Lower Ordovician mud mounds from the St. Petersburg region, northwestern Russia

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Hecker-type mud mounds are calcareous-clay buildups occurring in the Lower Ordovician (Billingen and Volkhov regional stages), condensed cool-water carbonates of northwestern Russia. The unusual feature of these buildups is the dominance of terrigenous clay in their cores. In all the buildups an initial gently-sloping mound of unconsolidated fossiliferous clay rests on a hardground surface. A layer of microsparite overlies the clay, with another hardground surface on the top. The mud mounds vary in diameter from tens centimetres to hundreds metres. Large mounds form complex multi-storey structures and contain sedimentary facies, which differ markedly from the facies of surrounding rocks. There is evidence that siliceous sponges formed these mud mounds. The Hecker-type mud mounds are moderate to cold-water sponge buildups with a unique combination of features found in their cold and warm water Phanerozoic counterparts.

Key words: Mud mounds, sponges, facies, Ordovician, Russia.

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Vishnjakov & Hecker (1937) described a 30 m long and 1.5 m high dome-shaped structure exposed in the banks of the Sjas' River in the St. Petersburg region, northwestern Russia (Fig. 1). It was recorded in the part of the Ordovician succession that is referred to the Volkhov Regional Stage (Lower Ordovician) and the two authors interpreted the dome-shaped structure as a peculiar synsedimentary structure initiated by tectonic movements. The same location was later investigated by Dronov & Ivantsov (1994), who did not find evidence for a tectonic origin for the dome-shaped structure. Instead, these latter authors concluded that the dome-shaped structure represents a mud mound with a core composed of unlithified clay covered by fine-crystalline mudstone and the stratification in the clay was probably a result of primary sedimentary accretion. Moreover, a fine-grained mudstone located in the core of the mound was different from the surrounding bioclastic limestones and thus could hardly be a product of their deformation.

The interpretation of the dome-shaped structure as a mud mound (Dronov & Ivantsov 1994) agrees well with the earlier ideas of Männil (1966), who suggested a reef-related origin for the dome. However, the identification of a clay core is a new observation. Later, additional two large mud mounds with clay cores were discovered in the Volkhov strata and several smaller mounds were found in the limestones of the Billingen Regional Stage (Dronov & Fedorov 1994).

The mud mounds of the St. Petersburg region differ markedly from other described mud mounds (Wilson 1975; James & Bourque 1992) by having unlithified clay bodies. In contrast to modern sponge mud mounds, consisting of clay with siliceous sponge spicules (Conway *et al*. 1989; van Wagoner *et al.* 1989), the Ordovician mounds have complex calcareous-clay compositions, lacking a biogenic silica component. Because of their unique characteristics, the Lower Ordovician mud mounds of St. Petersburg area are considered to represent a new type of mud mound named Hecker-type mud mounds (Dronov & Fedorov 1994) and the Hecker-type mud mounds probably represent the oldest Phanerozoic organic buildups in Europe. To date, the oldest Phanerozoic buildups in Europe were those known from the Upper Caradoc successions of Estonia, Sweden and Norway thought to be reefs and bioherms (Webby 1984).

During the last decade most of the natural and

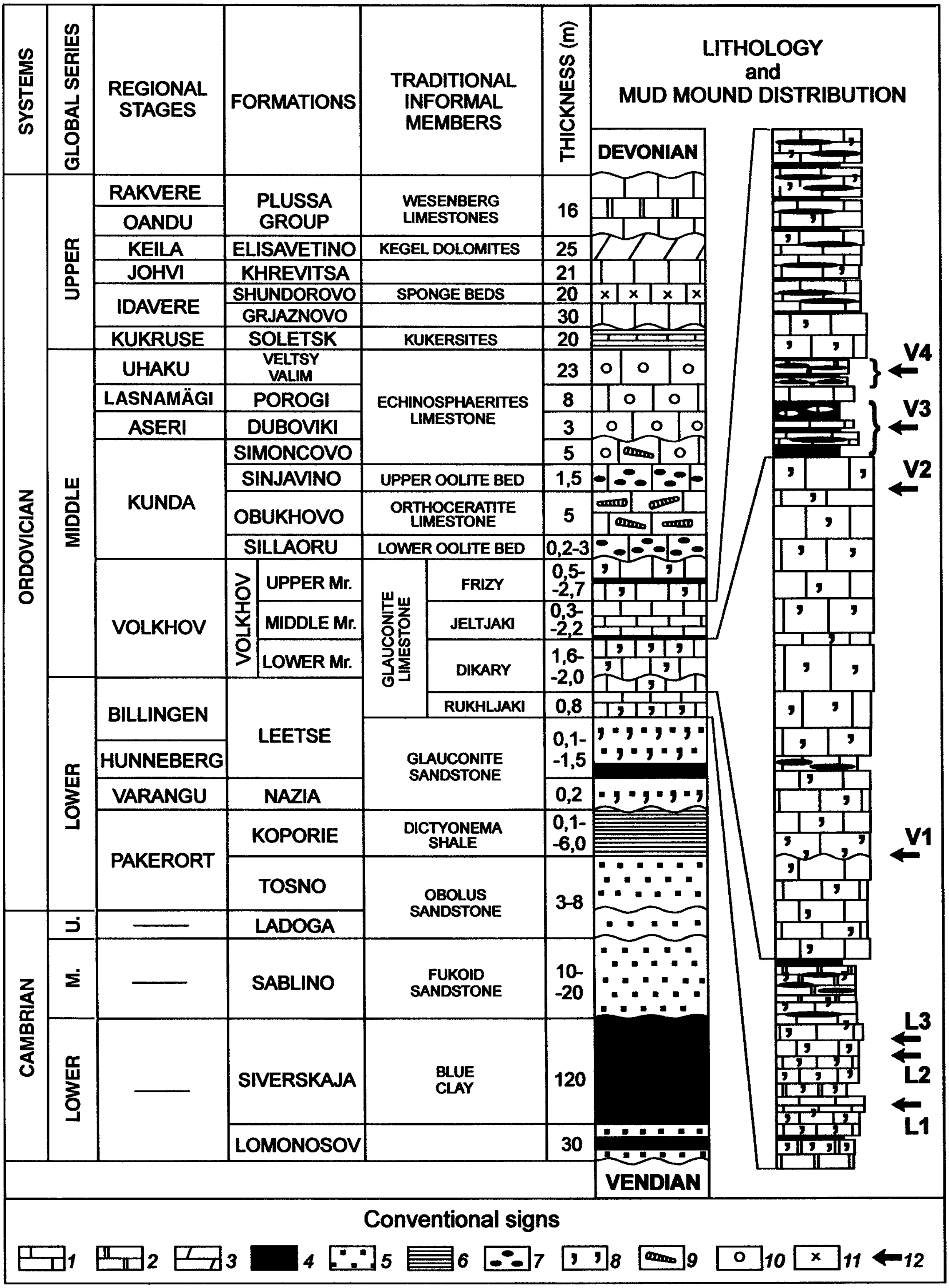
Fig. 1. Schematic geological map of the St. Petersburg Region with locations of the studied calcareous-clay Hecker-type mud mounds. The locations: 1 –Narva River, 2 – Kingisepp quarry, 3 – Izhora River, 4 –Tosna River, 5 – Putilovo quarry, 6 –Lava River, 7 – Volkhov River, 8 – Babino quarry, 9 – Sjas' River.

artificial outcrops of the Lower Ordovician of the St. Petersburg region have been revisited and reinterpreted. As a result tens of previously unknown Hecker-type mud mounds of various sizes from several stratigraphic levels have been found. The mounds were primarily discovered and described from localities with extensive exposure i.e. in the larger quarries and in the valleys of the larger rivers (Fig. 1). The results of this study are presented below.

Regional geology and stratigraphy

In northwestern Russia and northern Estonia Upper Vendian and Lower Palaeozoic rocks form the lower part of the sedimentary cover of the Russian platform. The sediments crop out along an east-west striking zone extending along the southern coast of the Gulf of Finland to the southern coast of Lake Ladoga, a total distance of about 600 km (Fig. 1). These strata are undisturbed and accumulated in a broad structure known as the Baltic monocline, and rest unconformably on the eroded surface of the Precambrian Baltic Shield. To the south, the Baltic monocline interfaces with another regional structure: the Moscow syneclise. In the Baltic monocline, the strata dip southwards at low angles (2.5–3.5 m per km). In the St. Petersburg region, the thickness of the Cambrian succession ranges from 120 to 150 m and the Ordovician

Fig. 2. Stratigraphical scheme of the Lower Palaeozoic of the St. Petersburg Region with levels at which the Hecker-type mud mounds occur. Modified from Selivanova & Kofman (1971). Legend: 1 – limestone, 2 – dolomite, 3 – marl, 4 – clay, 5 – quartz sand and sandstone, 6 – bituminous shale, 7 – iron ooids, 8 – abundant glauconite grains, 9 – orthoconic nautiloids, 10 – *Echinosphaerites sp.*, 11 – siliceous sponges, 12 – stratigraphical levels at which Hecker-type mud mounds occur indexed L1 – V4.


SYSTEMS
GLOBAL SERIES
REGIONAL STAGES
FORMATIONS
TRADITIONAL INFORMAL MEMBERS
THICKNESS (m)
LITHOLOGY and MUD MOUND DISTRIBUTION
DEVONIAN
ORDOVICIAN
UPPER
RAKVERE
OANDU
PLUSSA GROUP
WESENBERG LIMESTONES
16
KEILA
ELISAVETINO
KEGEL DOLOMITES
25
JOHVI
KHREVITSA
21
IDAVERE
SHUNDOROVO
SPONGE BEDS
20
GRJAZNOVO
30
KUKRUSE
SOLETSK
KUKERSITES
20
MIDDLE
UHAKU
VELTSY VALIM
23
LASNAMÄGI
POROGI
ECHINOSPHAERITES LIMESTONE
8
ASERI
DUBOVIKI
3
KUNDA
SIMONCOVO
5
SINJAVINO
UPPER OOLITE BED
1,5
OBUKHOVO
ORTHOCERATITE LIMESTONE
5
SILLAORU
LOWER OOLITE BED
0,2-3
VOLKHOV
VOLKHOV
UPPER Mr.
GLAUCONITE LIMESTONE
FRIZY
0,5--2,7
MIDDLE Mr.
JELTJAKI
0,3--2,2
LOWER Mr.
DIKARY
1,6--2,0
LOWER
BILLINGEN
LEETSE
RUKHLJAKI
0,8
HUNNEBERG
GLAUCONITE SANDSTONE
0,1--1,5
VARANGU
NAZIA
0,2
PAKERORT
KOPORIE
DICTYONEMA SHALE
0,1--6,0
TOSNO
OBOLUS SANDSTONE
3-8
CAMBRIAN
U.
LADOGA
M.
SABLINO
FUKOID SANDSTONE
10--20
LOWER
SIVERSKAJA
BLUE CLAY
120
LOMONOSOV
30
VENDIAN
V4
V3
V2
V1
L3
L2
L1
Conventional signs
1
2
3
4
5
6
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8
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10
11
12

from 100 to 200 m (Selivanova & Kofman 1971). Post-Caradoc and Silurian deposits are missing (Männil 1966).

Cambrian and Tremadocian sediments in the region are mainly clays and quartz sands, while the Ordovician sediments from the Upper Arenig to Caradoc are characterised by argillaceous carbonates with thin interlayers of unconsolidated clay (Fig. 2). Ordovician carbonate rocks in the region occupy an elevated area known as the 'Ordovician Plateau'. Geomorphologically, the northern boundary of the 'Ordovician Plateau' coincides with a distinct natural escarpment, up to 30–40 m high, which is known as the Baltic-Ladoga Klint (Lamansky 1905). Numerous rivers flowing northwards into the Gulf of Finland and Lake Ladoga cross the klint and locally form canyons creating a large number of natural exposures. The Ordovician carbonate rocks in the vicinity of St. Petersburg have been quarried and used as building material since 1703 and two limestone quarries are still in use. Exposures in the abandoned and working quarries are accessible for observation.

The Ordovician succession of the Russian part of Baltic-Ladoga Klint is subdivided into 19 regional stages (Fig. 2; Männil 1966). The Billingen Regional Stage is represented by clay in the lowermost part, and successively glauconitic sand, calcareous sandstone and mottled argillaceous glauconitic limestone. Limestone strata with a total thickness up to 0.8 m vary in lithology from mudstone to bioclastic grainstone in the middle and upper parts. There are several hardground surfaces within this unit.

The Volkhov Formation represents the Volkhov Regional Stage. It consists of non-magnesian, bioclastic wackestone-grainstone with scattered glauconite grains and clay intercalations. The lower boundary of the formation is an easily recognizable hardground surface with a glauconite veneer and numerous amphora-like borings, traceable along all the Baltic-Ladoga Klint (Lamansky 1905).

The Volkhov Formation is subdivided into three members. The lower member consists of hard-bedded, multicoloured, mainly red and grey glauconitic limestone (bioclastic wackestone to grainstone) up to 2 m thick marked by numerous yellow hardground surfaces. The middle member comprises up to 2.2 m of red and yellow-coloured argillaceous limestone interbedded with clay. This member is marked by several hardground surfaces. The upper member consists of glauconitic limestone (up to 2.7 m), light grey in colour, intercalated with numerous irregular layers of clay. Hardgrounds are not common.

The following Kunda Regional Stage is represented by light grey argillaceous limestone intercalated with ginger limestones rich in oolites of ferric oxide. The grey limestone contains abundant orthoconic nautiloid. Total thickness of the stage ranges from 3 to 14 m.

Methodology

All the representative rock types comprising the mounds were carefully sampled. Chemical and mineral compositions of clays were identified by XRF analysis, scanning electron microscope and X-ray methods in St. Petersburg State University. About 150 samples of clays and unlithified marls have been processed and the calcareous components of the samples have been separated. All fossils were then separated from detritus, sorted by taxonomic groups and identified. About 200 thin sections and 50 large polished slabs have been made and studied to characterize the limestone units.

The Hecker-type mud mounds

General outline

The calcareous-clay mud mounds include simple individual mounds and complex multi-storey buildups. A simple individual mound consists of calcareous-clay core and a fine-crystalline carbonate cap (microsparitic wackestone or mudstone) covered by a hardground surface. The core is a lens-shaped body or a

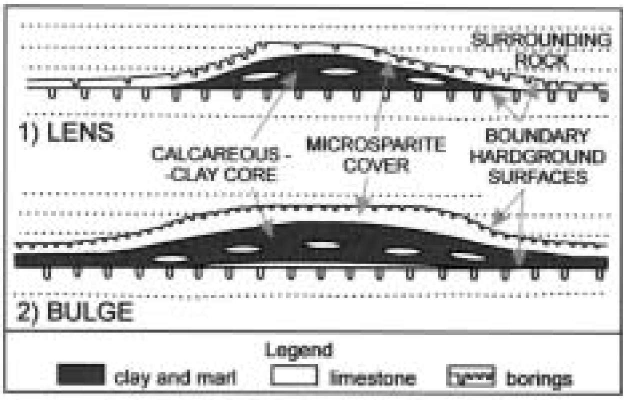

Fig. 3. Schematic cross-sections of two types of the individual Hecker-type mud mounds: a lens (1) and a bulge (2). Note that in the lens-like mounds the clay core thins out and does not continue into the surrounding rocks while in the bulge-like bodies the clay core as well as the carbonate cover continue as thin layers in surrounding succession. The figure illustrates the structures but not the size. The size of both types of mounds may vary significantly (see text for further explanation). Dotted lines show bedding in surrounding rocks.

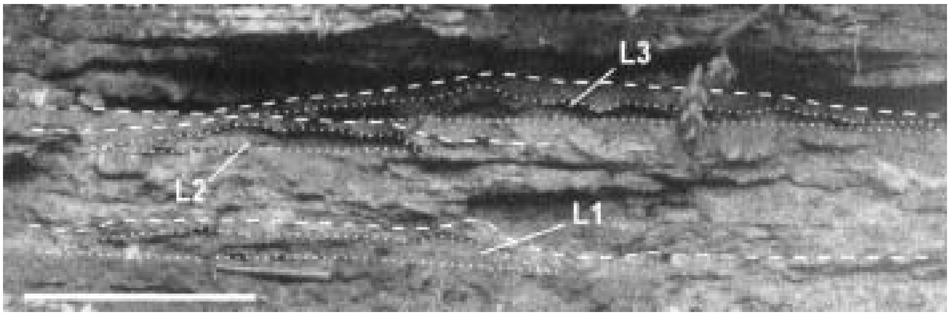

Fig. 4. Photograph of three small Hecker-type lens-like mud mounds at levels L1, L2 and L3 in the limestone strata of the Billingen Regional Stage. The calcareous-clay cores are outlined in dotted lines. The bottoms of the mounds coincide with the bottoms of the cores. The upper hardground surfaces of the mounds are shown in dash lines; Lava River. Scale bar 0.5 m.

bulge of calcareous-clay (Fig. 3). The core consists of clay and marl with limestone lenses and nodules. The core rests on a hardground, rarely a firmground, surface of the underlying limestone bed and is commonly associated with a basal lens of bioclastic material or with a small scale development of the roof of underlying bed. Each part of the mound laterally thins out into a bed within the surrounding succession marked by a hardground surface.

Stratigraphical position

In NW Russia all the known mud mounds are developed at seven specific stratigraphic levels associated with hardgrounds (Fig. 2). Three levels are identified in the Billingen limestone (L1, L2, and L3); one level coincides with the base of Volkhov Formation (V1), one level occurs near the top of the Lower Member of Volkhov Formation (V2), and two levels are in the lower part of the Middle Member of Volkhov Formation (V3 and V4). At several locations the uppermost level of the Billingen mud mounds is capped by a firmground.

Classification, geometry and features

The calcareous-clay mud mounds are subdivided by their size into three groups: (1) small, (2) intermediate and (3) large. The small mounds range from 20–60 cm to several meters in diameter and their height may be up to 15–20 cm. They are round or slightly elongated in a plan view. The intermediate buildups are lens-shaped elongated bodies tens of meters in diameter with heights of 3–5 to 10–15 cm. Small and intermediate mounds as a rule represent individual, isolated buildups. However, horizontal chains consisting of 2 or 3 mounds are locally found in the outcrops (Fig. 4). Small and intermediate mud mounds dominate at stratigraphical levels L1–3.

The individual large mounds may be more than 350 m long and their height may reach 2 m. All known large mounds are part of complex multi-storey buildups (Figs 5, 6 and 10) and most of them have the lowermost mound resting on the characteristic hardground surface that divides the Billingen and Volkhov regional stages (level V1). More rarely, the large mounds are present in the limestone strata of the Billingen Regional Stage (levels L1– L3). However, the

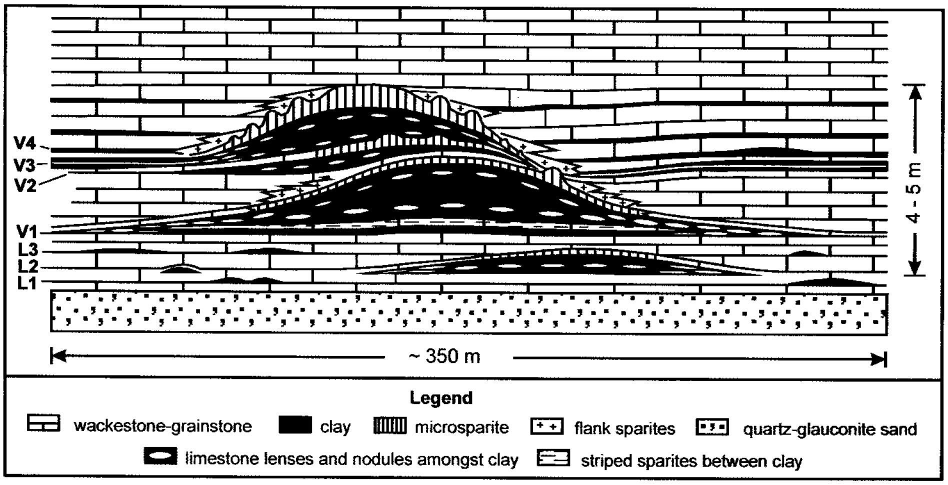

Fig. 5. Schematic cross-section of a complex multi-storey Hecker-type mud mound consisting of four large individual mounds at levels L2, V1, V2 and V3. The mound at V3 level is a bulge-like body. Mounds at L2, V1 and V2 are lens-like. The largest individual mound is always that resting on the omission surface dividing the Billingen and the Volkhov regional stages. Note small and intermediate mud mounds at the flanks of the multi-storey buildup.

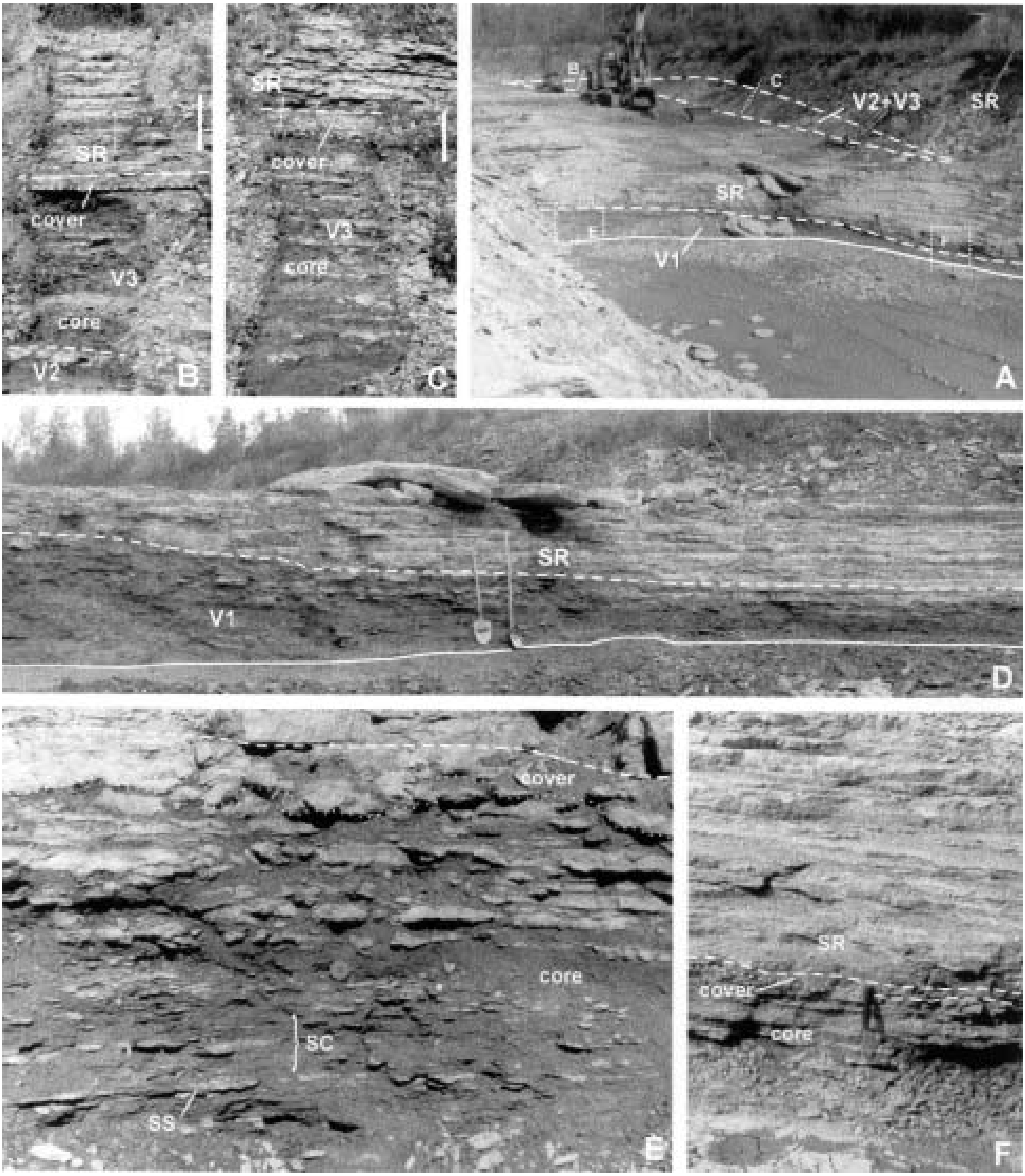

Fig. 6. Photographs of the large complex three-storey Hecker-type mud mound in Babino limestone quarry. V1, V2 and V3 – stratigraphical levels shown in Fig. 2. Solid line shows the bottom of the whole buildup. SR – surrounding limestone strata. SS – striped sparites. SC – striped clays. A – General view. Two calcareous-clay bodies are outlined. Lower contour (solid and dash lines) shows a 35 m long fragment of a basal mound at level V1. Upper contour shows a 100 m long body consisting of two individual mounds on levels V2 and V3. Dotted lines and frames show locations of photographs B, C, E, F. B and C – cross-sections of calcareous-clay body on levels V2+V3. The bedding in the core is represented by limestones layers within indistinctly bedded clay. The cover consists of microsparite. Note increasing thickness of the core from B to C. Scale bars – 0.5 m. D – a section of the lower individual mound on level V1 with max thickness 1.7 m (left). Note the unconformity on the boundary between the upper surface of the mound (dash line) and surrounding strata. E – clay and marl of the mound core (level V1) with lenses and nodules of limestone (wackestone-grainstone and striped sparite). The clay is predominantly homogeneous with a thin layer of striped clay. The uneven boundary between the core and microsparite cover is shown by dotted line. Camera cap 5.8 cm in the center of the photo for scale. F – cross-section of marginal part of mud mound on V1 level. Limestone beds and layers dominate in the core. Microsparite cover is thin. Hammer for scale is 32 cm.

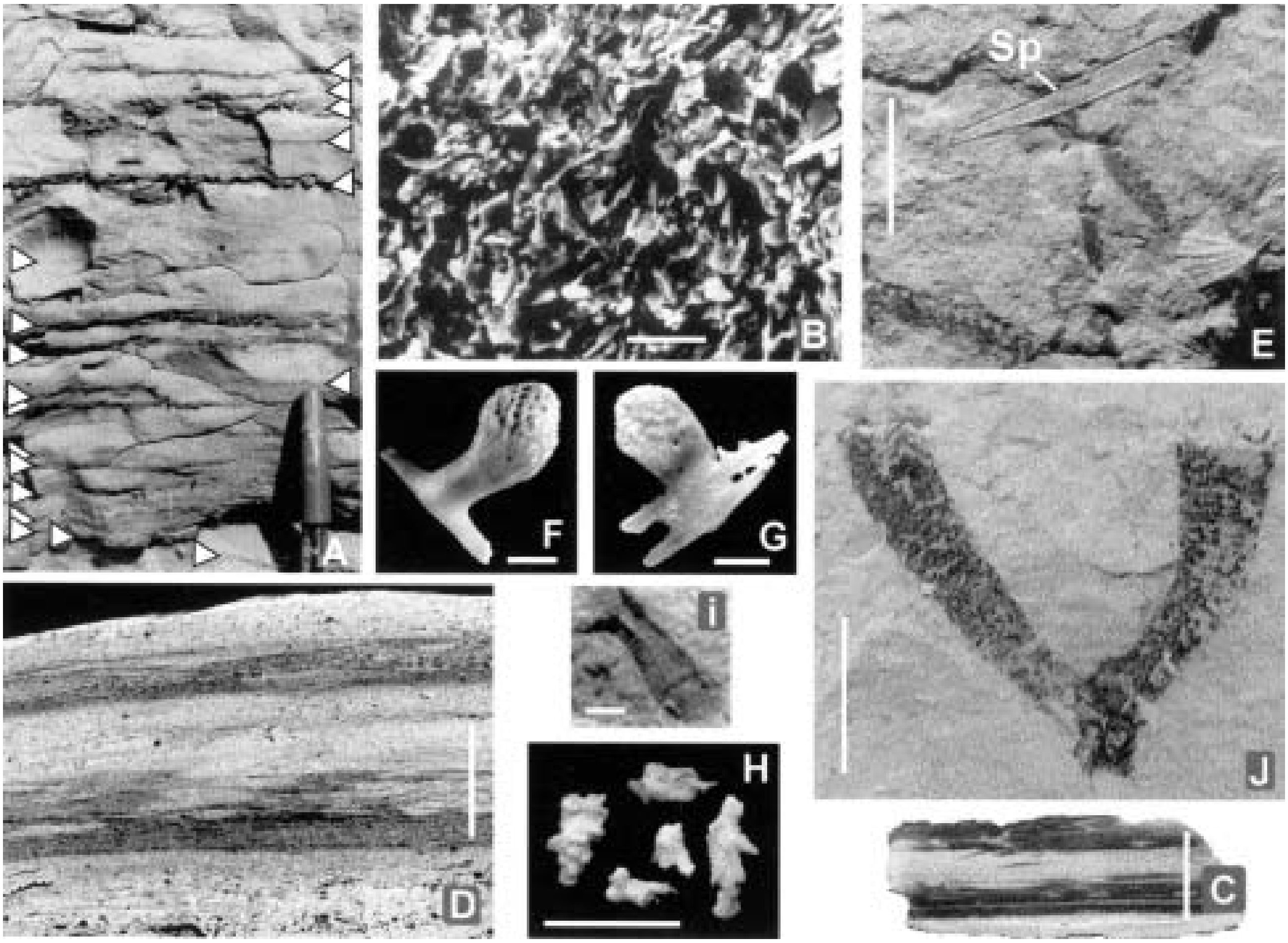

Fig. 7. Core clay of the Hecker-type mud mounds and its fauna. A - striped clay with irregular claret-red (dark on the photo) bands marked with triangles. Core of the large complex mud mound on level V1; Putilovo quarry. Pen cap 4 cm. B – stacked texture of clay; Kingisepp, quarry 4. Secondary electron image. Scale 10¼ m. C – claret red bands in a striped clay. Clay core; Putilovo quarry. Scale 1 cm. D – striped clay: claret-red (dark on the photo) bands in indistinctly striped light-grey matrix; Kingisepp, quarry 4. Polished slab. Scale 1 cm. E – graptolites, articulate brachiopods, and *Sphenothallus* tube (Sp) on a fresh clay surface; Babino quarry. Scale 1 cm. F – bryozoan with the tube-like holdfast in a spicule mould filled by crystalline calcite; Volkhov River Scale 1 mm. G - bryozoan, which grew on two spicules. Putilovo quarry. Scale 1 mm. H - stub-like crinozoan roots; Putilovo quarry; Scale 1 cm. I – bilateral-symmetrical, segmented imprint of soft-body worm-like animal; Kingisepp, quarry 4. Scale 1 mm. J – segmented chitin (?) tubes of worm-like animals; Volkhov River Scale 1 cm.

mound at the V1 level is always the largest part of a multi-storey buildup (Fig. 5).

The large, individual mounds comprising the complex buildups completely or partially overlap in a plan view. As a rule, the mounds at V2 level entirely overlap the mounds at V3 level forming a single carbonate-clay body (Fig. 6A, B). The depocentre of this body is usually displaced relative to depocentre of the mud mound at the level V1. Total thickness of the complex buildups may reach 4– 5 m. Large mud mounds are often surrounded by small and intermediate mounds at levels V1–V4.

The primary positive relief of the mud mounds is emphasized by the geometry of the mounds and by the thinning out of surrounding strata close to the surface of the limestone cover of the mounds (Fig. 6D, 10A). Sparitic flanks also characterize the large complex mud mounds.

The calcareous-clay cores

The cores of the Hecker-type mud mounds consist of clay containing various amounts of detritus and are transitional in composition to marl. Mineral composition of the clay is characterised by illite (61–89%) as well as less abundant chlorite (10–36%) and mixed-layer clay minerals (1–3%). Variations in the mineral composition of the clay have no stratigraphical or spatial significance. Scanning electron microscope

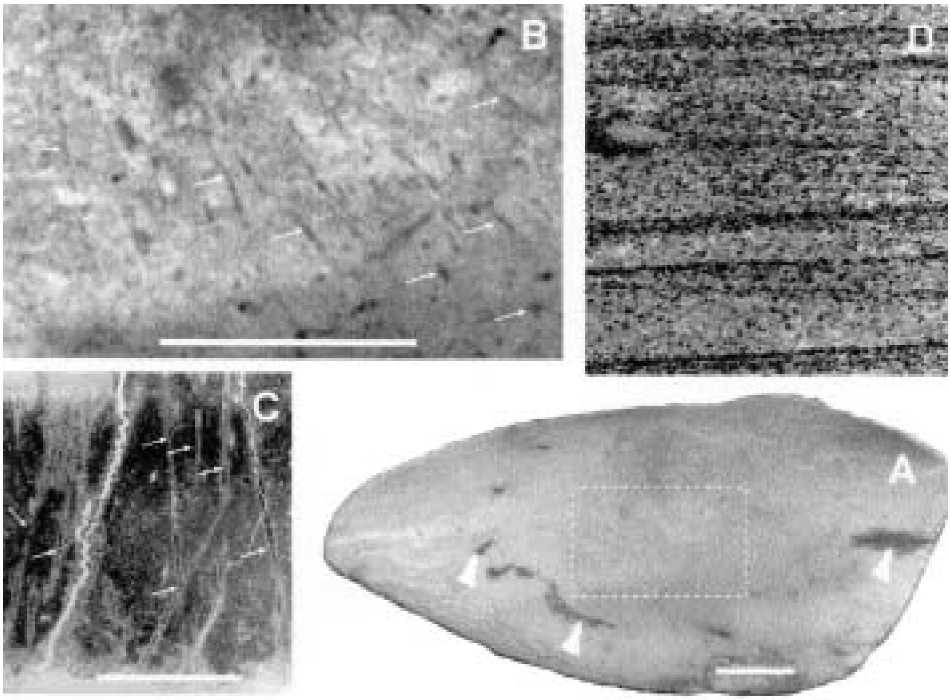

Fig. 8. Limestone types from lenses and nodules of the clay cores of the Hecker-type mud mounds. A – nodule of light-grey microsparite with dark spots colored by powdered pyrite (arrows); Putilovo quarry. Polished slab. Scale 1 cm. Frame shows the area of the photo B. B – microsparite with numerous spicules (arrows), mainly monaxons. Scale 1 cm. see A for location. C – root tuft of aligned monaxial spicules replaced by calcite in a wackestone lens; Volkhov River. Thin section, parallel nicols. Scale 1 cm. D – striped sparite with dark-green (dark-grey on the photo) stripes rich in glauconite grains and light-grey biosparite stripes; Babino quarry. Thin section, parallel nicols. Width of picture 1cm.

study of the clay revealed a stacked texture (Fig. 7B). The clay and marl contain varying amounts of fauna, calcareous detritus 5 to 25%, rare elongated crystals of calcite (length 0.010–1.5 mm), grains of glauconite (0.05–0.1 mm) as well as lenses and nodules of limestone.

The fauna of the clay is dominated by small articulated brachiopods, ostracodes and pelmatozoans. Small bryozoan, phosphatic-shelled inarticulated brachiopods, problematic tubular phosphatic skeletons of *Sphenothallus* sp. (Fig. 7E), ring-like phosphatic holdfasts *Phosphannulus* sp. and sclerites of paleoscolecids are common associates. Fragments of small trilobites, chiolites, bolboporites, and conulariids are less common. Accumulations of well-preserved graptolite rhabdosomes and, rarely, segmented chitinous (?) tubes and imprints of worm-like problematica (Fig. 7I, J) occur.

The numbers of shells of small articulated brachiopods vary from 100 to 6000 per kg of dry clay. Quantitative analysis by Eva Egerquist (Tolmacheva, Fedorov & Egerquist 2003) showed that the concentration of juvenile brachiopods in the clays of the cores of Hecker-type mounds is much higher when compared to the concentrations of brachiopods in the clay interbeds of surrounding strata. Numbers of ostracode carapaces per kg of clay usually does not exceed hundreds but, locally, may reach one thousand.

Pelmatozoan ossicles are distributed irregularly. Locally, they form accumulations, probably, indicating sites of original pelmatozoan animals. Pelmatozoan holdfasts are also present in clays. Small size (1–1.5 cm) and stub-like shapes of the holdfasts (Fig. 7H) indicate their original occurrence on the consolidated seabed.

Bryozoans are commonly small bulb-like trepostomes less than 10 mm in length. The numbers of such colonies are in the order of 10–100 per kg. Many bulb-like bryozoans have in their basal tubular holdfasts perpendicular to their long axes (Fig 7F). The ecological significance of the tubular holdfasts was emphasized by the discovery, in thin section, of root-tuft fragment of aligned monaxial spicules of a siliceous sponge with a bryozoan attached to one of the spicules. Further scrutiny of the holdfasts showed that the bryozoans of the mud mounds commonly used large sponge spicules as a substrate. Colonies growing on pentactin and even on two nearly parallel straight spicules (Fig. 7G) have been found. However, the spicules in the clay may be recognized only by calcite-filled moulds surrounded by bryozoan holdfasts.

Six main rock types comprise the clay-calcareous cores: (a) indistinctly bedded clay and marl, (b) lenses of limestone, (c) striped clay, (d) bioturbated clay and marl, (e) striped sparite and (f) microsparite nodules.

(a) Indistinctly bedded clay and marl green-grey, claret-grey and red-grey in colour comprise most of the cores of the small mounds and dominate in the cores of the intermediate and large mounds. Lamination is seen only in the weathered zone close to erosion surface. This rock type is relatively inhomogeneous with varying amounts of detritus and glauconite grains. Rare striped-like traces of bioturbators may be distinguished by slightly different colours.

(b) Lenses of bioclastic glauconite limestones (wackestone – grainstone – biosparite) are found in all types of clays in mounds of various sizes. Moulds of large spicules of siliceous sponges, replaced by crystalline calcite, are often found in wackestone-packstone. Occasionally, the lenses are filled with monaxons of root tuft; however, no traces of spicules have been detected in surrounding clay (Figs 8C, 9). The main components of the grainstones and sparites are pelmatozoan ossicles and brachiopod shells. At the marginal parts of the large mounds, the limestone lenses dominate: only thin layers of bioturbated clay divide the numerous lenses.

(c) Striped clay appears only in the clay cores of the large mounds at the levels V1, V2 and V3. The striped clay is characterised by irregular dark-grey or red bands (1–8 mm) in the light-grey matrix (Fig. 7A, C, D). An insignificant admixture of dispersed black iron sulphides causes the dark colour, whereas a secondary oxidation of these sulphides locally turns the dark-coloured bands to red. Relatively rare trace fossils are represented by the pale-coloured ‘shadows’ 3–3.5 mm wide and 5–15 mm long. The striped clay contains a large number of intact graptolites.

Amount of the striped clay varies significantly. The striped clay comprises the whole vertical extent of the core at some places whereas at other exposures the striped clay comprises only 10–15% of a section in some cases or the striped clay is almost missing.

(d) Bioturbated clay and marl are characterised by a spotted hue, lack of lamination and by the occurrence of limestone-filled moulds of worm tracks. This rock type comprises the cores of some small mounds as well as the marginal parts of the intermediate and large mounds.

(e) Striped sparite is represented by a biosparite rich in glauconite grains which are concentrated in numerous thin laminae elongated parallel to bedding (Fig. 8D). The glauconite laminae may be traced for significant distances. The glauconite laminae are usually flat but occasionally they bend and resemble wavy lamination. This rock type was found only in the large mounds at V1 level and in the intermediate mounds at L3 level. The striped sparite rests on a hardground surface at the base of a mound or inside the core close to its base. The roof zone of the striped sparite is usually bioturbated. The thickness of the sparite is 3–15 cm. At the marginal parts of the mounds the striped sparite turns into a thin layer of fully bioturbated limestone. Outside the mounds this layer is undistinguishable from the surrounding limestone beds.

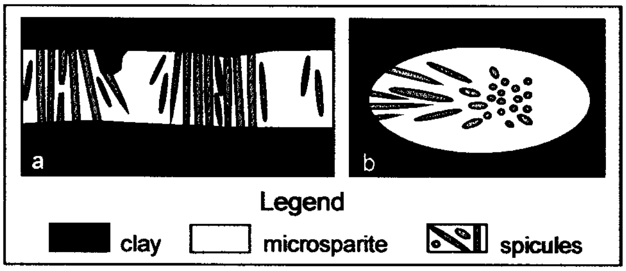

Fig. 9. Sketch showing distribution of siliceous sponge spicules in limestone lenses of the clay cores of the Hecker-type mud mounds. A – limestone lens with spicules, B - nodule containing numerous spicules. Spicula molds filled with crystalline calcite can be seen in limestone, but they are not observed in surrounding clay presumably due to dissolution.

(f) Microsparite nodules (1–30 cm in length) consist of clay microsparite containing noticeable amounts of large hexactinellid sponge spicules, mostly, monaxons (Fig. 8A, B). The silica of the spicules is entirely replaced by crystalline calcite. Spicules in the marginal parts of the nodules do not penetrate the surrounding clay (Fig. 9). Some nodules are locally enriched in powdered pyrite (Fig. 8A). Nodules are found only in the large and intermediate mounds where they form rare dotted horizons in the striped and indistinctly bedded clays. These horizons are found only in the central parts of the mounds.

Facies (a), (c), (e) and (f) are absent in the surrounding Ordovician strata. They occur only in the Hecker-type mud mounds of St. Petersburg region.

Microsparite cover

Microsparite wackestone and microsparite mudstone are the two types of microsparite that cap the mud mounds. Wackestone is characteristic for the caps of the small and intermediate mud mounds and for the marginal parts of the large mounds. Microsparite mudstone comprises the upper parts of the caps of the large mounds. Those covering the small mounds are 1–5 cm thick. The caps of the individual large mounds contain microsparite bioherm-like bulges in their upper parts. Because the bulges apparently formed without the assistance of frame-building organisms such as sponges, the term ‘pseudobioherm’ is used here. The bulges are 3–5 m long. Microsparitic layers under the pseudobioherms are up to 65 cm thick. Outside the pseudobioherms, caps are 10–15 cm thick with local discontinuities. Tops of the mounds represent a complex of laterally coalescing

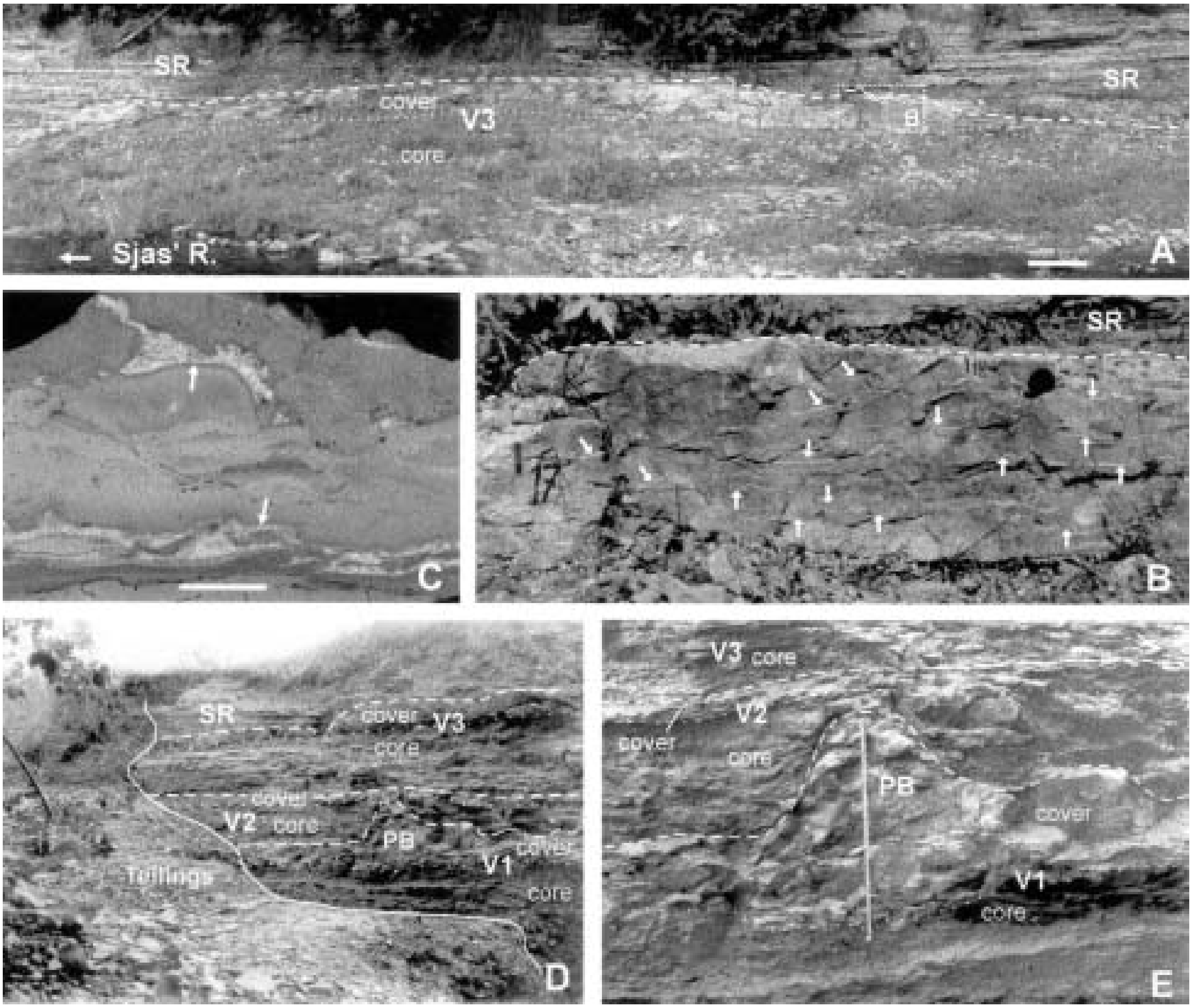

Fig. 10. Microsparite covers of the Hecker-type mud mounds. SR – surrounding rocks, PB - pseudobioherm. A - mud mound on level V3 in the bank of Sjas' River described by Vishnjacov & Hecker (1937) is an outcropped upper part of the large multi-storey buildup. The mound has thick microsparite cover. The microsparite cover consists of numerous pseudobioherms. Note an unconformity on the boundary between the mound surface and surrounding rocks; Sjas' River. Scale 1m. Dotted frame shows area of photo 10 B. B – part of the large pseudobioherm. The pseudobioherm consists of massive microsparite and stromatactis (arrows). Camera cap 5.8 cm. C – stromatactis fabric from the microsparite cover of mound (arrows); Sjas' River. Polished slab. Scale 3 cm. D – fragment of the large complex mud mound outcropped in Simankovo, Volkhov River. Three successive individual mounds are seen in the outcrop. Every mound has calcareous-clay core and microsparite cover. Microsparite cover of the lower mound (level V1) includes a pseudobioherm. E – same area as on D, enlarged. Note steep slopes and asymmetrical shape of pseudobioherm. Scale bar 65 cm.

'pseudobioherms' (Fig. 10A). The surface of the microsparitic layers contains the boring *Trypanites* (3–4 mm in diameter and 10–15 mm deep) and pelmatozoan holdfasts (Fig. 11A). Sometimes, this surface is covered with glauconite veneer.

The microsparite is a pale yellow, pale grey or pale pink rock. It comprises two textural varieties: (1) fine-grained, and (2) coarse-grained. The fine-grained microsparite has grain sizes of 5–10 µm with scattered calcite crystals (10–20 µm to 20–50 µm; Fig. 11B, C). Similar calcite crystals from the Lower Ordovician limestone of Sweden were described as 'ant-eggs' by Lindström (1979). The coarse-grained variety consists of 'ant-eggs' only (Fig. 11D) and was defined by Lindström as 'ant-egg' microspar (Lindström 1979). Thin sections show that the fine-grained microsparite is replaced by the coarse-grained fabric. The coarse-grained 'ant-egg' microspar dominates in the micro-

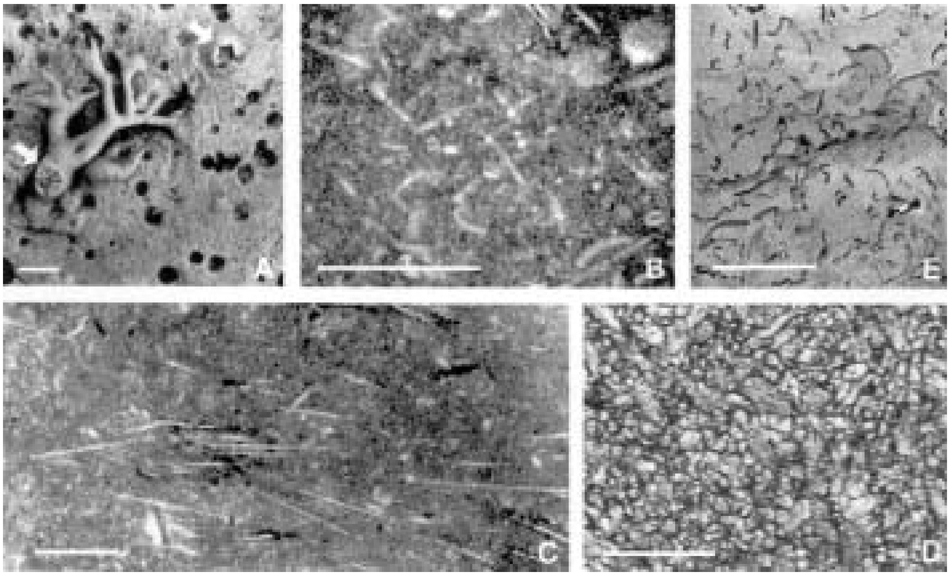

Fig. 11. Surface and fabrics of the microsparite covers of the large Hecker-type mud mounds. A – pelmatozoan holdfasts (arrows) and Trypanites borings (dark holes) on a hardground surface; Sjas' River. Scale 1 cm. B – fine microsparitic matrix with peloidal texture containing well preserved hexactinellid sponge spicules replaced with calcite. Thin section, parallel nicols; Volkhov River. Scale 1 mm. C – peloidal texture with monaxial sponge spicules; from Putilovo quarry. Thin section, parallel nicols. Scale 0.2 mm. D – 'Ant egg' microspar – microsparite consisting of 'ant-egg-shaped' crystals of calcite; from Putilovo quarry. Thin section, parallel nicols. Scale 0,2 mm. E – fine-grained microsparite with numerous trilobite fragments from 'trilobite pocket'; from Volkhov River. Polished slab. Scale 1 cm.

sparite layers of the mud mounds. Both types contain spicules of hexactinellid sponges entirely replaced by calcite. They are usually represented by large monaxons, isolated or forming clusters (Fig. 11C). Large hexactins are less common. In the fine-grained microsparite smaller spicules and small clusters of irregular peloidal networks occur (Fig. 11B). The peloidal network is similar to the classic peloidal texture described in ancient sponge mud mounds elsewhere (Reitner & Neuweiler 1995). Peloidal texture is characteristic of automicrites, which are the result of anaerobic decay of organic matter *in situ*. Relics of peloidal texture suggest that formation of microsparite was mainly a result of the recrystallization of automicrites. Small ostracodes, brachiopods, bryozoans and carbonate detritus also occur in the fine-crystalline microsparite. Pseudobioherms of the large mounds contain approximately 10–100 times fewer conodonts compared to the surrounding rocks (Tolmacheva & Fedorov 2000). The conodonts in the pseudobioherms are usually coated by iron hydroxides.

Peloidal texture and other features of the microsparite caps of the Hecker-type mud mounds resemble ordinary carbonate buildups (for example, Bourgue & Gignac 1983; Reitner *et al.*1995; Warnke & Meischner 1995). Common characteristics include the occurrence of small cavities filled with laminated internal sediment and the occurrence of so-called 'trilobite pockets' (Fig. 11E) similar to those recently described in Upper Ordovician Boda buildups (Suzuki & Bergström 1999) and occurrence of stromatactis, which is occasionally found in the microsparite pseudobioherms of the Hecker-type mud mounds (Fig. 10C).

Genesis of the Hecker-type mud mounds

The new model for the origin of the Hecker-type mud mounds presented in this study is based on the presence of sponge spicules in clays and microsparites, suggesting that siliceous sponges were widespread in the mud mounds. The mud mounds were probably formed by dense concentrations of sessile siliceous sponges, which were later destroyed by diagenetic processes. The size and position of the mounds were probably controlled by the amount of suspension-rich food particles available for a particular sponge aggregation.

The hardground surfaces were suitable for aggregations of siliceous sponges. Populations of Ordovician siliceous sponges lived similar to their modern cold-water analogues in areas of reduced sedimentation, where they filtered out small suspended particles (van Wagoner *et al*. 1989; Conway *et al*. 1989). Clay and marl together with the sponge spicules gradually formed the mound-shaped bodies. The striped clays probably accumulated as redeposited spicula mats in areas in more quiescent conditions. Infauna is not common in the mud mound facies because both spicule-rich and decaying organic matter substrates are not suitable for its development (e.g. Petelin 1954; Gerdes & Krumbein 1986).

The gradual decay of the organic components of the clay and marl probably resulted in high pH values sufficient for dissolution of siliceous spicules but not sufficient for automicrite formation. Probably formation of automicrite was also inhibited by the high concentration of clay. The dissolved silica was used to form grains and films of authigenic glauconite in and around the mounds. The striped sparites presumably were a result of episodic strong currents, which redistributed shells and authigenic glauconite.

The changes in sedimentation rates, for example those associated with the formation of new storm-related limestone layers, might have suppressed the growth of sponge mounds. However, scenarios for the evolution and final destruction of the small and the larger mounds were probably different. The relatively low and small mounds and marginal parts of the larger mounds were rapidly covered with a newly formed layer of carbonate material. The tops of the larger mounds probably survived burial and later formed new parts of the complex multi-storey buildups. The increase in alkalinity in the presence of significant amounts of unlithified carbonate mud in combination with decomposing organic matter favoured formation of the sponge organomicrite. Carbonate suspension was available in the ambient water during a certain period after deposition of every storm-related limestone layer. This suspension provided material for the allomicritic component of the carbonate caps. A similar origin was proposed for Cretaceous carbonate mounds of the Soba Reef area (Reitner *et al*. 1995). Recrystallisation of the micrite resulted in the formation of thick microsparitic caps characteristic of the large Hecker-type mud mounds.

Concluding remarks

The Hecker-type mud mounds are characterised by containing a significant amount of clay; carbonate material dominates in other known pre-Holocene mud mounds (Bosence & Bridge 1995; Monty 1995 and references therein). Recent clay mud mounds have been described from cold-water shelf environments, where clay suspension occurs in ambient water (Conway *et al*. 1989; van Wagoner *et al*. 1989). The main textural feature of these modern clay mounds is a framework of lithistid sponges or a network of separate spicules of nonlithistid siliceous sponges.

A number of ancient carbonate mud mounds were formed by siliceous lithistid and nonlithistid sponges (James & Bourque 1992; Reitner & Neuweiler 1995; Krautter *et al*. 2001). *In situ* automicrite formation is considered to be one of the main processes for the generation of these sponge mounds (Reitner & Neuweiler 1995). The sponge automicrite is formed in the course of bacterial decomposition of organic matter of the sponges. The process of decomposition causes a high alkaline environment suitable for precipitation of carbonate from water (Reitner & Neuweiler 1995). The consequence of high pH values is the dissolution of siliceous spicules, the removal of silica and replacement of the spicule moulds with crystalline carbonate (Warnke & Meischner 1995).

The ancient carbonate sponge mud mounds probably lived in warm water environments at low palaeolatitudes (Kiessling 2001) whereas modern sponge mud mounds are known from high-latitude cold-water environments. In modern high-latitude sponge mud mounds formation of automicrite as well as dissolution of spicules is probably suppressed by the low temperature of ambient water. intermediate

The Hecker-type mud mounds are thus moderate to cool-water sponge buildups with a unique combination of features found in their cold and warm water Phanerozoic counterparts.

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