Carbonate cementation in the late glacial outwash and beach deposits in northern Estonia

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Abstract. The sedimentary environments, morphology and formation of carbonate cement in the late glacial glaciofluvial outwash and beach deposits in northern Estonia are discussed. Cementation is observed in well-drained, highly porous carbonaceous debris-rich gravel and sand-forming, resistant ledges in otherwise unconsolidated sediments. The cemented units occur as laterally continuous layers or as isolated lenticular patches with thicknesses from a few centimetres to 3 m. The cement is found in two main morphologies: (1) cement crusts or coatings around detrital grains and (2) massive cement almost entirely filling interparticle pores and intraparticle voids. It is exclusively composed of low-Mg calcite with angular equant to slightly elongated rhombohedral and scalenohedral or prismatic crystals, which indicate precipitation from meteoric or connate fresh surface (glacial lake) water and/or near-surface groundwater under low to moderate supersaturation and flow conditions. The absence of organic structures within the cement suggests that cementation is essentially inorganic. The cement exhibits both meteoric vadose and phreatic features and most probably occurred close to the vadose–phreatic interface, where the conditions were transitional and/or fluctuating. Cementation has mainly taken place by CO_2-degassing in response to fluctuations in groundwater level and flow conditions, controlled by the Baltic Ice Lake water level, and seasonal cold and/or dry climate conditions.

Key words: calcite cementation, micromorphology, beach and outwash deposits, late glacial, Pleistocene, Estonia.

INTRODUCTION

Carbonates can precipitate through a range of climatic conditions. They are mainly formed biogenically in warm tropical climates, but are also widespread in cold and glacial environments. Carbonate cementation in polar regions or within glacial deposits in formerly glaciated areas have attracted interest as a potential indicator of hydrologic and permafrost conditions and palaeoclimatic proxies (e.g. Leonard et al. 1981; Aharon 1988; Sharp et al. 1990; Vogt & Corte 1996; Lauriol & Clark 1999; Candy 2002; Lacelle et al. 2006, 2007; Goodwin & Hellstrom 2007; Lacelle 2007). Carbonate precipitates, occurring as a cement in unconsolidated glacial sediments in different geomorphic and hydrologic settings, can be formed by a variety of mechanisms that lead to their dissolution and reprecipitation. In glacial settings carbonate precipitation is mainly a result of inorganic processes, such as subglacial regelation, periglacial freeze–thaw processes, evaporation and CO_2-degassing. Biogenic processes, such as photosynthesis, skeletal mineralization and bacterial oxidation of organic matter, are involved in proglacial settings (Fairchild & Spiro 1990; Fairchild et al. 1994). Precipitation of carbonates in glacial sediments may also have occurred during subsequent non-glacial conditions, due to meteoric or terrestrial solute-bearing waters.

This paper describes for the first time the sedimentary setting, texture and micromorphology of carbonate cements in North Estonia. Laterally extensive cemented beds have been recorded in five outcrops hosted in glacial outwash and beach sand and gravel deposits that accumulated during the Late Weichselian deglaciation about 15.7–12.5 ka BP (Kalm 2006; Kalm et al. 2011). We consider that controls on carbonate precipitation include the changes in local hydrologic conditions and in the subsurface thermal regime during the last deglaciation and the regression of the Baltic Ice Lake (BIL).

REGIONAL SETTING

The five studied outcrops are located on the edge of a carbonaceous bedrock cliff, the Baltic Klint in North Estonia (Fig. 1). The Ordovician limestone plateau lies at altitudes of 35 m a.s.l. near Laagna to about 70 m a.s.l. at Kunda. To the north the Ordovician escarpment borders the Cambrian and Ordovician terrigenous rocks (sand- and siltstone, clay) with several exposed or more or less buried terraces (Suuroja 2006). The Ordovician

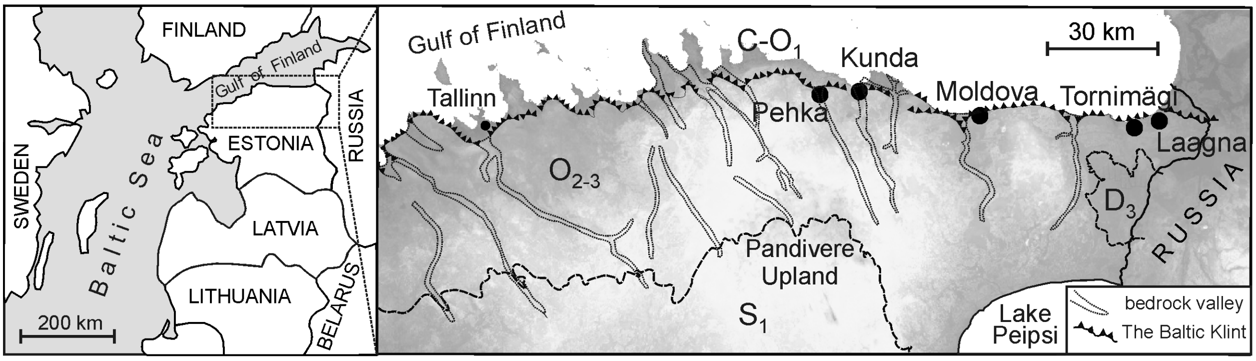

Fig. 1. Location of the studied sites on the edge of the Baltic Klint in northern Estonia. Shading indicates the topographic relief (darker means lower elevation, lighter – higher elevation). Simplified bedrock geology: C–O_1, Cambrian and Lower Ordovician terrigenous rocks; $O_{2–3}$, Middle and Upper Ordovician carbonaceous rocks; S_1, Lower Silurian carbonaceous rocks; D_3, Upper Devonian carbonaceous rocks.

limestone plateau is covered by rather thin Quaternary sediments, usually less than 1 m. Thicker deposits, up to 10 m, are connected with glacial landforms, like eskers, ice-marginal ridges, kames and drumlins from the Late Weichselian deglaciation stages of North Estonia, ca 13.7–12.7 cal ka BP (Kalm 2006). In the foreklint area, including klint bays and bedrock valleys, the thickness of Quaternary deposits may reach more than 100 m. They are represented by glacial and interglacial deposits from the Early Saalian through the Eemian to the Late Weichselian and are followed by Holocene marine and terrestrial deposits on the top.

During the Late Weichselian deglaciation of Northern Estonia the Baltic Klint might have become an obstacle to the movement of the otherwise degrading ice. Due to stresses in the ice a number of crevasses, mainly of marginal orientation, became the favoured channels for glacial meltwater drainage. In addition, isostatic tilting at that time promoted periglacial surface water flow close to and along the ice margin. Outwash and delta sands and gravels are deposited in the form of ice-marginal ridges and outwash fans on the fringe of the Baltic Klint. The waters of the BIL inundated large areas of the carbonaceous plateau with a maximum water level of about 90 m a.s.l. in stage A_1 at around 13.3 ka BP and about 40 m a.s.l. in the final, B_{III} stage at about 11.6 cal ka BP (Björk 1995; Rosentau et al. 2009). During the regression of the BIL the elevated glaciofluvial ridges gradually rose above the lake water level, forming either small isolated islands or barrier spits. In response to the water level fluctuation and the accompanying alongshore waves and currents, the underlying glaciofluvial material was reworked and/or subjected to littoral transport. The elevated glaciofluvial ridges and their unconsolidated sandy-gravelly deposits encouraged the formation of beach ridges along coastlines that had a windward exposure to open water from the north. In the following stages of the Baltic Sea (from the Yoldia to Limnea seas) the water levels were generally lower than the carbonaceous klint edge and their waters did not affect sedimentation.

Glacial outwash and beach deposits of the studied sites, composed of bedded well-rounded and sorted pebble-cobble gravels with variable contents of sand and fines, contain carbonate-cemented layers and lenses (Table 1). Both types of sediment are quite similar lithologically, which is not surprising, since beach sediments are largely reworked from outwash deposits. Therefore, in some sections it was difficult to draw a line between outwash and beach deposits. The coarse-grained material mainly consists of local carbonaceous debris (>70%) derived from the underlying Middle Ordovician strata. Scandinavian Shield-derived debris (igneous and metamorphic rocks) makes up about 10–20% and local Cambrian and Ordovician terrigenous silt- and sandstone from the foreklint area less than 5%. The texture of the deposits is highly variable and will be described in detail for each studied site later in this paper.

All these sand and gravel deposits and cemented zones presently lie well above the modern water table, i.e. in the vadose zone. This does not exclude the possibility that cementation occurred when water table level was higher than today and sediments were permanently water saturated, i.e. in the phreatic zone.

METHODS

The samples were collected from both the laterally continuous horizons and vertical features, depending on the variations in sediment facies, cement distribution and cementation rate. Thin section petrography, X-ray

Table 1. Summary of the sedimentology and cement characteristics of the studied sites

Studied site	Coordinates and altitude	Landform type	Sedimentological sections (from top downwards)	Description of the cement
Pehka	59°29′34″N 26°20′20″E Abs. 58 m	Beach ridge/ ice-marginal ridge	6 m: well-sorted, cross-bedded coarse gravel, pebbles and boulders with little sand; 2+ m: massive fine sand	Extensive, up to 3 m thick cemented layer covers almost the whole ridge; cement occurs as a visible crust around the clast surface
Kunda	59°25′25″N 27°06′27″E Abs. 60 m	Beach ridge/ ice-marginal ridge	7 m: cross-bedded clayey gravel alternately with layers of sorted pebbles and cobbles; 3+ m: medium to coarse sand with gravel and few pebbles	Laterally discontinuous cemented layer or patches in the topmost part of the clayey gravel unit; cement occurs as a crust around coarser clasts or as massive cement in fine-grained matrix
Moldova	59°29′46″N 26°32′49″E Abs. 50 m	Littoral terrace	4 m: well-sorted, cross-bedded gravel with sand interlayers; 2 m: sandy gravel with few pebbles; 0.5+ m: bedrock (limestone)	Up to 2 m thick cemented layer/lense at a depth of 0.5–1 m; 1 m thick cemented layer in the lower gravel unit conterminously above bedrock; cement occurs as a crust around coarser clasts or as massive cement in the fine-grained matrix
Tornimägi	59°22′28″N 27°50′46″E Abs. 55 m	End moraine ridge	2 m: brown sandy loam till with well-rounded pebbles; 1 m: medium to coarse sand; 3 m: cross-bedded coarse gravel; 2+ m: cross-bedded fine to medium sand with gravel, few pebbles and a bedrock raft (limestone)	Two thin (2–4 cm) cemented layers in the sand unit just below the till; up to 2 m thick cemented layer on the top of the gravel unit; massive cement in fine-grained matrix
Laagna	59°23′18″N 27°58′04″E Abs. 42 m	Beach ridge/ ice-marginal ridge	5 m: well-sorted, rounded gravel and pebbles intercalated with fine to medium sand layers; 3+ m: poorly-sorted coarse gravel with well-rounded pebbles and cobbles	Up to 0.8 m thick cemented layer in the lower part of gravel; massive cement in fine-grained matrix

diffraction (XRD) and scanning electron microscopy (SEM) were used to determine the mineralogy and texture of the cement.

The mineral composition was determined from powdered samples (cement coatings). The powder was spread over an aluminium slide and analysed using a *DRON 3M* X-ray diffractometer at the Institute of Ecology and Earth Sciences, University of Tartu. Diffractograms were measured with Cu Kλ radiation in the range 10–55° 2θ with a step size of 0.03 and scanning speed of 3 s per step. Identifications were made based on comparisons with standard diffractograms and data from this analysis, and the result received was a comparison of the relative contents of minerals (mainly calcite, dolomite, quartz).

The micromorphology and chemical composition of the cement were examined using a scanning electron microscope SEM Zeiss DSM 940, equipped with an Idfix silicon drift technology energy dispersive analyser (EDS) for semi-quantitative element analysis at the Institute of Ecology and Earth Sciences, University of Tartu. The samples (about 0.1 cm^3) were mounted onto an aluminium stub, using a double-sided carbon tape and then sputter-coated with gold for 230–250 s prior to examination under SEM.

Before thin section production the soft-cemented samples were first impregnated with an epoxy resin to make them harder for cutting. All samples were sectioned, glued to a glass slide (3 × 5 mm) and polished, using progressively finer abrasive grit until the sample was 20–30 μm thick. Thin sections were visually analysed under an optical microscope and photographed with a digital camera at the Institute of Ecology and Earth Sciences, University of Tartu, and at the Faculty of Geography and Earth Sciences, University of Latvia.

The Geological Base Map at a scale of 1 : 50 000 and LIDAR elevation data from the Estonian Land Board were evaluated for regional background information and description of the sites.

DESCRIPTION OF SITES

Pehka site

The 300 m long and 4–6 m high Pehka exposure (59°29′34″N, 26°20′20″E) is located on the NE–SW orientated ridge along the fringe of the carbonaceous escarpment (Fig. 2A). The limestone plateau lies at an altitude of 40–60 m and borders the 15–20 m high buried klint terrace in the north (Suuroja 2006). The Pehka ridge is about 2.3 km long, 100–300 m wide and with a relative height of about 6 m in the NE part and up to 13 m at its SW end. The southwestern part of the ridge acts as a dam in the mouth of the ancient bedrock valley cut into the carbonaceous plateau.

The ridge is entirely composed of sand and gravel. The thickness of the deposits varies from about 5 m on the limestone plateau in the NE to 18 m within the river valley at the SW end of the ridge. Two laterally continuous lithofacies associations are distinguished, separated by a sharp apparently erosional contact. The upper lithofacies is composed of high-energy variably sorted well- to sub-rounded cross-bedded coarse gravel with pebbles and boulders with little sand and fines. The total thickness is up to 6 m (Figs 3A and 4). Coarse-grained material originates from the underlying carbonaceous bedrock (up to 90%) and is more likely derived from the klint edge. The cross-bed dip direction records palaeoflow mainly towards the south and south-west. This upper coarse-grained gravel–pebble–boulder facies is typical of wave-built beach ridges related either to storms or exceptionally high water stages, often occurring on erosionally sculpted bedrock terraces (Otvos 2000).

The gravel unit is underlain by low-energy massive fine-grained sand, which expands upon the fore-klint area and fills most of the bedrock valley. The thickness of the sand unit reaches 12 m. The OSL age of sand has been dated as 26.8 ± 3.5 ka and related to the terrestrial interstadial sands of Middle Weichselian age (Kadastik 2004; Kalm et al. 2011).

The strong cemented unit forms a lateral up to 3 m thick layer in the top part of the gravel unit (Fig. 4). The cemented layer is followed along the entire 300 m long exposure, forming precarious overhangs (Fig. 3A). It is traceable along the whole of the ridge top beneath a thin soil layer and probably wedges out either on slopes or just at the foot of the ridge. The degree of cementation is variable, mainly depending on the grain size of the sediments and the texture of the cement. Coarse gravel and pebbles are mostly cemented by thin carbonate crusts or coatings around the clast surface, which act like glue sticking them together. In finer, sandy material the cement is distributed uniformly in the matrix, forming a strong massive cement between coarser particles.

Kunda site

The 800 m long and 10–15 m high Kunda exposure (59°29′46″N, 26°32′49″E) is situated 11 km east of the Pehka site (Fig. 1), also on the NE–SW orientated arced ridge (called Hiiemägi) in the mouth of an ancient bedrock valley (Fig. 2B). The up to 30 m deep Kunda bedrock valley is incised into Middle Ordovician carbonates as well as Cambrian and Ordovician silt- and sandstone. The bedrock lies at altitudes of 20 m within the valley and 50–55 m on the adjacent limestone plateau. The Kunda valley is mostly filled with till and glaciolacustrine silt and clay deposits with a thickness of 15–20 m. The present-day Kunda River flows above the ancient valley and has eroded a narrow deep-sided gully through the Hiiemägi ridge.

The Hiiemägi ridge is 2.5 km long, 100–400 m wide and has a relative height up to 13 m. The ridge comprises mainly outwash deposits represented by cross-bedded clayey sand, gravelly sand and rounded gravel deposits alternating with well-rounded cobble–pebble interlayers almost lacking fine-grained material. The topmost part of the section contains discontinuous layers of slightly rounded platy limestone boulders. General cross-bed dip directions record palaeoflows towards the south and southwest. Some fine sand layers show also ripple marks. The Hiiemägi ridge has been interpreted as an ice-marginal formation, which was later flooded and reworked by the BIL. Therefore, the topmost part of sediments could also be observed as beach deposits. As a result of the lowering of the BIL the higher northeastern part of the ridge formed a spit, which later became a dam separating the ancient Kunda Lake in the south from the BIL in the north (Karukäpp et al. 1996).

Cementation occurs as lateral patches or 2 m thick lenses in the topmost part of the sediment complex, mainly between the two uppermost cobble–pebble layers (Fig. 4). The extent of cementation in the pit wall is difficult to observe because the outcrop is almost completely covered by a scree. Many large rafts of cemented material have been left at the bottom of the quarry (Fig. 3D), mostly in its central part. Therefore it seems that the cementation principally took place just in that specific sloped zone of the ridge. The cement is predominantly strong and massive in a fine-grained matrix, but occasionally highly weathered and crumbly.

Moldova site

The Moldova exposure (59°25′25″N, 27°06′27″E) is a part of a 12 km long and about 1 km wide NW–E directional arced ridge with a relative height up to 5 m (Fig. 2C). It is observed as a complex of glacial outwash forefield and littoral beach system of the BIL on the fringe of the Baltic Klint. At Moldova the Ordovician limestone escarpment, together with the escarpment in terrigenous rocks, forms an up to 15 m high terrace stepwise descending northwards (Suuroja 2006). The Ordovician limestone crops out in the bottom of the pit at an altitude of about 44 m a.s.l. and rises southwards to 50 m a.s.l.

At Moldova an up to a 600 m wide littoral terrace is formed either on the carbonaceous bedrock or the glacial outwash terrace. The overall thickness of sand and gravel deposits is about 6 m. The upper 4 m of sediments are typical beach deposits consisting of seaward dipping cross-bedded well-sorted and well-rounded, often matrix-free coarse gravel with pebbles alternating with layers of sandy gravel and sand (Figs 3B, 4). These littoral deposits were formed in the repeatedly changing coastal environment, either with variable water levels and/or wave energies. The bottom 2 m of the deposits are made up of horizontally-bedded poorly graded sandy gravel with well-rounded pebbles and cobbles, which are most likely of glacial (outwash or fluvial) origin.

Carbonate cementation is observed at two levels. The upper, extensively cemented layer with a thickness of 0.7–2 m occurs in beach deposits at a depth of 1 m, forming a distinctive ledge in the outcrop section (Fig. 3B). A second, 1 m thick cemented layer is present on the bottom of the quarry, in outwash deposits just above the bedrock. Several cemented rafts (quarrying residuals) that have dropped around the quarry bottom indicate a wider distribution of cementation than currently visible. Massive cement is mainly found in the fine-grained sand matrix, or in the absence of sand a thin cement crust surrounds coarse gravel and pebble clasts.

Tornimägi site (Hills of Sinimäed)

Tornimägi is one of the three hills forming the west–east orientated Sinimäed ridge with a length of 3 km and width up to 400 m (Fig. 2D). The Sinimäed ridge is located about 2.2 km south of the Baltic Klint rising up to 50 m above the surrounding area with a generally flat topography. Three bedrock blocks of Middle Ordovician limestone form the cores of the three hills. The limestone beds are strongly inclined (18°–70°) and folded, and in places overthrusted. The hills are fully buried under Quaternary glacial deposits, while the limestone mainly crops out on the northern slopes as a 40–50 m high vertical wall.

The formation of the Sinimäed ridge is still under discussion. According to one hypothesis (Orviku 1960; Suuroja 2006), the limestone blocks may have been squeezed upwards by the Cambrian clays along a pre-existing tectonic fault zone under the pressure of continental ice. Others (Orviku 1926; Miidel et al. 1969) have suggested a glaciotectonic origin, that these are glacial rafts transported from the klint edge to the present location by continental ice. Based on that supposition, the hills have been interpreted as a push (end) moraine of the Pandivere stage (Raukas et al. 1971) about 13.3 cal ka BP (Kalm 2006). The entire ice-marginal formation includes the end moraine chain, comprising deformed limestone blocks with glacial till and outwash deposits between them in the proximal and glaciofluvial delta plain in the distal part.

The exposure (59°22′28″N, 27°50′46″E) is located on the southern slope of Tornimägi hill, where glaciofluvial outwash deposits outcrop as a 5 m high and 150 m long escarpment (Figs 3C, 4). Outwash deposits consist of planar cross-bedded poorly graded sandy gravel with a few purely pebble layers. Gravel deposits change gradationally downwards into medium to fine sand with little coarse-grained material, yet containing a large limestone raft that can be observed in open section. The gravel unit is partially covered by a thin, less than 1 m thick layer of medium to coarse-grained sand, which in turn is covered by an up to 2 m thick sandy loam till layer.

The main, 2 m thick uniformly cemented layer occurs in the gravel unit. Very strong massive cement is found in the fine-grained gravel–sand matrix between coarser clasts. The lower boundary of the cemented layer is sharp and traceable along the entire open section. In addition, two thin (2–3 cm) strongly cemented layers are observed in the sand unit above the cemented gravel layer.

Laagna site

The Laagna exposure (59°23′18″N, 27°58′04″E) is situated 7 km to the northeast of the Tornimägi site (Fig. 1), in the southern part of Laagna klint bay that cuts as an up to 6 km long and 1.5 km wide incision into the limestone plateau (Suuroja 2006). Laagna klint bay is located in a faulted area where Ordovician carbonate rocks are missing and Cambrian blue clay lies at 25–30 m a.s.l. Several limestone blocks bordering the klint bay are squeezed upwards and form up to 15 m high escarpments partly buried under glacial outwash and beach deposits. Two NE–SW-trending ridges are observed on the edges of such limestone escarpments at Laagna (Fig. 2E). The ridges marks short standstills of the ice margin during the Pandivere phase and were later strongly reshaped by the coastal processes of the BIL. The overall thickness of gravel deposits is up to 10 m. The upper 5 m of the ridge consists of well-sorted well-rounded gravel and pebbles with fine to coarse sand interlayers typical of beach ridge sediments. The lower,

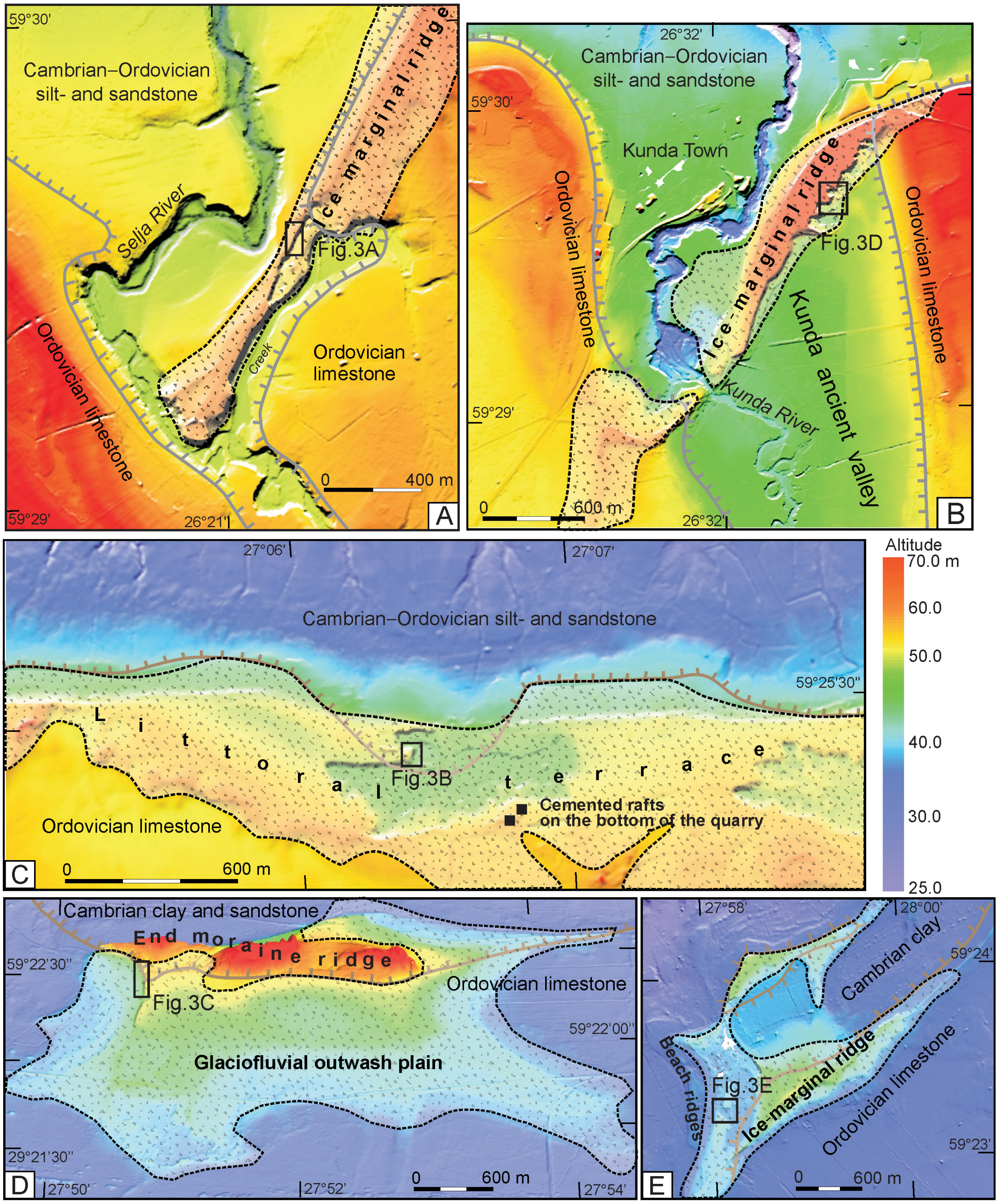

Fig. 2. Geomorphological and geological settings of the studied sites: **A**, Pehka; **B**, Kunda; **C**, Moldova; **D**, Tornimägi; **E**, Laagna. Colour-scaled topography is based on LIDAR measurements by the Estonian Land Board.

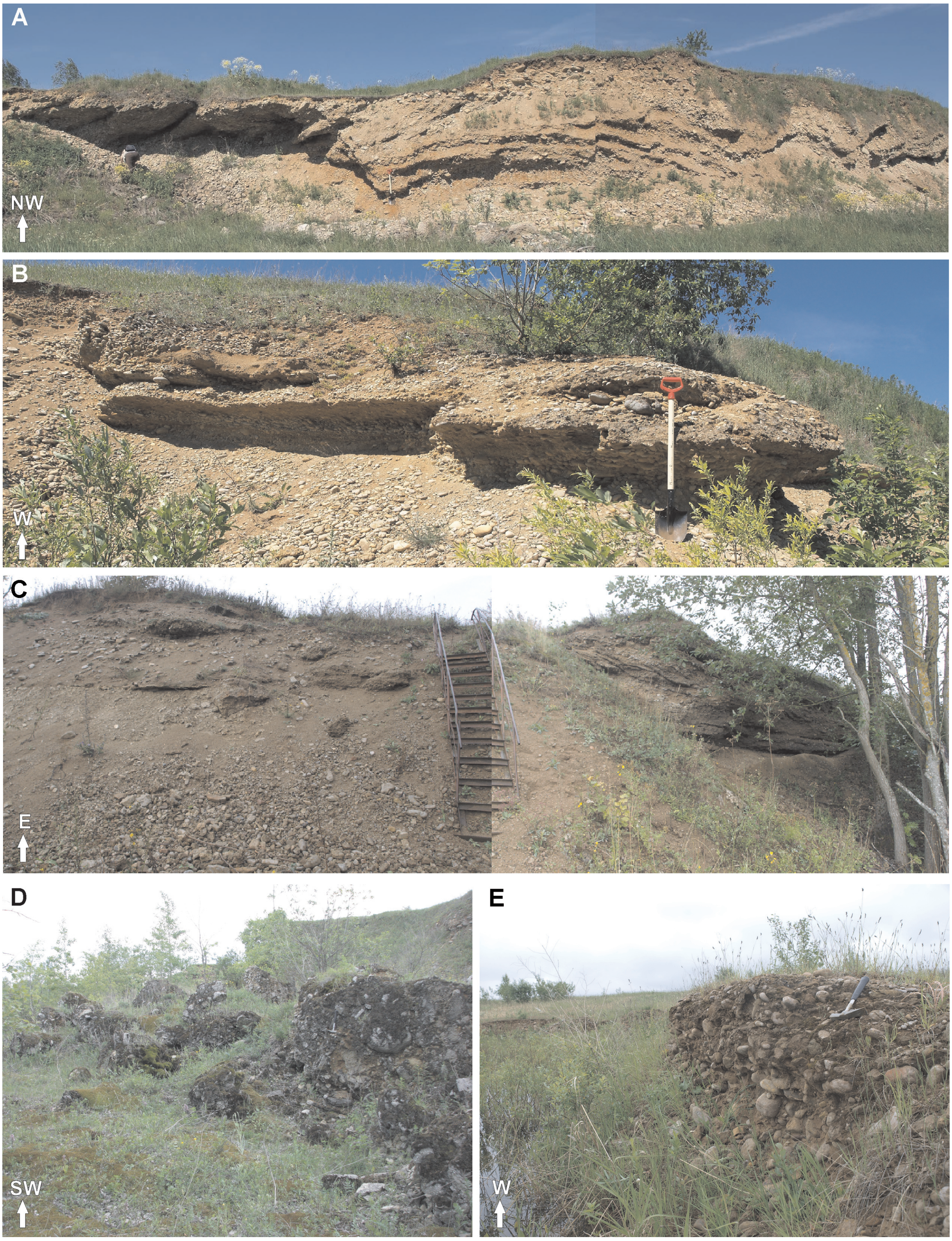

Fig. 3. Studied exposures. See Fig. 1 for locations and Fig. 2 for geological settings. **A**, a lateral continuous up to 3 m thick cemented gravel layer on the top of the ridge, Pehka site; **B**, a cemented up to 2 m thick layer in the upper part of the gravel unit, Moldova site; **C**, a cemented 2 m thick gravel layer on the top of outwash deposits, southern slope of the Tornimägi hill; **D**, cemented rafts from outwash deposits left at the bottom of the quarry, Kunda site; **E**, an up to 1 m thick cemented layer on the bottom of the quarry, Laagna site. Hammer length 30 cm.

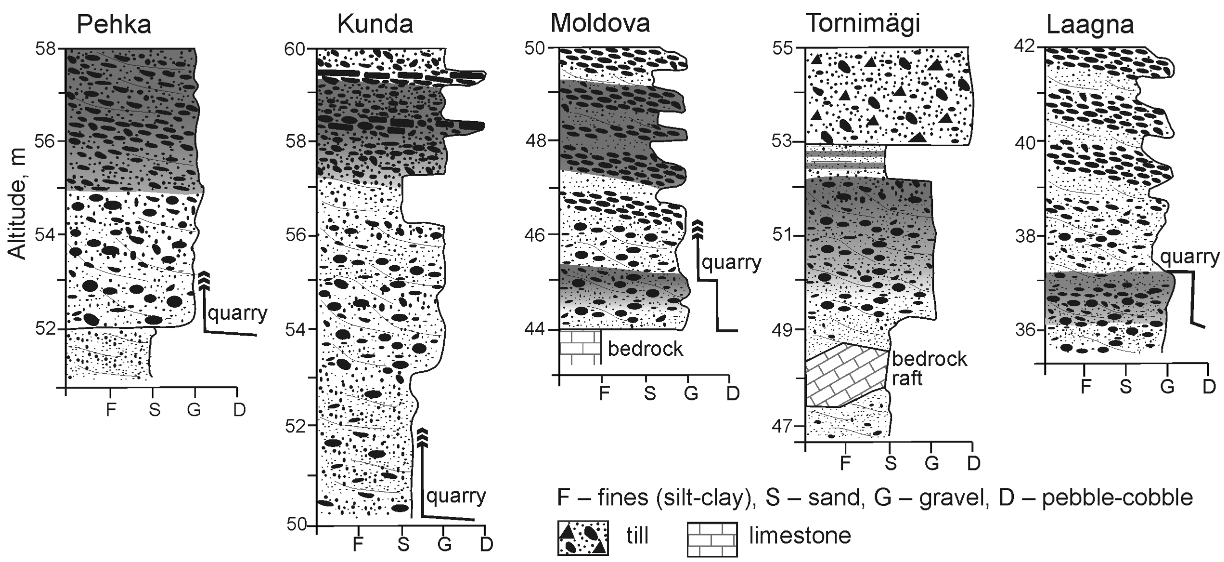

Fig. 4. Sedimentological profiles of the studied exposures. Cementation is marked in grey.

presumably up to 7 m thick part of the sediment complex consists of poorly graded sand, gravel and pebbles suggesting a glacial outwash origin. The boundary between the two genetic types of sediment is not traceable (Fig. 4).

The upper 6 m of deposits have been excavated in the Laagna exposure. Cementation occurs as a lateral discontinuous layer with a thickness of 0.5–0.8 m in outwash deposits on the bottom of the quarry (Fig. 3E). Massive cement appears in the fine-grained sand matrix between coarse-grained material. The degree of cementation is variable, decreasing downwards.

CEMENT DESCRIPTION

Texture

The texture of carbonate cement is similar in all sites. The cement mostly occurs as a carbonate crust or fringe of variable thickness around detrital grains or fills interparticle pores (Fig. 5). Macroscopically (i.e. visible to the naked eye) the cement is highly visible in the coarse matrix as an up to 1 mm crust thick around the clast surface. Such a carbonate crust acts like a glue, sticking coarse clasts together. In some pebble layers

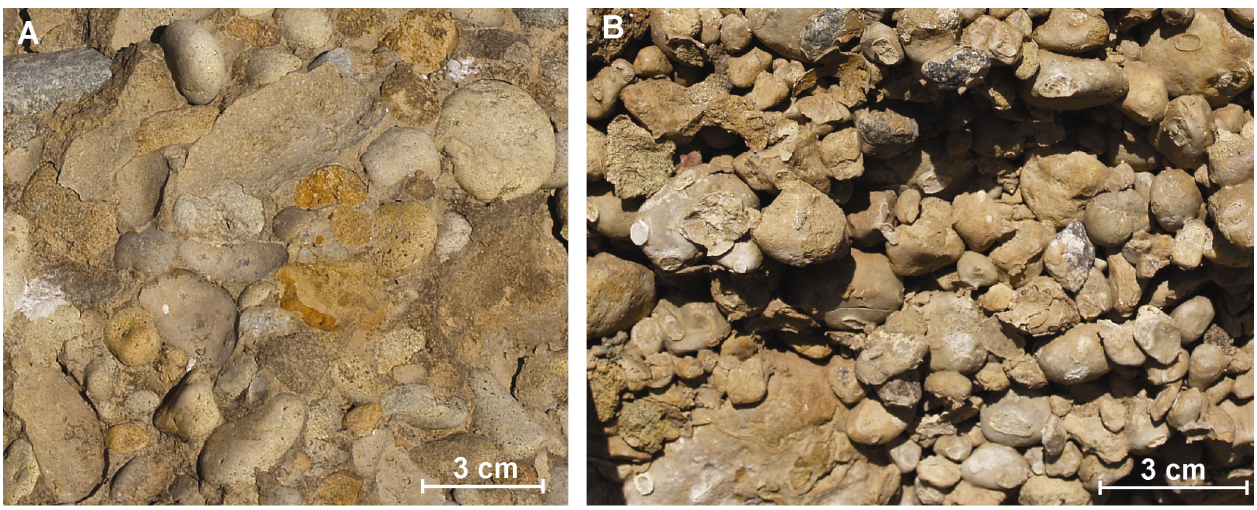

Fig. 5. Texture of the cement. **A**, uniformly-cemented fine-grained material between coarser clasts; **B**, cement crust between well-sorted porous coarse material.

the crust is only present on the upper surface of the clasts as highly characteristic of evaporative crusts, and occasionally slightly pendant morphology is observed. Several frost-cracked pebbles, probably caused by freeze–thaw processes, are also found in the cemented layers, where the cracks and fissures are filled with cemented fine-grained material. In fine-grained material the cement is distributed uniformly in the matrix, filling almost all intergranular space as massive cement between coarser material. The degree of cementation is variable throughout the cemented body due to sediment texture and porosity. Commonly the massive cement filling the pore space of the fine matrix is stronger than the carbonate crust around highly porous coarse material.

Composition

The mineral and chemical composition was determined from powdered cement using an X-ray diffractometer. The dominant minerals are calcite and quartz, but also minor amounts of dolomite are present. This suggests that the cement is not pure secondary carbonate, but also contains fine-grained detrital material from outwash and/or beach deposits. Microscopical thin-section and SEM examinations confirm that calcite is the main mineral that fills the pore space and cements the initial debris. Clay minerals were not analysed in detail due to their low content.

Detailed examination with a SEM analyser shows that the cement is mostly composed of CaO (up to 50%), and contains minor amounts of SiO_2, Al_2O_3 and Fe_2O_3 and trace amounts of MgO, MnO, K_2O and Na_2O. The minor amounts of silica and alumina could point to clay minerals, which were difficult to distinguish even under SEM.

Micromorphology

Closer examination of the cement with SEM and in thin sections indicates that it is composed of micritic (≤4 μm), microsparitic (4–10 μm) and sparitic (from 10 to 200 μm) angular equant to elongated rhombohedral and scalenohedral or prismatic calcite crystals (Figs 6, 7).

A specific morphology of micritic calcite crystals is often difficult to distinguish. It mostly occurs as massive subhedral calcite with some rhombohedron faces (Figs 6D, E, 7G). Micrite usually forms coatings or isopachous rims tightly around the grains or completely fills interparticle porosity or intraparticle voids. Micrite often changes to microsparite and sparite towards the intergranular pore space, indicating that micrite preceded microsparite or sparite precipitation (Figs 6F, 7D, F). The thickness of the micritic rims is variable (up to 20 μm).

Microsparite and sparite calcite crystals are mostly equant to elongated rhombohedrons or scalenohedrons, but also a few prismatic crystals were observed. Elongated crystals often have sharp tips and stand perpendicular to grain surfaces towards the intergranular pore space. Occasionally equilateral, almost cube-shaped crystals with a size of 20–50 μm have developed (Fig. 7D). Sparite crystals also form assemblages, filling larger intergranular voids and microfractures, although larger intergranular voids have not always been completely filled.

The thickness of the micritic and sparitic cement together ranges from 40 to 300 μm, whereas larger voids have not been fully filled by the cement. The cement is uniformly fringing the grains and no specific downward dragging pendant structures have been observed. In smaller pores the cement rims around the neighbouring clasts are grown together, being somewhat similar to the meniscus bridges. In addition, the peculiar meniscus cement with smooth ends of flattened calcite crystallites, which defines the water–air interface in pores, has not been observed in larger pores.

The different texture of cement shows very clearly that crystal growth has taken place either in separate stages or in changing hydrological regimes. Traces of dissolution and secondary formations are found on the surfaces of crystals, referring to some later dissolution and reprecipitation of secondary calcite.

DISCUSSION

Hydrologic environment of cementation

Carbonate cement can precipitate in both vadose and phreatic hydrologic environments, which are distinguished by specific mechanisms and cement characteristics that are unique to or more prevalent in particular environments (Vogt & Corte 1996; Hall et al. 2004; Elbracht 2010). In the vadose zone, where water is retained by a combination of capillary force and adhesion action, precipitation can take place from the infiltrated or percolated waters that permeate through sediments at intervals. In a general way, vadose cements tend to be made of micrite due to high levels of supersaturation and rapid precipitation, either by rapid transpiration or evaporation or chemical reactions causing rapid CO_2-degassing (Folk 1974; Given & Wilkinson 1985; Hall et al. 2004). Vadose cement is characterized by the meniscus cement at grain contacts or pendant textures, in which vertically-orientated crystals grow downwards from the lower faces of clasts. Vadose cement is preferentially located in fine-grained sediments because of higher matrix suction and increased capillary tension (Hall et al. 2004). Sparitic crystals may be associated with a greater water supply (e.g. seasonal) into sediments, leading to a decrease in carbonate concentration and deceleration of precipitation.

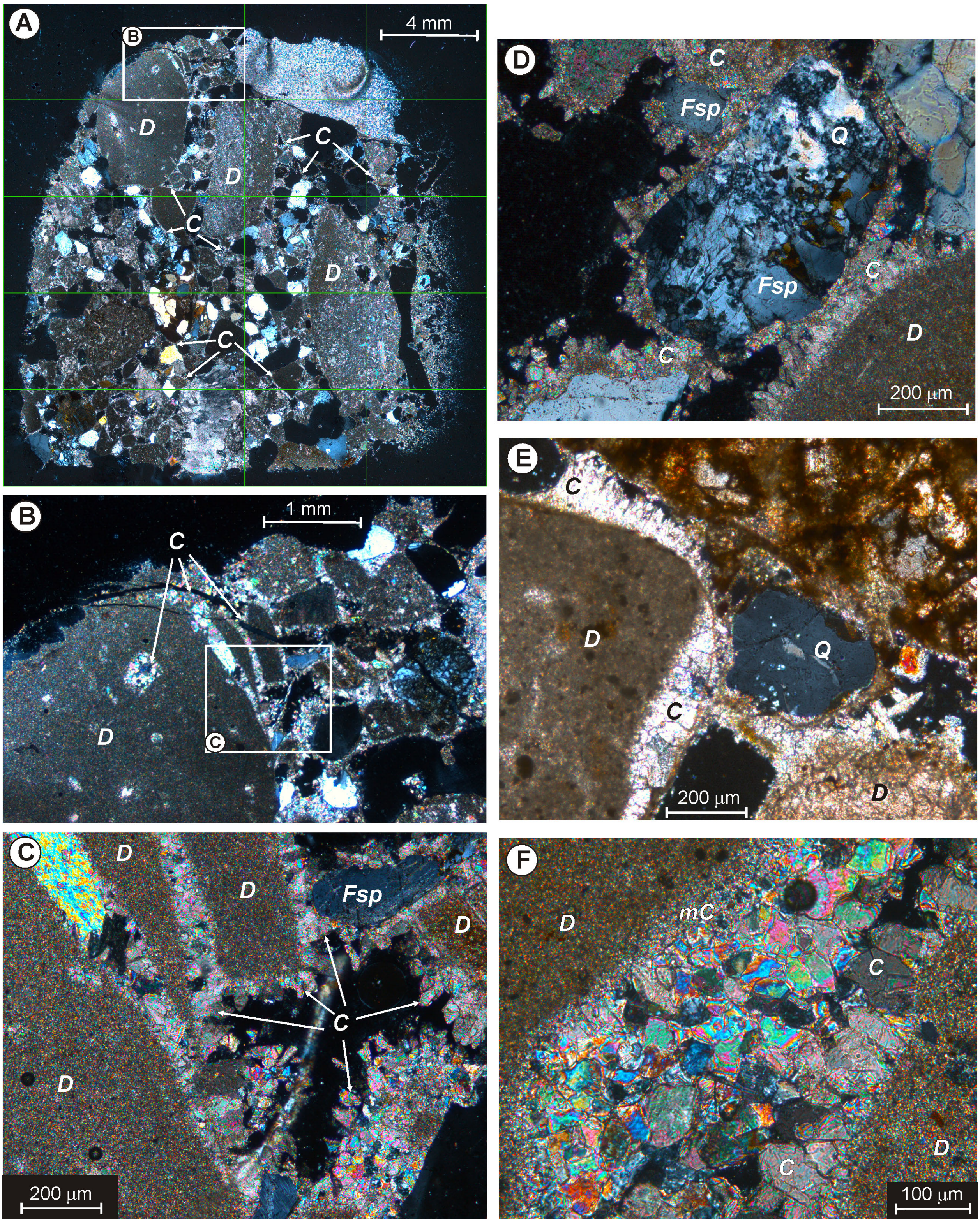

Fig. 6. Microphotographs of cemented outwash sediments. **A**–**C**, images of thin sections showing the texture of cemented outwash deposits: calcite crystals form a rim around detrital grains or completely fill intergranular pores and intragranular microfractures and voids; **D**, **E**, micritic cement between detrital grains sticking them together; **F**, close view of the cement entirely filling the pore space between detrital grains; the micritic carbonate-siliciclastic cement rim grades into distinguishable elongated calcite crystals. Key: *D*, detrital grain of source sediment; *C*, calcite crystals; *mC*, micritic calcite cement; *Q*, quartz; *Fsp*, feldspar.

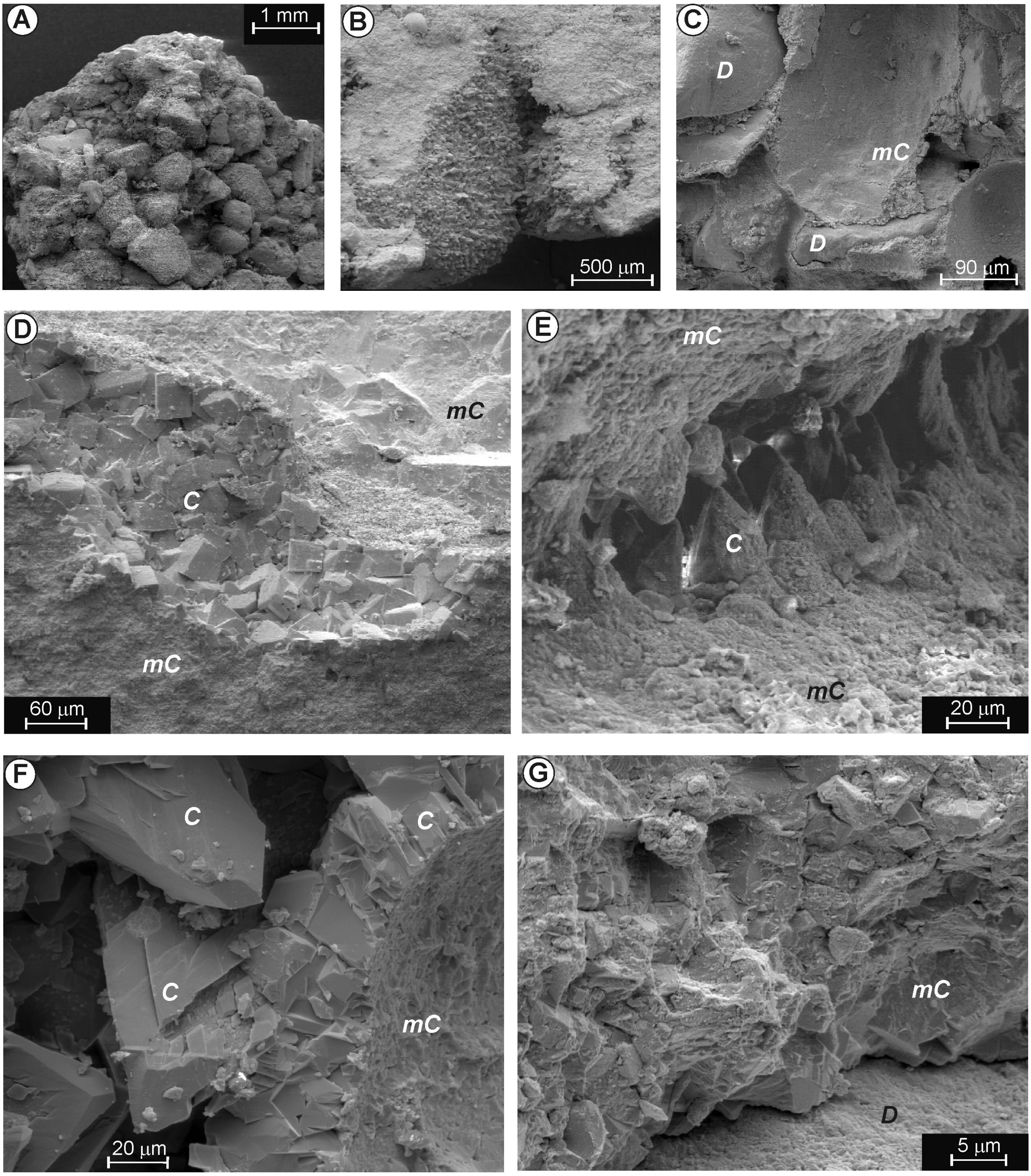

Fig. 7. Micromorphology (SEM images) of calcite cement. **A**, view of a cemented sand deposit, where a secondary calcite coating covers detrital grains sticking them together; **B**, detrital grains covered by a coating of elongated calcite crystals, and this in turn by micritic (<4 μm) massive calcite; **C**, micritic cement between detrital grains; a smooth cement surface had formerly been fringing a detrital grain; **D**, sparite with equilateral, almost cube-shaped calcite crystals in the subhedral calcite mass with some rhombohedron faces; **E**, scalenohedral calcite crystals grown perpendicular to grain surfaces towards the intergranular pore space; **F**, rim of the elongated calcite crystals with sharp tips orientated towards intergranular voids; **G**, massive micritic cement fringing a detrital quartz grain. See Fig. 6 for key.

In phreatic conditions all pores and fractures of sediments are saturated with water. Phreatic cements may exhibit a broad scale of crystal size and morphology depending on the degree of supersaturation and flow rate of fluids (Given & Wilkinson 1985; Gonzalez et al. 1992; Vieira & Ros 2006). Phreatic cements preferentially form coatings or isopachous rims tightly around the grains growing perpendicularly from the grain surfaces towards the intergranular pore space, eventually infilling all intergranular voids. Generally the formation of cement in phreatic conditions is slower than in the vadose environment, therefore distinct and well-developed crystals can form. General successions of cementation often demonstrate a variety of textures, which would imply that the formation of cement can take place in changing, even at micro-scale, hydrologic and/or climatic conditions attributed to drainage, fluctuations in the water table and triggering mechanism of precipitation (e.g. Aber 1979; Knight 1998; Candy 2002; Hall et al. 2004; Vieira & Ros 2006).

The absence of organic structures within the studied cements suggests that cementation is essentially inorganic. The few macroscopic evidences, such as meniscus bridges and pendant texture between larger clasts (Fig. 5B) observed in the outcrops, are indicative of precipitation in the vadose zone. Likewise, micritic coatings and rare meniscus bridges concentrating mainly at grain contacts are observed in the fine-grained sand matrix between gravel and pebbles. No apparent micro-scale pendant texture or any influence of gravity was found in the fine matrix. Distinct evidence of phreatic cementation includes well-developed microsparite to sparite equant to elongated scalenohedral crystals forming isopachous rims around the grains (Figs 6D, 7E). These rims are sporadically surrounded or engulfed by dense massive micritic cement (Fig. 7D). Together they fill the bulk of the pore space. In turn, massive micrite includes dispersed microsparitic and sparitic crystals. This indicates phreatic rather than vadose conditions.

The presence of bilaminar cement with thin inner micrite laminae and thicker outer microsparite and sparite rims of calcite crystals may refer to two-step cementation that started in the vadose and continued in the phreatic environment. The inner micritic cement (coating or meniscus) is explained by a high carbonate concentration during the initial stages of rapid precipitation produced by the repeated wetting and drying cycles of sediments. Such a recurrence most probably occurred on a seasonal or annual basis, when water could seep into sediments during storms and rains or exceptionally high water levels. The formation of micrite envelopes reduced permeability. Subsequently pore water drained and evaporated more slowly, leading to lower nucleation rates and thus permitting the growth of larger crystals at the outer rim. In addition, a coarser crystal size may have resulted from a progressively decreasing supersaturation due to the more limited access of carbonate ions in the vadose zone. On the other hand, sediments may have entered the phreatic zone due to groundwater table fluctuation, i.e. a rise in the water table. In that instance the dense sporadically sparry micritic cement resulted from rapid precipitation stimulated either by evaporation or the CO_2-degassing of water.

The studied cements exhibit both meteoric vadose and phreatic features. Most probably cementation occurred close to the vadose–phreatic interface, where conditions were transitional and/or fluctuating. The uniformly-cementated layers indicate carbonate precipitation in a low-energy water-saturated phreatic environment (e.g. at Pehka, Tornimägi and Moldova), whereas in vadose conditions preferentially more irregular scattered cemented bodies developed (e.g. at Kunda).

Controls on spatial distribution of cementation

The degree of cementation within sediments can vary widely and is controlled by the characteristics of environmental conditions. A number of factors either inhibit or facilitate the process of cementation, contributing to its variability. Considerable control on cementation is derived from the hydrologic conditions, i.e. water table depth (vadose/phreatic environment), pore-water chemistry (degree of supersaturation) and ambient fluid pattern (the influx of calcium and/or bicarbonate ions). Several studies (e.g. Jacka 1974; Aber 1979; Khadkikar 1999; Hall et al. 2004) show that cementation is also strongly controlled by sediment texture (grain size and porosity), which in turn determines the permeability and thus the migration of fluids in sediments. Coarser-grained and more porous sand and gravel as more permeable media tend to be preferentially cemented, whereas fine-grained silt and clay, or poorly-graded tills, as less permeable beds, are rarely cemented.

It is more usual to find (including this study) that particular gravel and sand beds are firmly cemented, whereas adjacent layers remain uncemented. The beach and outwash deposits with similar textures are widespread on the limestone plateau in North Estonia, but most of them do not exhibit calcite cementation. In the studied sites lateral cementation of variable thickness occurs in well-drained poorly- to well-graded gravel with a sand matrix either on the surface or some 1–5 m below the surface. The cemented layers do not exhibit apparent textural differences compared to the non-cemented poorly consolidated beds of similar texture (Fig. 4). Furthermore, the boundary between cemented and underlying uncemented sediments is mainly sharp and sub-horizontal, showing an abrupt interruption of cementation (e.g. at Pehka, Moldova and Tornimägi). Thereby cementation seems to be mainly controlled by the groundwater level, and is independent of sediment textural differences.

The formation of near-surface lateral cementation probably requires the occurrence of an elevated near-surface water table. The large volume of surface water in the form of BIL definitely produced a raised water table, which later started to decline gradually. Additionally, the perched water table could have been produced by the permafrost or seasonal freezing, which in turn may have promoted the supersaturation of CO_2 in water. A shallow layer of discontinuous permafrost would explain the formation of more restricted cemented layers or zone of cemented pones (e.g. at Kunda) between permafrost patches. Changes in the thermal regime and air–water exchange through the talik zone may have triggered CO_2-degassing, causing the supersaturation of water and precipitation of carbonates (Fairchild et al. 1994; Knight 1998).

Carbonate precipitation occurs preferentially in a zone of elevated supersaturation that forms as a function of reactants supplied by the surrounding waters. The composition and morphology of carbonate crystals are controlled by the Mg/Ca ratio of the solution and water flow characteristics, such as flow direction and velocity (Folk 1974; Given & Wilkinson 1985; Gonzalez et al. 1992). The studied cements consist exclusively of low-Mg calcite, preferentially precipitating in the meteoric or connate surface freshwater environments, which generally contain little Mg^{2+}. As the majority of calcite crystals are only slightly elongated or equant, the degree of supersaturation generally had to be low. Commonly equant fabrics are also associated with lower flow rates (Gonzalez et al. 1992). More elongated crystals, terminated by shallow rhombohedral faces, are produced at higher supersaturation, which may have been driven by a greater flux of Ca^{2+} and HCO_3^{2-} ions or other reactants transported by groundwater, or can be due to faster evaporation and/or CO_2-degassing. Groundwater influx could be related to the overall raised groundwater levels in the sediment profile or may have resulted from provisional seepage (including pressurized) along the beach zone or klint edge.

Under changing hydrologic conditions cementation could take place continuously at levels of low to moderate supersaturation. As calcite precipitation occurs, the porosity of sediments decreases, leading to a diminished or interrupted fluid flow and thus to retarded crystal growth. Sediments with lower porosity, where the flow is initially slow to non-existent, become water-saturated for a time. As a result, dense massive micritic or small equant cements are formed, distinctive to meteoric phreatic conditions. In this case, cementation was controlled by the spatial distribution of early, probably vadose, micritic cement, which formed preferentially in the fine-grained matrix. This could in turn reduce the overall subsurface drainage and water percolation in the coarse-grained units, where there was sufficient space for the growth of sparitic crystals. It may be the reason why there are no specific pendant structures, or if there were early vadose micritic pendant structures, they were overprinted by later phreatic sparitic cement apparently precipitating on the micrite substrate.

Formation of cements and implication for late glacial hydrologic conditions

Extensive calcite cementation discovered within beach and outwash deposits in North Estonia probably started soon after accumulation of sediments in late glacial time during the Allerød and Younger Dryas periods, and could episodically occur in the early Holocene only due to meteoric waters. The variable hydrologic conditions and amelioration of climate have had a great influence on the cementation process. However, the texture and composition of the cements detected in either the outwash or beach sediments do not exhibit high variability. This indicates that cementation did not occur under the influence of rapidly shifting parameters, thus the parent waters and the precipitation conditions had to be relatively comparable.

Given the palaeogeographic settings of the studied sites and the position of cemented bodies in sediment succession, in each place the cement was formed in somewhat different ways and at relatively different time periods. Subaqueous outwash deposits were deposited during the BIL stages A_1–A_2 in the front of the retreating ice margin at water levels of about 60–70 m a.s.l. (Saarse et al. 2007; Rosentau et al. 2009). During the continuous regression of the BIL (stages BI–III) the water level dropped to about 50 m a.s.l. at Pehka and to 32 m a.s.l. at Laagna. Everywhere along the coastal zone various beach formations such as spits, beach ridges and terraces developed at different levels. As a common feature the cement occurs near the top of elevated landforms, on the surface or a few metres below, either in glaciofluvial or beach deposits. Moreover, the cemented layers are stronger in the topmost part and tend to follow the landform topography, although they may be covered by younger sediments (e.g. till at Tornimägi and a beach ridge at Laagna). If cementation became possible just after the formation of these landforms or rise above the BIL water level, the water table in beach sediments close to the shoreline was strongly controlled by the BIL water level. In view of this, the cementation level at each site conforms well to the water table level derived from the water level of the BIL at different stages. Further, this suggests that the major changes have been attributed to water drainage and evaporation rates in the vadose zone, which were in turn influenced by influx of percolating rainwater, and water-level fluctuations. Therefore, depending on the volume of water and early vadose cement, the sediments in the vadose zone could be fully saturated and thus cementation continued in phreatic conditions. As elevated landforms extended above the BIL water level and thus to colder climates, and during the whole of the Younger Dryas cold period, it might be possible that a permafrost horizon or seasonally frozen sediments produced either a perched water table or barriers to water flow and thus created episodic water-saturated conditions.

CONCLUSIONS

Based on the results presented in this study the following main conclusions can be made.

1. Lateral cementation of variable thickness occurs in porous well-drained gravel and sand either on the surface or a few metres below the surface. The spatial distribution of cementation is controlled in part by the texture of the initial sediments, but mainly derived from some specific confined hydrologic conditions in limited areas, bringing about the formation of the restricted cemented beds or scattered patches within the outwash–beach sediment succession.
2. The cement is exclusively composed of low-Mg calcite appearing in angular equant to slightly elongated crystals, which indicates precipitation from the meteoric or connate fresh surface (glacial lake) water and/or near-surface groundwater at low to moderate supersaturation and flow conditions. The absence of organic structures within the cement suggests that cementation is essentially inorganic.
3. Near-surface extended cemented layers are ascribed to the near-surface water table produced and controlled by the BIL water level. As the cements exhibit both meteoric vadose and phreatic features, cementation occurred at the vadose–phreatic interface, where the conditions were transitional and/or fluctuating. The presence of bilaminar cement with thin inner micrite laminae and thicker outer microsparite and sparite rims of calcite crystals indicates that cementation started in vadose conditions and continued in a water-saturated phreatic environment.
4. Cementation has mainly taken place by CO_2-degassing in response to fluctuations in groundwater level and flow conditions, controlled by the BIL water level, and seasonal cold and/or dry climate conditions. Further studies, including the application of isotope analysis and radiocarbon dating of cements, may shed some light on the source and isotope composition of the parent waters, kinetic controls of precipitation and precise time of formation.

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Sekundaarne karbonaatne tsementatsioon hilisglatsiaalsetes glatsifluviaalsetes ja rannikusetetes Põhja-Eestis

Maris Rattas, Pille Lomp ja Argo Jõeleht

On kirjeldatud karbonaatse tsemendi levikut, morfoloogiat ja väljasettimise tingimusi hilisglatsiaalsetes glatsifluviaalsetes ning rannikusetetes. Poorsetes vett hästi läbilaskvates karbonaatse purdmaterjali rikastes liiva-kruusalasundites esinevad tsementeerunud kehad kuni 3 m paksuste ulatuslike laminaarsete kihtide või läätsedena. Tsement esineb kahe peamise vormina: 1) koorikuna purdmaterjali terade ümber ja 2) massiivse tsemendina teradevahelises pooriruumis ja terades esinevates lõhedes ning tühikutes. Tsement koosneb eranditult ainult madala Mg-sisaldusega kaltsiidist, mis esineb peamiselt võrdkülgsete või nõrgalt piklike romboeedriliste, skalenoeedriliste või prismaliste kristallidena. See viitab kaltsiidi väljasettimisele madala kuni keskmise küllastusastme ja voolukiirusega magedatest meteoorsetest, pinna- (jääjärvevesi) ja/või pinnasevetest (maapinnalähedane põhjavesi). Orgaaniliste struktuuride puudumine viitab kaltsiidi anorgaanilisele tekkele. Tsemendi tekstuur viitab karbonaatide väljasettimisele nii alaliselt küllastumata kui ka veega küllastunud keskkonnas peamiselt CO_2 lendumise või vee aurustumise tagajärjel. Maapinnalähedane tsementeerumine toimus tõenäoliselt pinnasevee taseme vahetus läheduses perioodiliselt muutuvates keskkonnatingimustes, olles mõjutatud peamiselt Balti jääpaisjärve veetaseme kõikumistest ning sesoonsetest külmadest ja/või kuivematest kliimaperioodidest.