the coefficient of cryogenic contrast (Formula 1):

$$CCC = (Q_1/F_1)/(Q_2/F_2) \quad (1)$$

where CCC - coefficient of cryogenic contrast; Q_1, F_1 - the content of quartz and feldspars in the fraction with a particle size 0,05–0,01 mm, respectively; Q_2, F_2 - same in fraction 0,1–0,05 mm.

The main characteristics in this approach are not the absolute mineral content, but the features of the distribution curves of the quartz-feldspar ratio over the particle size distribution. This coefficient reflects the cryogenic organization of the substance; this expedites comparison of the current and the paleogeographic conditions of formation of deposits in the field, with a state of continuous cryolithogenesis (Konishchev et al., 2005). The coefficient value increases with the activity of cryogenic weathering, while deposits formed under permafrost conditions have a CCC value of more than 1.

Thus, while studying the influence of cryogenesis on the composition of sediments, the results from particle size analysis can be supplemented by the results of mineralogical analysis, in accordance with the results of the CCC calculations.

As a preparatory stage prior to mineralogical analysis it was necessary to obtain coarse silt and fine sand fractions; wet sieving was deemed the most appropriate method for this purpose. The sample was then dried, gently ground in an agate mortar and placed in a cuvette before loading into a diffractometer. Mineralogical composition was determined using a Bruker D2Phaser X-ray diffractometer. Quartz and feldspar obtained from both fractions was used to calculate the CCC.

3.4. Absolute dating

The age of the deposits was determined by optically stimulated luminescence dating, undertaken at the Nordic Laboratory for

Luminescence Dating (Risø, Denmark). A total of 11 dates were obtained, effectively characterizing the main stages of formation of the section. The first dating results were published in Yanina et al. (2017). All samples were prepared for measurements by standard chemical procedure (as described in Kurbanov et al., 2020). Quartz dose estimates were made following a standard SAR protocol using blue light stimulation at 125 °C for 40s with a 260 °C preheat for 10 s, a 220 °C cut heat and an elevated temperature (280 °C) blue-light stimulation at the end of each SAR cycle (Murray & Wintle, 2000, 2003). K-feldspar dose estimates were measured using the post-IR IRSL SAR procedure (Thiel at al. 2011, Buylaert et al., 2012) adopting preheats of 320 °C for 60 s (following regeneration doses) and 310 °C for 60 s (test doses). After preheating, the aliquots were stimulated at 50 °C with IR for 200 s (IR_{50} signal) and subsequently stimulated again at 290 °C with IR for 200 s (post-IR $IRSL_{290}$ signal, $pIRIR_{290}$). No correction was made for possible $pIRIR_{290}$ (Thiel et al., 2011; Buylaert et al., 2012) or IR_{50} signal instability.

Feldspar $pIRIR_{290}$ sensitivity correction is satisfactory (recycling ratio 0.98 ± 0.01 (n = 15), and the recuperation is on average 0.06 ± 0.1% (n = 15) of the natural signals. Dose recovery experiments used 3 aliquots of each sample and given doses of between 50 and 300 Gy, depending on the approximate D_e of each sample. Samples were bleached using a solar simulator for 48 h before the given dose. The pIRIR average dose recovery ratio for all samples is 1.06 ± 0.03 (n = 33) after residual subtraction, demonstrating that our $pIRIR_{290}$ protocol is able to accurately measure a known dose given before any thermal treatment.

4. Results

4.1. Section lithostratigraphy and chronology

A detailed description of the section (layers 22–1, Fig. 3), its stratification and the results of absolute chronology are presented in (Yanina et al., 2017). The lowest exposed part of the section (layers 22–19) begins with a loam horizon intercalated with sand. This is overlain by a homogeneous unit composed of silty sediments deposited in a lacustrine-estuarine setting. The uppermost part of the unit (layer 18) has been modified into a well-defined paleosol horizon around 0.4 m thick, that displays a dense blocky structure. This soil is covered by the first unit of loess-like loams (layer 17) which maintain an average thickness of 0.75 cm. Layer 17 contains what appear to be krotovinas (infilled burrows). A quartz OSL date of 112.6 ± 5.4 ka (sample 150 829) was obtained from this horizon. The loessic-loam is topped by a second paleosol (layer 16), which again contains krotovinas, but is also crossed by thin post-cryogenic cracks, and weakly expressed soil wedges. Quartz OSL from this unit yielded an age 102.5 ± 5.2 ka (sample 150 827). Above the paleosol a second horizon of grey-brown loess (layer 15) can be seen. This unit maintains an average thickness of 0.7 m, is mottled with precipitated iron oxides, and contains manganese and calcareous inclusions, and once again krotovinas; quartz OSL dated this unit to 87.6 ± 4.1 ka (sample 150 824). Layer 14 is a well-defined buried soil containing pseudomorphs of melted ice wedges. The pseudomorphs are filled with the overlying pale yellow loess, and display a characteristic ''wedge'' shaped geometry (the width in the upper part is 7–18 cm, the lower part is 2–3 mm). In plan view they form a lattice with sides of 45–50 cm. A quartz OSL date of 68.3 ± 4.2 ka (sample 150 822), was obtained from the boundary of the paleosol and overlying pale yellow loess. This date constrain the timing of wedge formation to the beginning MIS 4.

Facies from layers 13-8 display a greater degree of variation, being comprised of sandy and finer silty units with markedly different subaqueous and subaerial origins. The top of layer 8 is marked by a sharp erosional boundary (sharp change in colour, grain-size, structure and unconformity). These strata represent the Atelian suite in the stratigraphic scheme of the Lower Volga region (Yanina et al., 2017). Layers 13 and 12 constitute two units of loess-like loams with a combined thickness of 4.5 m, that together form much of the vertical walls of the section. The lowermost unit (layer 13) is a thick (~3.5 m) accumulation of loess of uniform light brown colour, with rare nodular manganese and gypsum inclusions. The upper (layer 12) is richer in sand sized grains, is replete with manganese oxide and gypsum inclusions, but also contains rare dark spots of organic matter. Quartz OSL dates the upper part of this loessic sandy loam to 48.7 ± 3.1 ka (sample 150 814). Layers 11 and 10 are composed of fine and medium-grained sand intercalated with loessic sediments; layer 11 exhibits some signs of soil formation, calcareous inclusions and traces of manganese oxide. For the upper part of the horizon (layer 10), a date of 36.8 ± 3.0 ka was obtained using quartz OSL (sample 150 812). These deposits are covered by a horizon of sand (layer 9), the lower part of which yielded a date of 35.5 ± 2.8 ka (quartz OSL, sample 150 810). The uppermost part of the Atelian suite (layer 8) is represented by a layer (0.5 m) of dense unstratified loess loam that is pale beige colour, vertical in profile, and contains at least one poorly developed/insipient paleosol horizon. The upper part of the loess horizon dates to 27.0 ± 1.6 ka (quartz OSL, sample 150 809). An abrupt erosional unconformity tops the Atelian suite of sediments, demarcating the start of the transgressive sequence of Khvalynian marine Chocolate Clays that stand out above.

The Lower Khvalynian sediments (layers 7–3) are structured as follows: alternating layers of loam and silty-clays with prismatic cleavage and intercalations of sand (layers 5 and 6); two layers of chocolate clay (layer 4) with thinly laminated intercalations (from 0.5 to 3 cm) of fine-grained sand (dated to 13.0 ± 0.5 ka by quartz OSL, sample 150 806); and penultimately, a layer of sandy loam of dark beige colour with rare laminae of fine-grained sand (layer 3). In the highest part of the Srednyaya Akhtuba section sits the modern soil that developed above subaerial Holocene sandy loam deposits (layers 1–2). For this, a quartz OSL date of 720 ± 70 years was obtained (sample 150 801).

4.2. Cryostructure characterisation

A unique feature of the Srednyaya Akhtuba section is the presence of distinct relict permafrost formations (cryoturbations, polygonal wedge-shaped structures, and small-polygonal fractures) that are clearly discernible across several horizons; this allows four separate phases of cryogenesis to be identified. Traces of the fourth are expressed in the soil horizon of layer 14, and correspond to marine isotope stage (MIS) 5a. The wedge-shaped structures are most developed in this paleosol, penetrating through the two lower levels of buried soils (layers 16–18, as illustrated in Fig. 4). Their width in the upper part of the wedge is 12–20 cm, and their height varies from 0.8 to 2.5 m; the distance between the soil wedges is 40–60 cm. All the wedge-shaped structures originating from layer 14 are filled with the lighter coloured overlying loessic material (from layer 13). The wedges have a relatively wide cone at the top, but quickly taper and continue in the form of branching structures, which sometimes split into 2-3 separate tails.

The third phase of cryogenic modification becomes apparent in the upper part of the layer 13 loess horizon (dated to MIS 3). Here (~9.15 m from the top of the section), the contact between the underlying pale coloured loess and the overlying layer of medium-grained homogeneous sand of layer 12 is disrupted (Fig. 5a). The top of the loess layer is cut by a series of large cryostructures and thin cracks that penetrate several meters. The cleaned cryostructure illustrated in Fig. 5a is a bag-like pocket 70–75 cm deep filled with unconsolidated, heterogeneous sandy loam (from layer 12) of a darker hue compared to the surrounding pale loess. Inside the pocket, distinct layering is noticeable, indicating a gradual filling from the edges to the center. The boundary of the cryostructure and the host loess is emphasized by a thin line of white carbonates. This border is uneven, with numerous swirls and folds. The material filling the cryostructure is dissected by a crack along its boundary, which continues below, forming a tail-shaped wedge. At the tip of the wedge, an inclusion of vivianite 5 mm in diameter across is

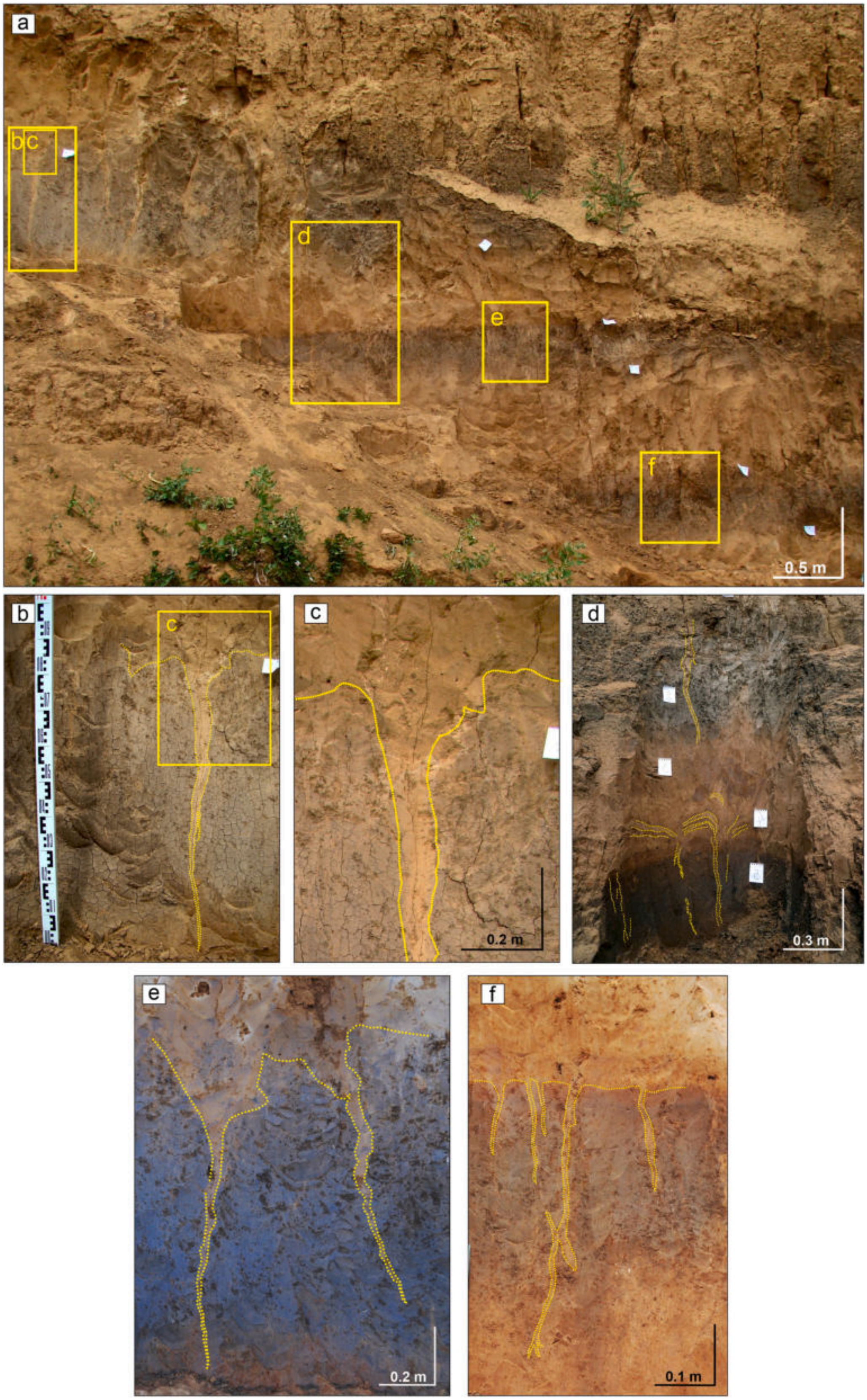

Fig. 4. Cryogenic structures of the fourth cryogenic horizon.

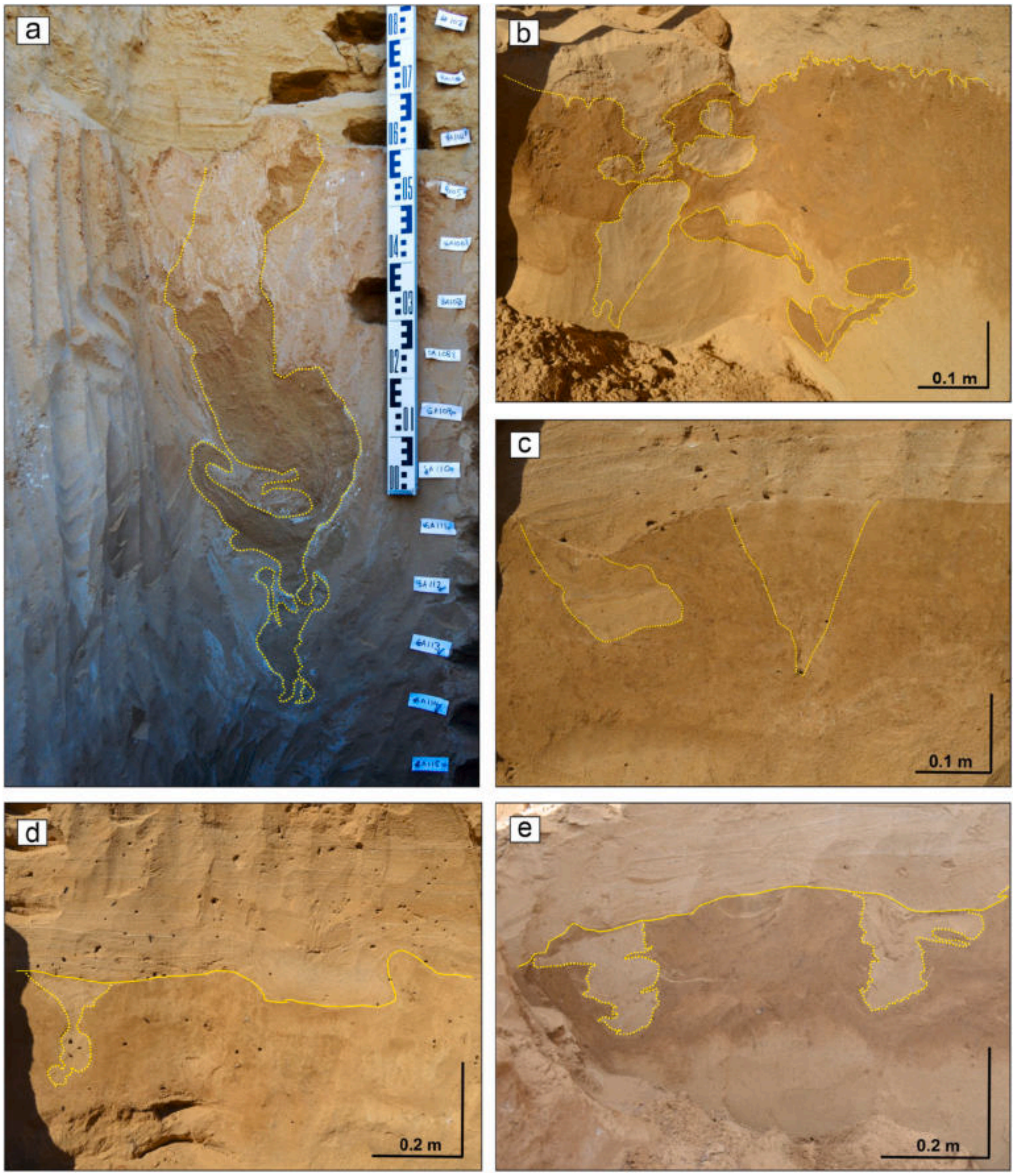

Fig. 5. Cryogenic structures of the third (a), the second (b) and the first (c-e) cryogenic horizons.

noticeable. The wedge ends with a thin crack (1–2 mm wide) extending to a depth of ~12.75 m from the top of the section.

A second phase of permafrost feature development is evident at a depth of 7.73–7.99 m from the top, where a series of rounded tuberous cryostructures cut through a layer of paleosol and penetrate into the underlying horizon (Fig. 5b). Here, the substrate material is a fine-grained sand and grey-yellow in colour. Central parts of the cryostructures are slightly ferruginous, and some of them, (those enclosed by a paleosol) have a rounded border; underlying features that penetrate the sandy loam horizon have wedge shaped tails.

At a depth of 6.26–6.48 m from the top of the section, a first cryostructure bearing horizon is observable (Fig. 5c–e). Several different wedge configurations are evident:

The first is a wedge with a rounded end. This form extends to around 17 cm in length, its body has a layered structure, and the margins are defined by a sandy loam of light brown colour, (similar to the mouth of the wedge). The middle part of the wedge has horizontal processes up to 7 cm breadthwise. Wedge fill is a well-sorted medium sand sourced from an overlying layer (since removed), has small inclusions of organics and vivianite; it is variegated in appearance, and layering is emphasized by a precipitated carbonate cement. The lower boundary of the layer appears to follow the configuration of the wedge.

A second distinct wedge configuration is observable, with dimensions of 20 cm vertical length, 12 cm width at the mouth, and a typical slope of around 30° (Fig. 5c). The wedge fill is a light brown sandy loam, wedge borders are uneven (composed of uncemented sand-sized grains), and a cavity ~5 mm in diameter is detectable at the tip of some of the wedges.

A third cryostructure, this time with a funnel-like geometry that swells to an irregular protuberance after the taper (Fig. 5d), is visible on certain horizons. This too is filled with sand, but there is also no penetration of the overlying layer, and the border is only visible where it is highlighted by a thin layer of ferruginized sand. The protuberance below the funnel-like structure is round, and has a noticeably weaker concentric structure; its border margins are lined by a whitish horizon of carbonates.

Adjacent to the cryostructure described above (also illustrated in Fig. 5d) a feature that resembles the form of a chest fold (dimensions 15 × 40 cm) is clearly visible. Composed of stratified sand, with the layers running parallel to the shape of the fold, the shape is highlighted by thin laminations of lighter coloured carbonates.

The final suite of cryostructures preserved in the sediments at Srednyaya Akhtuba also display a wedge-shaped geometry (Fig. 5e). Wedges up to 20 cm in size are dissected along the horizontal plane, forming extensions with crumpled or serrated edges. The cryostructure fill is entirely derived from the overlying sand, and ferrugination is noticeable.

4.3. Lithology

4.3.1. Particle size distribution

A more thorough analysis and description of the fine sand (100-50 μm) and coarse silt (50-10 μm) was deemed necessary for the purposes of this study. Sieved samples were divided in two - into a finer and coarser fraction. In the loessic horizons, the predominance of the coarse silt fraction was observed (up to 60% of the sample by dry weight), an insignificant presence of particles larger than 250 μm, and a small clay fraction (<1 μm), not exceeding 2–3% dry weight. Indeed, for the loessic horizons, the majority of the sample was found to consist of grains between 25 and 50 μm; the medium/coarse silt fraction using the classification proposed by Udden (1914), and Wentworth (1922). The granulometric composition of the paleosol horizons separating the loess strata does, on the one hand, contain more sand sized grains, but also contains a much higher clay component.

4.3.2. Microstructure of loess-soil strata

In the Srednyaya Akhtuba section, the microstructure of undisturbed loess was studied by cleaving small cohesive block samples. The microstructure of the loess (Fig. 6a–c) and soils should be classified as belonging to the aggregative type (after Grigoryeva, 2001), throughout the majority of the sequence. The basis of this type of microstructure is large aggregates (1–3 mm) with varying degrees of cohesion (Fig. 7c–f). These aggregates are separated by sinuous cracks and isometric irregular pores 0.1–0.3 mm in size, and are formed of particles of different sizes and composition. Typically, this can include acute-angled particles of fine quartz sand, to complex cohesive masses of inclusions containing iron, calcium and silicon. In addition, clusters of crystallized calcite are commonly found inside aggregates.

Interesting features of the microstructure found in loess are tubular pores with an almost perfect round shape in cross section (Fig. 7a and b). The diameter of pores in the loess samples was found to be 0.4–0.6 mm. Compaction of the soil mass observed on the walls, was found to involve

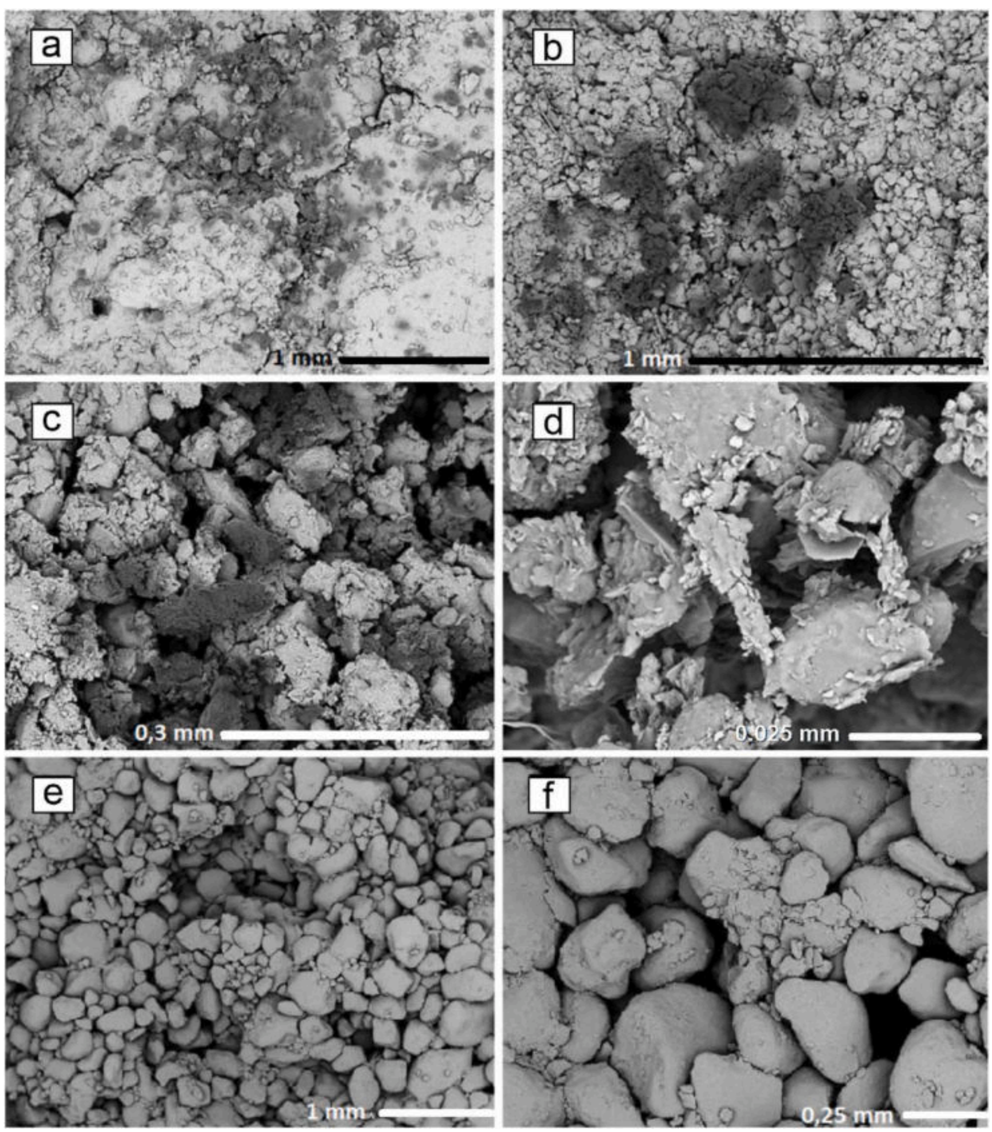

Fig. 6. SEM micrographs illustrating: a-c - microstructure of loess at different magnifications; d - silt-sized particles, contacting each other through clay “bridges”; e-f - microstructure of the sandy horizon (depth ~7.7 m from top).

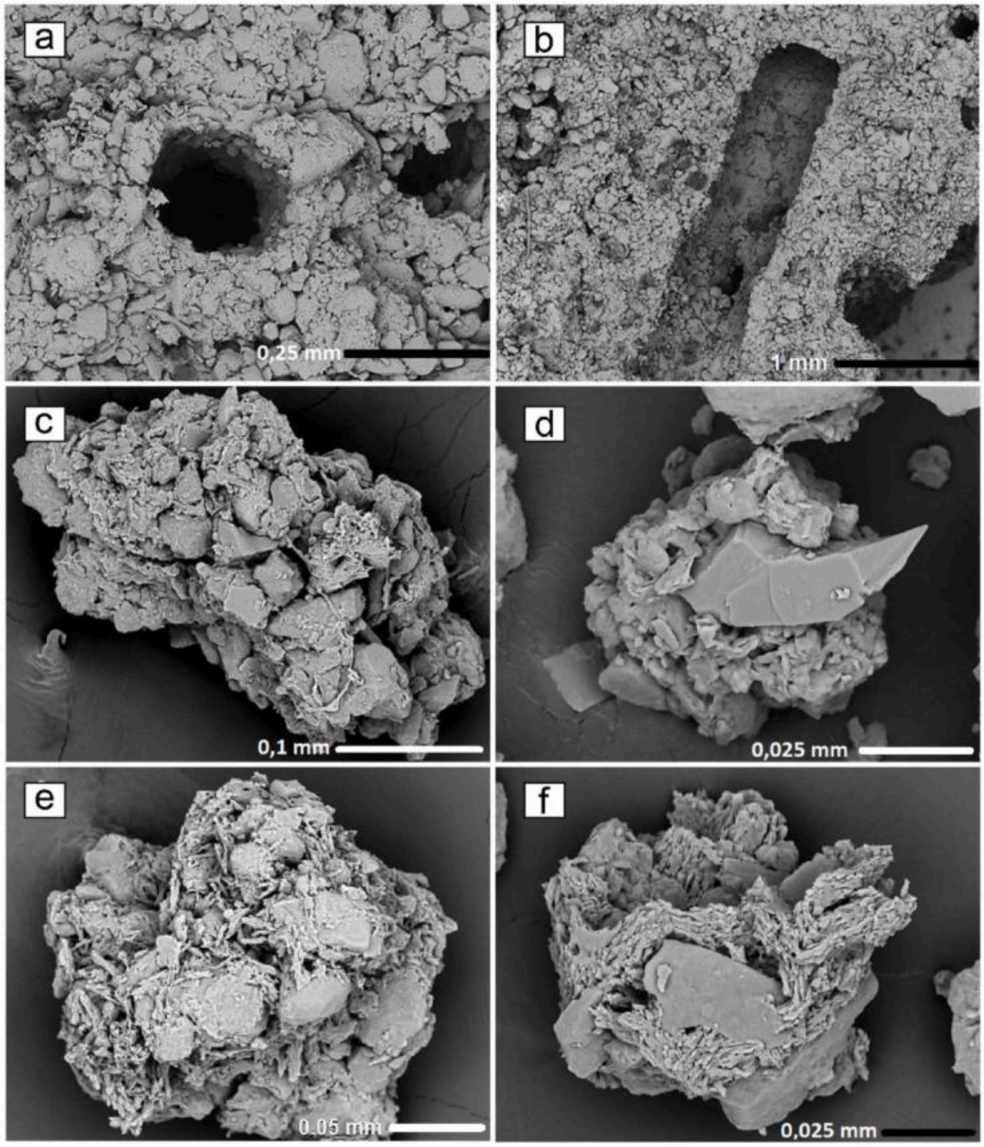

Fig. 7. SEM micrographs illustrating: a-b - tubular pores in loess microstructure (a, b); c-d - aggregates composed of sand, silt and clay particles with iron-carbonate cement, with varying degrees of cohesion; e-f - complex aggregates with calcite cement.

silty particles of silicate minerals, the distribution of which often forms a noticeable "ring". Radial cracks are often visible around the channels. In some cases, the distribution of particles was observed to be closer to hexagonal, rather than circular. In addition, radial cracks are often visible around the channels.

4.3.3. Morphology of sand particles and aggregates

The morphology of sand-sized quartz grains (Fig. 6e and f, depth 7.7 m from top; Fig. 7c and d, depth 17.3 m from top) in the studied section is very diverse, and is a reflection of the conditions that prevailed during the formation of deposits in different layers. Well-rounded grains, with a smooth and slightly eroded surface, are characteristics of the sand filling of wedges in the soils (Fig. 6e and f). However, more than half of the particles in the loess samples throughout the section are angular, with numerous chips and sharp edges (Fig. 7c and d).

In the loessic sediments of the section, aggregates of various types are found - both in size and in structure. Large aggregates with a loose structure (0.5–0.1 mm in size) are usually composed of ten or more silt-sized particles, contacting each other through clay "bridges" (Fig. 6d). These form the basis of intra-aggregate pores from 0.005 to 0.01 mm in diameter, and are usually isometric or slightly elongated in shape. Smaller aggregates are dominated by fine silt and clay particles; intra-aggregate pores in these are smaller and have a flattened shape. Most of the aggregates are formed by a combination of silt-sized and clay-sized particles, with a cement of an iron-carbonate composition (Fig. 7c and d). There are also aggregates formed exclusively from calcium carbonate crystals (Fig. 7e and f, depth 17.6 m from top). These units are competent enough not to disintegrate when they are washed with water or are exposed to ultrasound.

Authigenic minerals in the loess samples are represented by numerous druses (fine coatings) of calcium carbonate crystals (Fig. 8a, depth 8.5 m from top), and gypsum inclusions (Fig. 8c, depth 5.4 m from top). Iron is represented by amorphous films on the surface of the particles, in the form of siderite nodules, and also as rare growths of magnetite or titanium-magnetite (Fig. 8d). Witherite (a barium carbonate mineral of the aragonite group) crystals were found at a depth of 14.0 m from the top of the section (Fig. 8b).

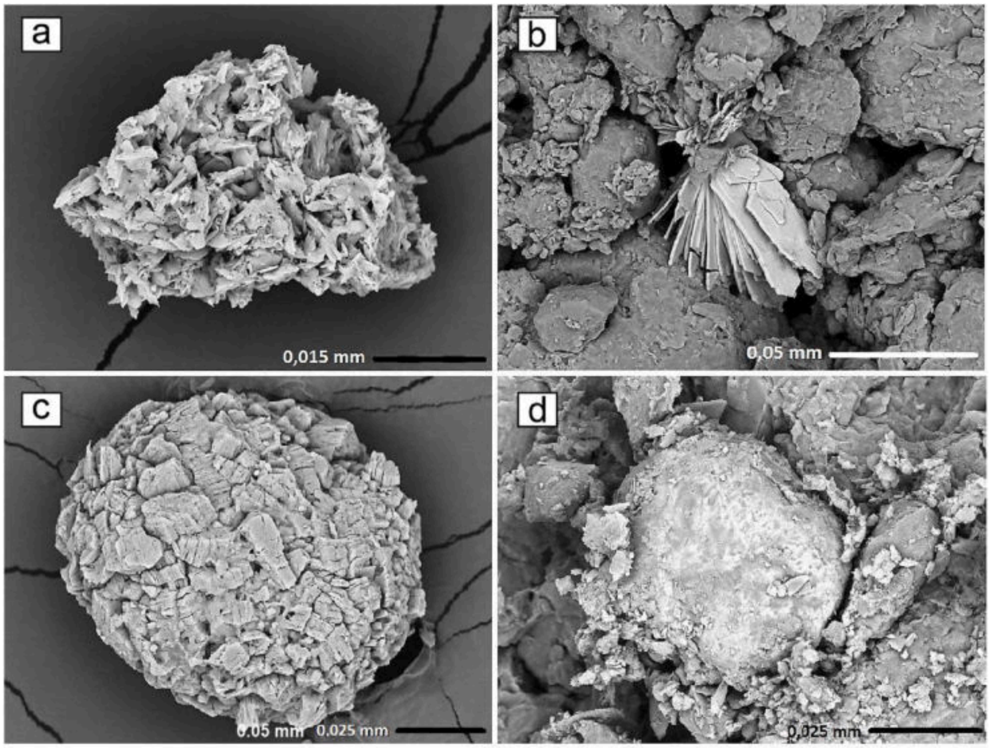

Fig. 8. SEM micrographs illustrating authigenic minerals and calcite aggregates: a – calcite aggregate ($CaCO_3$); b – neoplasms of witherite ($BaCO_3$); c – gypsum aggregate; в – titanium-iron concretions.

4.3.4. Mineralogical composition of sediments. Cryogenic contrast coefficient

The mineralogical composition of the sand and silt fraction (for the CCC calculation horizons) is complex: the majority is quartz (50–70%), followed by microcline (10–17%) and albite (10–16%), orthoclase (6–8%), muscovite (4–12%), augite (2–5%), and finally kaolinite (2–4%). The trace amounts of other minerals identified were not deemed significant enough to include in the calculation.

The CCC values along the Srednyaya Akhtuba section (Fig. 3) fluctuate over a rather wide range. The CCC value in the deposits of the Holocene stage (MIS 1, layers 2 and 1) decreases from 0.98 to 0.76, corresponding to the transition from the cold phases of the Valdai glaciation to the warmer Holocene period. The stage of accumulation of the alluvial stratum corresponding to the second half of the MIS 3 chronozone, and the early phase of the early Khvalynian transgression of the Caspian Sea (layers 11–8) is characterized at its beginning and end by low CCC values (0.82). These reach the CCC maximum at the boundary of layers 9 and 10 (value 1.06) in the sands accumulated in the middle of the chronozone. The Atelian regression stage is characterized by different CCC values: 0.79–0.86 for layer 12; layer 13 generated values of 0.86–0.93. The most transformed were layers 14 (MIS 5a, CCC 1.07), 16 and 17 (MIS 5c, 5d) with CCC values of 1.06 and 1.12.

5. Discussion

5.1. The morphology of cryogenic structures

We identified four cryogenic horizons, each of which is represented by structures of different morphology. Unfortunately, only the lower parts of the wedges of the fourth cryogenic horizon are clearly expressed, as the main cracking and growth of the wedges occurred during the formation of overlying loess. Due to the uniformity of the material and its colour, any traces of cryogenic transformation of sediments through much of lower portion of layer 13 are difficult to identify.

The formation of soil wedges of the second cryogenic horizon probably took place in the seasonally frozen active-layer of the underlying sand during the formation of the soil horizon. Post-pedogenesis, the formation of soil wedge probably took place again, however, due to the open framework nature of the substrate, clear wedge-shaped structures did not form.

The first cryogenic horizon is characterized by the most varied cryogenic structures. The structure represents the melted tail of the ice wedge, the upper part of which was destroyed by the waters of the early Khvalynian transgression. As the ice of the tail melted out slowly, the acute angle of the tail was gradually deformed, material then collapsed from the walls, partially filling the wedge. The layers of segregated ice adjacent to the tail of the wedge were also thawed and filled with the same material. Water erosion subsequently washed away the source of the material of the first layer, adjacent to the walls of the cryostructure. Subsequently, the incoming water deposited coarser material, filling the central part of the thawed tail of the wedge. When the entire core was filled, parallel horizontal layering at the boundaries was emphasized by the precipitation of carbonates.

Fig. 5c demonstrates the form that may also represent the melted tail of an ice wedge. However, unlike the previous form, the thawing and filling was more rapid (and quite possibly synchronous), since layers indicative of gradual filling are absent. Such rapid filling would explain the presence of a void in the lower part of the structure.

The cryostructure on Fig. 5d (left) also formed as a wedge, probably in a similar fashion as the previous ones. However, the end of the tail was icier, resulting in more severe deformation when complete sections of the wedge sides collapsed into the void left by melting of the supporting ice. The "chest" (also Fig. 5d, right side) was probably formed as a result of filling of the void left behind by the melting of the tail of the wedge located perpendicular to the adjacent one.

The forms on Fig. 5e also probably represent the melted tails of the more icy sections adjacent to the main body of the ice wedge. Therefore, the material that filled the void left by melted ice was able to penetrate into the lateral parts of the wedge and wedge tails, where ice still remained. The filling of voids left from the ice wedge proceeded gradually in this instance, allowing some collapse of the sides to take place.

5.2. Lithology

Sediments in the Srednyaya Akhtuba section are represented by alternating horizons of silty-clays, loess, loess-like sands-silts, interbedding of medium-grained well-sorted sands, and paleosols. The modern definition of loess (Muhs, 2013) describes these sediments as dominated by silt-sized (50–2 μm diameter) particles. According the author, most loess deposits are not composed completely of silt, but also contain measurable amounts of sand (>50 μm) and clay (<2 μm). A cursory glance at the results of the particle size analysis would indeed appear to show a typical distribution of fractions indicative of loess, across a number of horizons. Loessic horizons are dominated by the coarse silt fraction (25–50 μm). By some researchers (Deng et al., 2010) it has been interpreted as an indicator of loess formation in cold and dry climatic conditions.

5.3. Microstructural characteristics of sediments

The difference between deposits of aeolian origin and deposits transformed by cryogenesis is more evident at the micromorphological level: rounded particles with a fine-topped relief versus angular particles with cracks and chips on the surface. Particle distribution and aggregation are also very informative.

As it was found, the microstructure of the loess should be classified as belonging to the aggregative type, which does result from the presence of a clay fraction, although this does promote some aggregation of particles; of much greater significance is the role of structure-forming precipitates, such as gypsum and calcium carbonate.

Other interesting features are cracks and isometric irregular pores which are an important part of loess microstructure. The formation of such morphological features (radial cracks often visible around the channels/pores) could be directly associated with the growth of ice inclusions during the development of permafrost (Konishchev, 1981).

It has been demonstrated that size, shape and the surface of quartz particles can be utilised to determine the genesis of deposits (Woronko and Pisarska-Jamrozy, 2015). Well-rounded grains, with a smooth and slightly eroded surface, are characteristics of the sand filling of wedges in the soils (Fig. 6e and f), suggesting the predominance of aeolian transport during their formation. However, more than half of the particles in the loess samples throughout the section are angular, with numerous chips and sharp edges; a strong indication that cryogenic mechanisms dominated during their genesis (Fig. 7c and d).

Particular attention was paid to aggregates within the silt-sized fraction, which are reputed to be cryogenic in origin (Sergeev and Minervin, 1960; Popov, 1967; Konishchev, 1981).

According to (Rogov, 2009) authigenic minerals are the most important indicator of the Quaternary sedimentation conditions and the subsequent changes occurring in them in a particular physical and geographical setting. The composition of the authigenic minerals of loess in our samples indicates that cryoarid climatic conditions dominated during the formation of the loessic horizons in the Srednyaya Akhtuba section.

Utilising the micromorphology data as a proxy to reconstruct paleoclimate, indicates that the coldest phase of cryogenesis coupled with permafrost development occurred after the MIS 5a soil had formed. Significant cryoturbation with cracking and the formation of ice wedges occurred during MIS 4, in conditions of reduced soil moisture. These wedge features were later replaced (during middle MIS 3) with pseudomorphs when moisture of sediment appears to have grown in condition of developing Early Khvalynian transgression. This phase of cryogenesis was followed later in MIS 3 by short phases of warming and increased moisture availability resulting in at least two episodes of soil formation; the climatic amelioration was coincident with rising Caspian Sea level (Yanina et al., 2017). Increased moisture content in the sediment encouraged ground conditions where “high-temperature” permafrost developed, or where short-term low-temperature cooling initiated formation of poorly developed sporadic permafrost.

5.4. Description of the stages according to CCC

In order to fully characterise the influence of cryogenesis on the sediments, the mineralogy of the fine sand and coarse silt fraction of the loessic units was analyzed in detail, and the CCC was calculated. The wide range of CCC values along the Srednyaya Akhtuba section record both those horizons displaying evidence of cryogenic modification and others that do not bear its visible traces.

The values for layers 9 and 10 suggest a short, but cold climatic episode, with the presence of permafrost and polygonal cracking of soils, evidenced by pseudomorphs.

Layer 13 (Atelian loess) reflects colder accumulation conditions in comparison with layer 12. The values for last layer do not imply the presence of permafrost, but they do indicate a deep seasonal freezing of deposits.

In the series of sediments corresponding to the late Khazarian transgressive-regressive stage of the Caspian (MIS 5), the composition and structure of sediments clearly show the influence of cryogenesis against the background of regional permafrost development with polygonal frost cracking. Layers 14, 16 and 17 were also subjected to a degree of cryogenic modification during the cold conditions of MIS 4 that promoted permafrost development in the study area once again.

It must be acknowledged that CCC does not necessarily reflect low negative temperatures, but rather the development of cryogenic destruction during ice formation in microcracks of particles under conditions of sufficient soil moisture. In the dry stages of loess accumulation (Atelian chronozone loess for example), lower values of CCC reflects cold conditions and frequent freezing and thawing.

5.5. Loess sedimentation and cryogenesis

According to modern concepts, loess-soil series are formed under conditions of dynamic climatic change, with loess horizons being formed during the cooling phase (Velichko et al., 2015). At the same time, the recognition of aeolian processes as the main source of the material has become generally accepted. The most studied loess accumulation regions - the valleys of the rivers Danube and Rhine in Europe, and the Yellow River (east Asia), indicate that the formation of thick strata of loess-soil series are associated with the flow of material from large alluvial systems (Stevens et al., 2013). It is noted that the local transport of material (within tens of kilometres) is dominant; therefore, during cold-arid climatic phases aeolian processes would prove a very effective mechanism for stripping material from landscapes already denuded by periglacial action, and form thick loess strata proximal to their source. In this case, the cryogenic transformation of the primarily alluvial source material continued, finally forming the typical features of loess (the silty composition of the deposit, the structure and micromorphology of the mineral grains). Such an assumption is consistent with observations made in the Lower Volga region, where relatively thick, laterally continuous horizons of loess formed during cold and relatively dry phases of the Atelian regression of the Caspian Sea (in the Srednyaya Akhtuba section, the thickness is more than 7 m). The loess-soil formation during MIS 3 and 4 were influenced by cryogenic transformation recorded in four stages.

Field description of the Atelian formation, analyses of cryogenic structures and CCC of these sediments allows forming some preliminary conclusions concerning nature of cryogenesis in the Lower Volga region that is characterized by two main parameters. The first is cryogenic transformation of sediments evidenced in cryogenic structures. In the Srednyaya Akhtuba section, two types of cryostructures are found: (1) large ground wedges of long vertical scale (more than 2 m), which in our opinion can only form in loess of the arid Northern Caspian Lowland (precipitation less than 200 mm) in conditions of significant cooling; (2) relatively small-scale phenomena (involutions of 20–50 cm) formed as a result of insignificant cooling under frequent seasonal freezing of moist sediments, (without continuous permafrost).

The second indicator is the coefficient of cryogenic contrast, which reflects the number of transitions through 0 °C. The highest CCC values were obtained for the lower part of the Srednyaya Akhtuba section, and reflect the freezing of the underlying horizons (loess and paleosols, formed in MIS 5) during the cold conditions of MIS 4.

Thus, the analysis of these two indicators reflects the regularities of the formation of relatively large cryostructures (confirmed by the CCC) in loess – controlled by the regional climate, while smaller structures are indicators of local conditions. In same lithological and temperature conditions formation of cryostructures occurs more intensively during humid conditions.

For the first time we identified and characterized four stages of cryogenesis development in the Lower Volga region (Fig. 9). The earliest

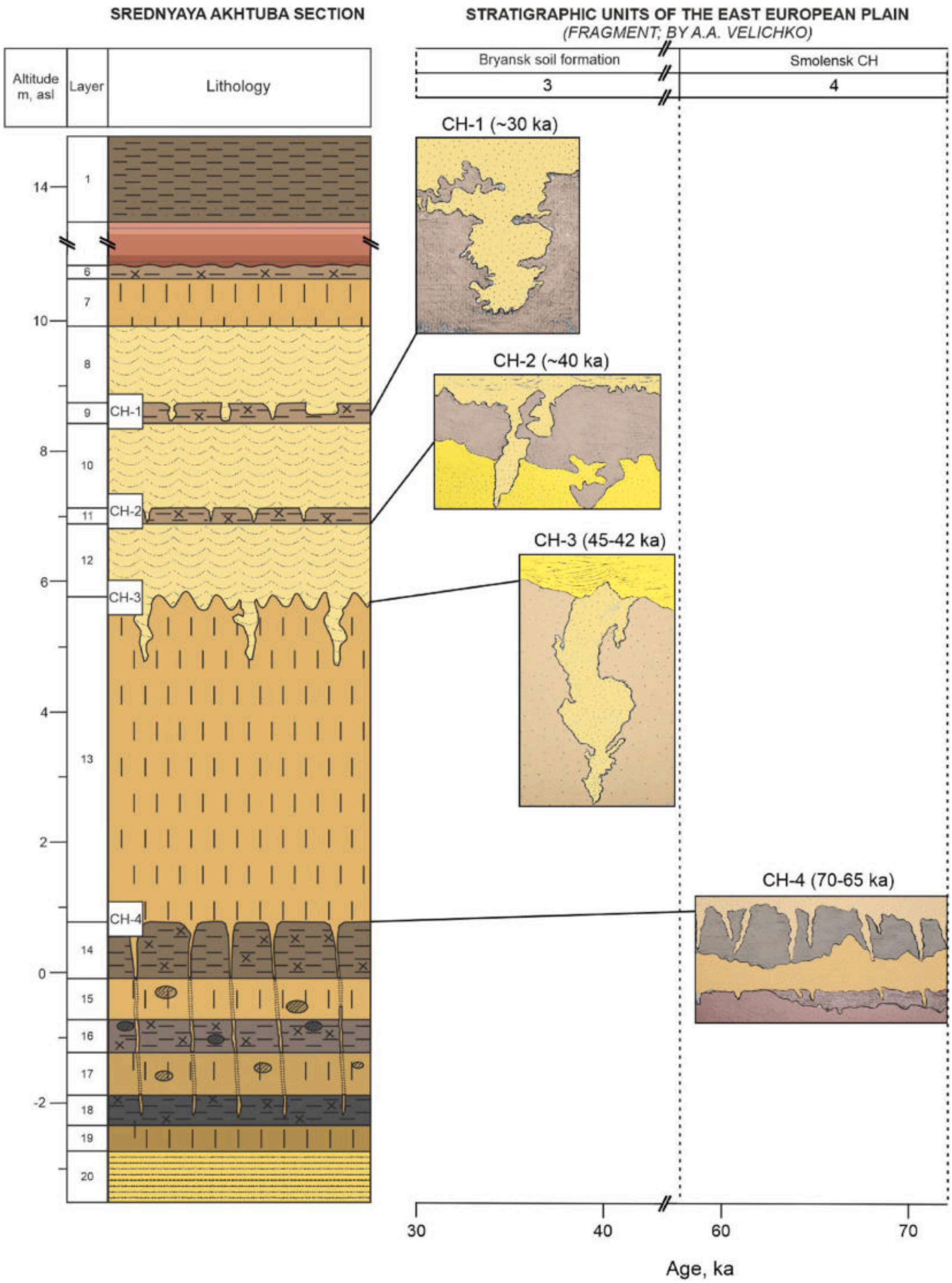

Fig. 9. Cryogenic horizons of Srednyaya Akhtuba section in context of stages of cryogenesis development in the East European Plain (Velichko et al., 2006). Symbols are the same as in Fig. 3.

stage (CH-4) is expressed in the form of large ground wedges, formed at the beginning of MIS 4 (70–65 ka). The upper three (CH-1, CH-2, CH-3) are formed as a result of short-term events of sporadic high-temperature permafrost development during different stages of MIS 3: CH-3 at 45–42 ka; CH-2 at ~40 ka, CH-1 at ~30 ka. Analysis of the regularities of the cryogenic structures' distribution within the Russian Plain in the Late Pleistocene (Velichko et al., 2006; Vandenberghe et al., 2014) suggests that the phases CH-1 – CH-3 of Srednyaya Akhtuba correspond to the time of Bryansk soil formation. Of particular interest is the presence of pronounced traces of the permafrost development in the region at the beginning of MIS 4 (Smolensk cryogenic horizon, second stage). New data indicate a significantly more southerly development of permafrost in the specified period at least 100 km from the border identified by A.A. Velichko.

6. Conclusion

The results presented here have enabled the reconstruction of a conceptual model for the key stages in the development of cryogenesis over the northern part of the Lower Volga region during the Late Pleistocene:

1 The fourth stage in the formation of cryogenic phenomena took place at the final phase of the Early Valdai glacial (MIS 4) during the Atelian regression of the Caspian Sea. Significant cracking of the horizons occurred with the formation of ice wedges. Thin wedges of considerable extent (up to 2.5 m in length) cross two paleosol horizons that formed during relatively brief episodes of climatic amelioration (MIS 5a, 5c); these features even penetrate into the Mikulino interglacial soil (MIS 5e). The wedges display a spacing of 40–45 cm from each other, forming a regular lattice-like structure in plan view.

2 The third stage is expressed in the form of pseudomorph development that penetrates deeply into the horizon of Atelian loess. Formation of these cryogenic structures took place mid-way though MIS 3 (about 45–42 ka), and was coincident with a transgressive episode of the Caspian Sea. At this time the Volga valley was under the influence of estuarine conditions that led to the deposition of the alluvial suite seen at the Srednyaya Akhtuba section. It would appear that development of cryogenic phenomena was enhanced by flooding of the adjacent plain by the Volga River, raising the level of the water table in the region and moistening the loessic sediments.

3 The second and the first episodes are preserved in the proxy record of the Srednyaya Akhtuba section and indicate that sedimentation was taking place under a climatic regime increasingly dominated by conditions of enhanced cooling and moisture availability: the third stage is observed at about 40 ka, the fourth - around 30 ka. The cryogenic modifications described in the deposits share characteristics recorded in sections from present-day tundra environments (patchworks of heave-like structures resulting from plastic deformation), developing at the indicated stages of formation of the alluvial pack.

4 In the Late Pleistocene, the main phase of development of cryogenic features in the Lower Volga region occurred during the cold periods of MIS 3 and 4, while the main factor determining the nature of permafrost was the regional availability of moisture. There are no traces of possible cryogenesis that correspond with the coldest, Late Valdai glacial phase (broadly coeval with the global Last Glacial Maximum of MIS 2). Presumably, sediments of this age (as well as the upper part of the paleosol forming layer 6–7) were destroyed by abrasion processes associated with Khvalynian expansion of the Caspian Sea.

Credit author statement

N. Taratunina: field studies, permafrost description, charts. V. Rogov: cryolithological analyses, permafrost features description. I. Streletskaya: regional description of permafrost history and correlations. T. Yanina: Caspian Sea paleogeography and correlations. A. Kurchatova: sedimentology, particle size analysis, micromorphology. W. Thompson: geochronology, sedimentology. R. Kurbanov: geochronology and Lower Volga stratigraphy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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