Estonian Journal of Earth Sciences, 2017, **66**, 4, 198–219 https://doi.org/10.3176/earth.2017.18

Typology and fossil assemblage of Sandbian (Ordovician) 'baksteenkalk': an erratic silicified limestone of Baltic origin from the northeastern Netherlands and adjacent areas of Germany

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Received 24 May 2017, accepted 6 September 2017, available online 7 November 2017

Abstract. This study seeks to describe 'baksteenkalk', an erratic silicified bioclastic carbonate of the Upper Sandbian from the eastern part of the Netherlands. To date, baksteenkalk has received little attention among palaeontologists. This is to be regretted on two grounds. First, baksteenkalk contains a varied fossil flora and fauna comprising many species, several of which are not or only rarely found in coeval rocks. Second, owing to a complicated silicification process, fossils, in particular algae, have preserved exceptional anatomical details. The primary aim of this study is to arouse the interest of professional, in particular, Estonian, palaeontologists in baksteenkalk.

Based on lithology and fossil assemblage (most conspicuously, with regard to the algal flora), two basic types of baksteenkalk are distinguished. A list of species, differentiated for both types, is provided. It is argued that baksteenkalk reflects the ecology of a shallow, subtropical, epicontinental sea. The distribution of erratics, facies and fossil content point to an origin within the North Estonian Confacies Belt, probably west of Estonia. Baksteenkalk survived as an erratic because it was already silicified at its place of origin. A potential source of silica may have been Upper Ordovician bentonite layers. The causes and mechanisms of the silicification process which gave shape to baksteenkalk are not yet understood, however. The palaeontology of baksteenkalk is compared with that of two other erratic Sandbian silicified carbonates of Baltic origin: German Backsteinkalk and 'Lavender-blue Hornstein'.

Key words: algae, Baltica, bioclasts, Eridanos, Haljala, Ordovician, silicified carbonate.

INTRODUCTION

'Baksteenkalk', literally 'brick-limestone', is the Dutch name for an erratic, entirely or partially leached, silicified carbonate, containing a Late Ordovician fossil assemblage, predominantly reflecting the Upper Sandbian Stage (Haljala Regional Stage C_{III}–D_I). Baksteenkalk occurs in fluvio-glacial deposits of the Appelscha Formation (early Pleistocene) in the northeast of the Netherlands. It is in particular common in gravel pits of the Twente district (Overijssel province) and adjacent German territory, i.e., the Niedergrafschaft Bentheim. For convenience, this area is referred to as the 'WWW-area', after the villages Wilsum, Wielen and Westerhaar (Fig. 1).

Baksteenkalk is one of various types of erratic Ordovician silificied carbonates occurring in the gravel assemblages of the Appelscha Formation. The fossil assemblages in these carbonates represent mainly two periods of the Ordovician: the Haljala/Keila stages (C_{III}–D_{II}) and the Pirgu/Porkuni stages (F_Ic–F_{II}). On the basis of lithological characteristics and fossil content, at least six different groups of silicified carbonates can be distinguished.

1. Baksteenkalk, the subject of the present study, will be treated extensively below.
2. Lavender-blue Haljala- and Keila-hornstein (D_I–D_{II}). In unweathered condition bluish-black or brownish-yellow, hard cherts; leached, porous parts with lighter colours, ranging from lavender-blue to bluish-white. Two types can be distinguished among these hornsteins: boulders with a knotty, irregular surface, containing crinoid segments and brachiopods, and massive blocks and slabs, often showing infiltration bands, in which sponges and cyclocrinitid algae are the dominant fossils (Van Keulen et al. 2012).
3. Lavender-blue Pirgu-hornstein (F_Ic–F_{II}). Cherts consisting of irregular, undulating lumps or layers marked by distinct colours. Holes and burrows are often filled with chalcedony (achates) and quartz crystals. Several types can be distinguished among these cherts. One type contains a fossil fauna of stromatopores, tabulates and rugosa; another type is characterized by the presence of *Plectatrypa*; a third type with slag-like crusts is dominated by fragments of *Incuhinzia syltensis* (Schallreuter 1990; Van Keulen et al. 2012).

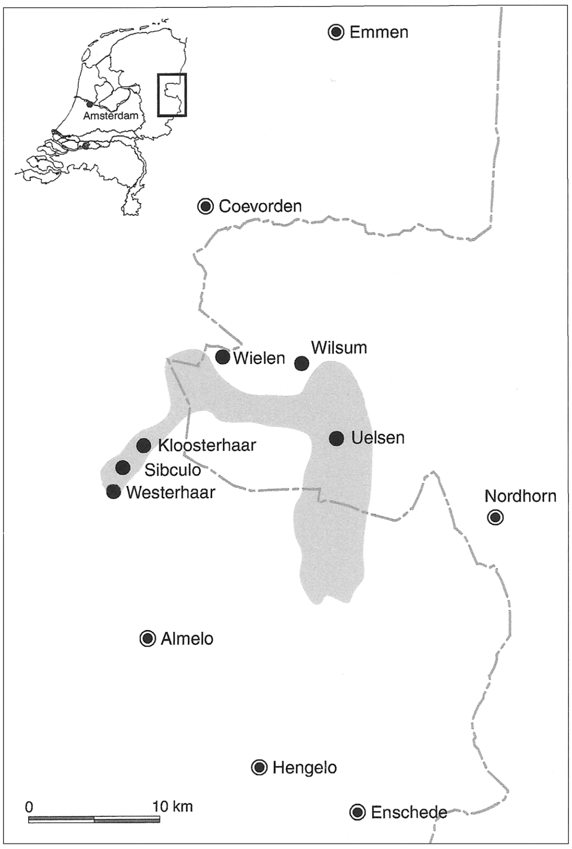


Fig. 1. Geographical map of the area from which most specimens of baksteenkalk have been collected. The highest concentrations occur in Early Pleistocene fluvio-glacial deposits which are exposed in Late Pleistocene (Saalian) ice-pushed ridges, the so-called WWW-area (grey).

4. Brown Pirgu-hornstein (F_Ic–F_{II}). In unweathered condition massive, hard, brownish-grey chert; boulders either with a light grey leached crust or entirely leached. Leached parts coarsely grained, crumbly, with uneven surface. Fossils of algae (*Vermiporella fragilis*, *Palaeoporella variabilis*) and bryozoans are common. Other fossils comprise sponges, gastropods, brachiopods, tabulates and crinoids. Trilobites are few. Algae and brachiopods are often preserved as massive, grey or white china-like chalcedony.
5. Öjlemyrflint of the 'Wielener type' (F_Ic–F_{II}). In unweathered condition splintery, brown-greyish chert; many blocks with one curved, whitish, leached side, possibly fragments of concretions. The fine-grained silicified limestone in the leached crusts of the Öjlemyrflints also occurs as homogeneous slabs and oblong blocks. The putative concretions may originally have been embedded in these blocks of silicified limestone (which is often referred to by the unfelicitous name 'Öjlemyrkalk' [literally 'Öjlemyr limestone']). The fossil fauna is rich in ostracods, bryozoans, brachiopods and trilobites (*Erratencrinurus kiaeri*, *Harpidella* sp., *Ascetopeltis bockeli*, *Pharostoma* sp., *Trochurus* sp.) but poor in gastropods and sponges. Fossils tend to be concentrated in layers and are more or less deformed by compression.
6. Small pebbles containing (casts of) goethitic ooids. These probably originate from the Estonian 'Linsenschicht', dating either from the Lower Kunda Stage (B_{III}) or the Lower Aseri Stage (C_Ia). They are rare in the gravel of the Appelscha Formation, but less so on Sylt (Hinz-Schallreuter & Schallreuter 2005; Van Keulen et al. 2012: 171).

Efforts to differentiate the silificied carbonates were only made in 1993 (Rhebergen 1993). Previously, Dutch palaeontologists distinguished between 'baksteenkalk' or 'rolsteenkalk' on the one side and lavender-blue silicifications on the other (e.g. Krul 1963: 148). The scarcity of erratic silicified limestones which they had at their disposal may have prevented them from making a more refined division. Today, silicified limestones are extant in substantial numbers due to the extraction of sands from various sandpits, but before the second half of the 20th century sandpits were not exploited on an industrial scale. If collectors were aware of the occurrence of various groups among the erratic silicified limestones, they were not able to distinguish between them because of lack of appropriate names, so they came to use the term 'baksteenkalk' as a generic term for all (greyish) Ordovician silicified limestones. In historical perspective this indiscriminate use may be pardonable. However, after Rhebergen's attempt at classification, the use of the term 'baksteenkalk' in an unspecific way should be avoided.

As unfelicitous as the way in which the term 'baksteenkalk' has been used, is the name as such. It is derived from German 'Backsteinkalk', which, like baksteenkalk, denotes a type of erratic silicified carbonate rock of predominantly Upper Sandbian age. The name 'baksteenkalk' implies its being identical to Backsteinkalk, whereas in fact it differs from the latter in several respects.

1. Boulders of Backsteinkalk are Saalian and Weichselian glacial erratics occurring over wide areas in the northern and in particular the northeastern parts of Germany. Boulders of baksteenkalk, on the other hand, are dropstones which fell from melting ice floes associated with the river system known as the 'Baltischer Urstrom' or the Eridanos (Rhebergen et al. 2001; Van Keulen et al. 2012). Their occurrence is more or less restricted to fluvio-glacial quartz sands of the Appelscha Formation which in the eastern parts of the Netherlands are exposed in ice-pushed ridges of the Saale glacial.

2. The rocks are petrologically different. Most boulders of Backsteinkalk are hard and solid and fossils cannot easily be extracted from them. Baksteenkalk, on the other hand, is largely, though to various extents, porous. Rocks tend to break along the surface of fossils, since these are often separated from the matrix by a thin layer of empty space caused by the dissolution of shells.
3. Backsteinkalk and baksteenkalk show marked differences in the composition of their fossil assemblages. In part this is due to the fact that their stratigraphical ranges as well as their geographical provenances are different.

Krueger (1995: 670) specifies the difference between baksteenkalk and Backsteinkalk by referring to the former as ‘backsteinkalkartige Gerölle’.

MATERIAL AND METHODS

The material discussed here has been collected by the authors in the WWW-area and derives from estimatedly 10 000 blocks. The collections comprise thousands of fossils set in fragments of boulders. Most boulders have been broken to expose fossils, but several boulders have been left intact. All fossils from the same boulder can be tracked down by means of electronic databases.

The specimens of baksteenkalk depicted in this paper are provided either with an RGM- or a PMU-number. The former will be stored in the collection of Naturalis Biodiversity Center, Leiden (Netherlands), the latter in the palaeontological collection of the Museum of Evolution, Uppsala University (Sweden).

RESULTS

Typology of baksteenkalk

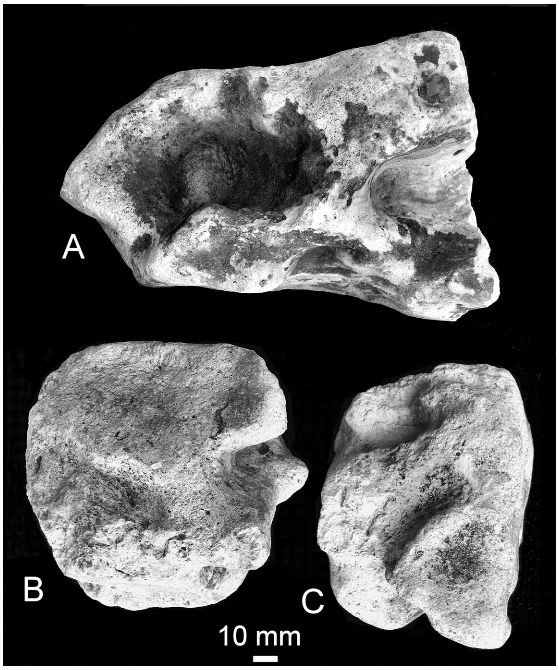
Entirely or partially leached, silicified carbonate containing marine fossils of Upper Sandbian age. Boulders with sub-perpendicular, straight sides and/or knobby surface. Diameter varies but never exceeds 300 mm. Colours vary from grey in barely leached parts to white in strongly leached parts.

Two main types (types 1 and 2) and one minor type (type 3) are to be distinguished among baksteenkalk (cf. Rhebergen 1993, 2009).

Type 1 (Fig. 2A, B)

More or less square or oblong blocks; one side (‘top’) often exhibits an undulating surface with rounded knobs and depressions, the opposite side (‘bottom’) is more flattened. The other sides are straight and sub-perpendicular. Blocks consist of fine-grained bioclasts. Leached blocks are more or less porous. All fossils occur as moulds, due to the dissolution of organically formed calcite and aragonite of exoskeletons. Fossils occur either isolated or in ‘nests’ up to 6 cm in diameter. Microfossils (<5 mm) are dominant; larger fossils are uncommon. Many blocks are poor even in microfossils. In general, fossils have not been deformed by compression. The fossil assemblage is characterized by the frequent occurrence of the alga *Apidium pygmaeum*. Other calcareous algae

A



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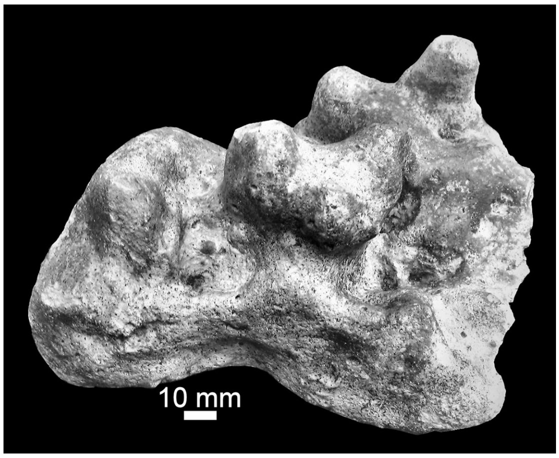


Fig. 2. A, boulders of baksteenkalk type 1: A, RGM 1317626, Itterbeck; B, RGM 1317627, Kloosterhaar; C, RGM 1317628, Kloosterhaar. **B**, a particularly knobby, undulose boulder of baksteenkalk type 1. RGM 1317629, Wilsum.

are an hitherto undescribed, hand-mirror- or key-shaped species of *Apidium* (henceforth *Apidium* sp. [provisional name 'claviformis']; Van Keulen 2014), *Vermiporella fragilis*, *Coelosphaeridium sphaericum*, *Mastopora concava*, *Hoeegonites kringla*, two other, hitherto undescribed species of *Hoeegonites* (an elongate form, henceforth *Hoeegonites* sp. A [provisional name 'elongata']; a bifurcate form, henceforth *Hoeegonites* sp. B [provisional name 'bifurcata']) and *Solenopora spongioides*. The fauna is composed of machaeridians (Rhebergen 1987, 1990), ostracods, crinoids, brachiopods (*Bilobia* aff. *musca*), trilobites (*Atractocybeloides berneri*, *Chasmops marginatus*, *Harpidella latifrons*, *Illaenus jewensis*, *Otarozoum peri*) and small gastropods (*Cymbularia compressa*, *Murchisonia* sp.). Bryozoans are few. About 65% of all baksteenkalk belongs to this type.

Type 2

More or less rectangular slabs or blocks with abundant fossils appearing concentrated in levels. In comparison with type 1, the fossil assemblage is characterized by different species.

Type 2A (Fig. 3). Rectangular slabs or blocks with a flat bottom and a top often marked by depressions and cavities. Blocks may comprise coarse-grained portions alongside fine-grained ones. Micro- and macrofossils are abundant and often appear concentrated in one or two level(s). As in type 1, fossils occur as moulds, which are sometimes filled in with chalcedony, predominantly in brachiopods, rugosa and trepostomate bryozoans. Fossils are not, or only slightly, compressed (e.g. *Mastopora concava*). Individual blocks always contain a variety of species (polyspecific). Occasionally, representatives of one taxon dominate, e.g. gastropods (*Brachytomaria baltica*), cyclocrinitids (*Coelosphaeridium sphaericum*, *Mastopora concava*), trepostomate and cryptostomate bryozoans, brachiopods (*Sowerbyella plana*). Blocks frequently contain tubes, pipes or pockets filled with debris of crinoid cirrae, bryozoans, small brachiopods and monaxons. Also frequent are filled-in burrows, which can be recognized as shades of grey different from the surrounding rock. The algal flora has a composition different from that of type 1. The fauna is more varied than that of type 1. Type 2A makes up about 15% of all baksteenkalk.

Type 2B (Fig. 4). A coquina or coquinites composed of fragments of brachiopods, cryptostomate bryozoans and echinodermates. Fragments of macrofossils may occur: valves of brachiopods (*Sowerbyella plana*, *Cyrtonotella* sp.), fragments of bryozoans and algae (notably *Mastopora concava*). In a few blocks the coquina occurs together with type 2A baksteenkalk. This type comprises 5% of baksteenkalk.

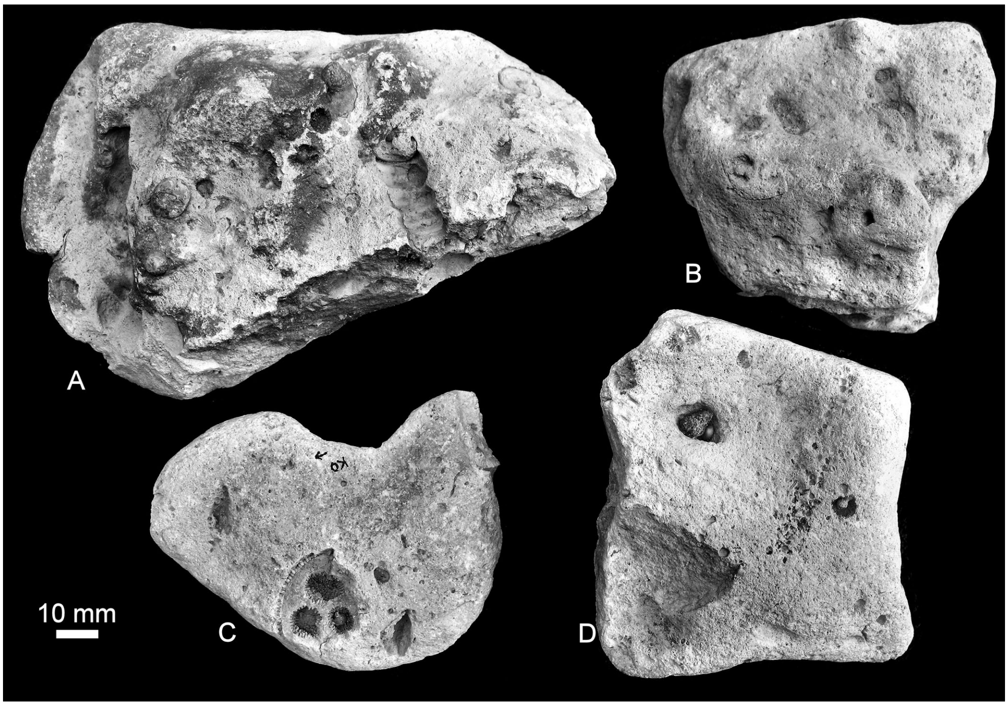


Fig. 3. Boulders of baksteenkalk type 2A: A, RGM 1317630, Wilsum; B, RGM 1317631, Wilsum; C, RGM 1317632, Kloosterhaar; D, RGM 1317633, Kloosterhaar.

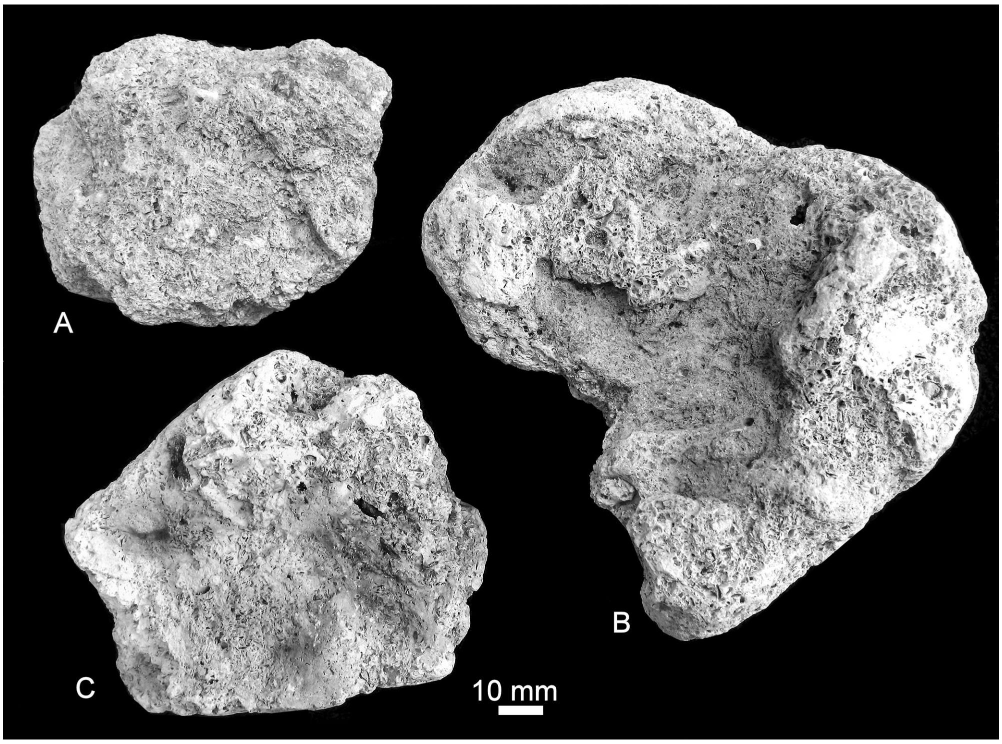


Fig. 4. Boulders of baksteenkalk type 2B: A, RGM 1317634, Wilsum; B, RGM 1317635, Kloosterhaar; C, RGM 1317636, Wilsum.

Type 2C (Fig. 5). 'Hardgrounds', i.e., silicifications of 'synsedimentarily cemented carbonate layers that have been exposed on an ancient seafloor' (Vinn & Toom 2015: 63), occur in two forms: (1) as slabs with rough irregular surfaces and wide burrows (Fig. 5, specimen D); (2) as slabs with a flat, reddish-brown bottom and a layer of heavily silicified fossils (Fig. 5, specimens A, B, C, E). Dominant fossils are *Coelosphaeridium sphaericum* and trepostomate bryozoans but in the second form of hardground all species of type 2A may be encountered. Fossils are massively silicified, with dark translucent chalcedony filling in cavities left by the dissolution of organic aragonite and calcite parts. 'Hardgrounds' comprise about 14% of baksteenkalk.

Type 3 (Fig. 6)

Porous blocks with numerous hollow burrows, 1–5 mm in diameter, and few microfossils (monaxons, fragments of brachiopods, bryozoans, crinoids). Blocks probably represent parts of a continuous layer (Fig. 6 specimen A). They form 1% of baksteenkalk.

Distinctive features of the main types

The distinction between the two main types of baksteenkalk is based on the following aspects.

Matrix

Both types consist of silicified bioclasts varying in grain size. In type 1, fine-grained bioclasts prevail. In type 2, bioclasts are more varied in grain size; coarse-grained portions are frequent, but occur alongside fine-grained portions.

Shape of boulders

Type 1 occurs as blocks with rounded knobs; type 2 is commonly found as slabs with right angles.

Size and distribution of fossils

In type 1 large fossils, exceeding 20 mm in size, are uncommon. Fossils larger than 2 mm in size tend to be concentrated in nests. In type 2 large fossils of gastropods, brachiopods, trilobites, cephalopods and bryozoans are more numerous. They occur either densely packed in one or more layers or hitched together in clusters. Tubes filled with debris of crinoids, monaxons and bryozoans are frequent in type 2 but lacking in type 1.

Epifaunal overgrowth and fecal pellets

Unlike type 1, type 2 is characterized by fossil remains showing a variety of traces and marks left by the activity

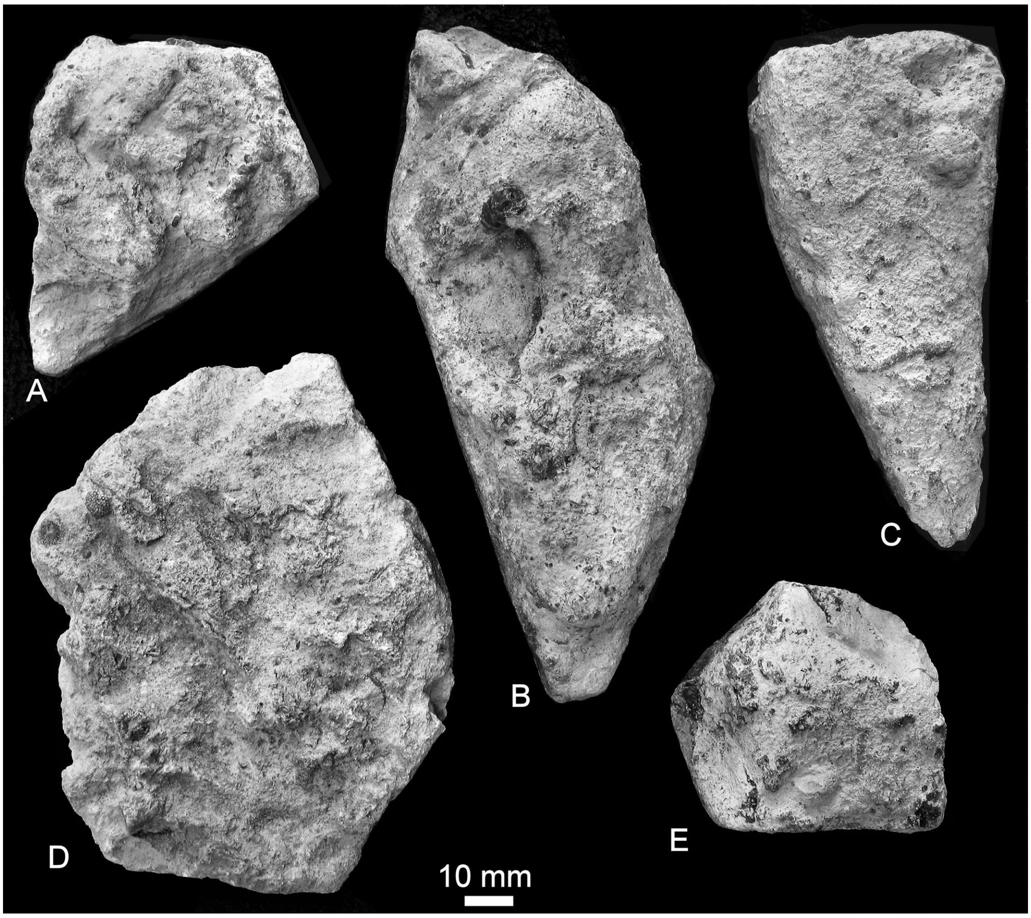


Fig. 5. Boulders of baksteenkalk type 2C: A, RGM 1317637, Wilsum; B, RGM 1317638, Wilsum; C, RGM 1317639, Wilsum; D, RGM 1317640, Kloosterhaar; E, RGM 1317641, Itterbeck.

of benthic organisms. Brachiopod shells, calcareous algae and hard parts of trilobites are overgrown by encrusting bryozoans or damaged by etching bryozoans, such as *Corynotrypa*. Thread-like structures in the interior of the cyclocrinitid alga *Coelosphaeridium sphaericum* were interpreted by N. Spjeldnaes as fungi (pers. comm. 1986). Shells of gastropods, cephalopods and brachiopods are sometimes filled with *Tomaculum problematicum*, little pellets which are currently understood as faeces deposited by an unknown organism (Eiserhardt et al. 2001; Bruthansová & Kraft 2003). Groups of polygonal dots on the inside of gastropod shells are possibly connected with *Tomaculum*. Rather common is *Arachnostega gastrochaenae*, burrows in shells of gastropods and brachiopods made by an unknown organism (Vinn et al. 2014).

Trace fossils

Trace fossils are abundant in baksteenkalk but each type has its own set. Long tubes with a core of chalcedony

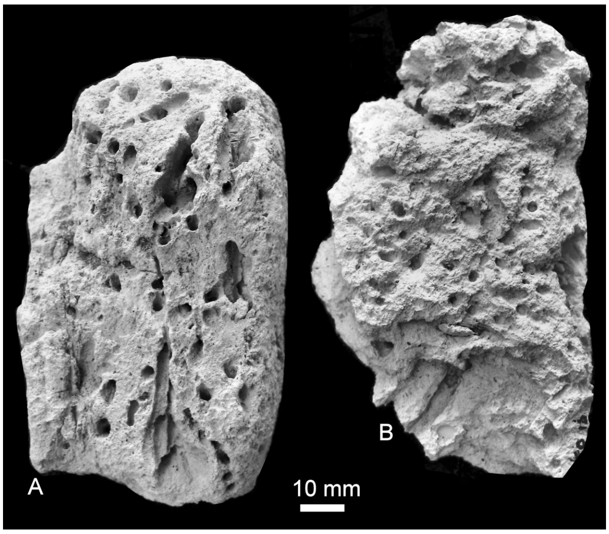


Fig. 6. Boulders of baksteenkalk type 3: A, RGM 1317642, Wilsum; B, RGM 1317643, Kloosterhaar.

surrounded by porous debris are frequent in type 1 but less so in type 2 (Fig. 7). On the other hand, the tubes filled with coarse fossil debris of crinoids and bryozoans which were mentioned above, are restricted to type 2 (Fig. 8). Concentrically structured spheres of porous debris, possibly transverse sections of burrows, are more frequent in type 2 than in type 1 (Fig. 9). *Chondrites* is common to both types, but differs in appearance.

Fig. 7. Tube of porous debris with a core of chalcedony, a common trace fossil in type 1. RGM 1317644, Wilsum.

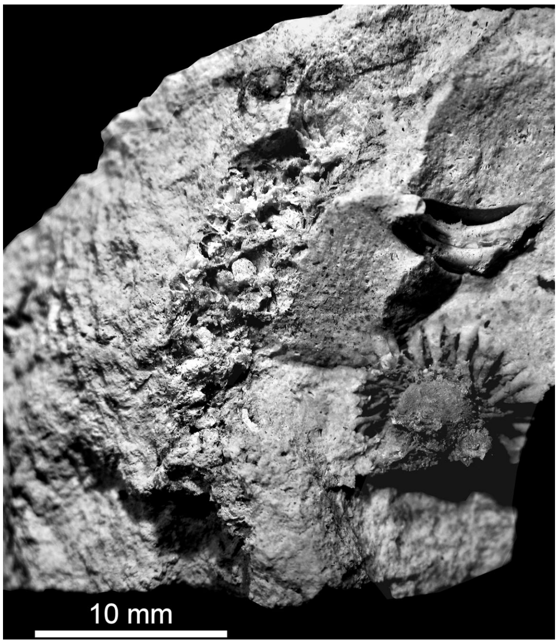


Fig. 8. Fragment of a type 2A boulder showing a tube-like infill. Right: *Coelosphaeridium sphaericum*. RGM 1317645, Wilsum.

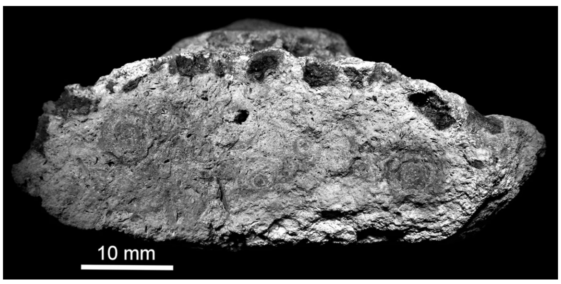


Fig. 9. Fragment of a type 1 boulder showing transverse sections of burrows. RGM 1317646, Wilsum.

Composition of the fossil assemblages

Central to the distinction of the two main types is the composition of their fossil assemblages. In particular algae, which are ubiquitous in baksteenkalk, provide a sound basis for the distinction. Species of *Apidium* (*A. pygmaeum*, *A.* sp. [‘claviformis’]) and *Cyclocrinites* (*C. porosus*, *C.* cf. *schmidti*) are almost never found together in one block. *Hoeegonites*, being a frequent companion of *Apidium*, has never been observed together with *Cyclocrinites*. Other species of algae known from baksteenkalk, i.e., *Coelosphaeridium sphaericum*, *Mastopora concava*, *Vermiporella fragilis* and *Solenopora spongioides* (the algal nature of which is contested, see Riding 2004) occur together with *Apidium* as well as with *Cyclocrinites* and as a consequence are not exclusive to a particular assemblage. Thus, the algal flora allows us to distinguish two distinct assemblages, corresponding to the two types of baksteenkalk (Table 1).

This basic distinction can be extended to elements of the fauna. The brachiopod *Bilobia* aff. *musca* frequently occurs together with algae of assemblage 1, but is not found together with *Cyclocrinites*. The same applies to the trilobite *Nieszkowskia inermis*. Conversely, the trilobites *Hemisphaerocoryphe pseudohemicranium* and *Paraceraurus elatifrons* occur exclusively with algae of assemblage 2. Other species which are probably restricted to assemblage 2 are *Astamena* cf. *inaequalis*, *Kurnamena taxilla*, *Sowerbyella plana* and *Cymbularia roemeri*.

The two assemblages share a high number of species. Some of the species which are common to both assemblages hold a prominent place as companions of species exclusive to assemblage 1. These are *Otarozoum peri*, *Harpidella planifrons*, *Atractocybeloides berneri*,

Table 1. Distribution of algae over the two distinct assemblages

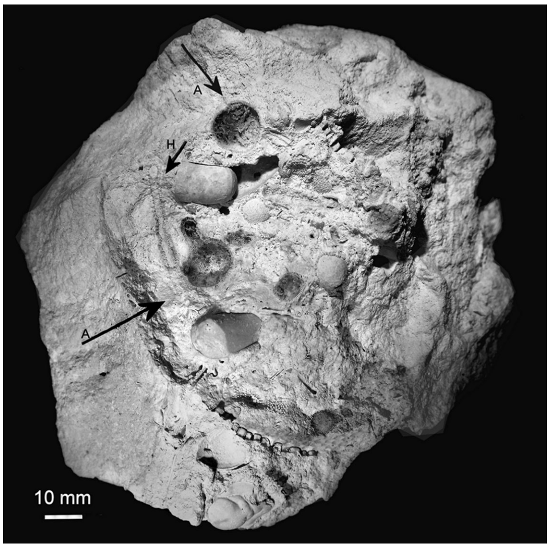
<table>
<tr><th>Assemblage 1 (type 1)</th><th>Assemblage 2 (type 2)</th></tr>
<tr><td>Apidium pygmaeum
Apidium sp. [‘claviformis’]
Hoeegonites kringla
Hoeegonites sp. A [‘elongata’]
Hoeegonites sp. B [‘bifurcata’]</td><td>Cyclocrinites porosus
Cyclocrinites cf. schmidti</td></tr>
<tr><td colspan="2">Coelosphaeridium sphaericum
Mastopora concava
Vermiporella fragilis
Solenopora spongioides</td></tr>
</table>

Chasmops marginatus, *Illaenus jewensis*, *Solenopora spongioides* and *Plumulites* sp. Species which are predominantly but not exclusively found in assemblage 2 are *Deaecheospira inflata*, *Brachytomaria baltica*, *Worthenia* sp., *Turbo balticus*, *Megalomphala contorta* and *Orthotheca* sp. (Figs 10–15).

A few aspects of the flora and fauna of baksteenkalk have been described, but hardly any work has been done on large groups, such as brachiopods, bryozoans, bivalves and echinoderms. To date, species determined in baksteenkalk have never been listed in a systematic way. As a first attempt to fill this gap, a list of taxa which we were able to determine (or discern) in our collections is presented here (Table 2).

The species listed in Table 2 are from the collections of the authors, but for the sake of completeness (which is of course a relative notion) a few rare species known from other collections have also been included.

A



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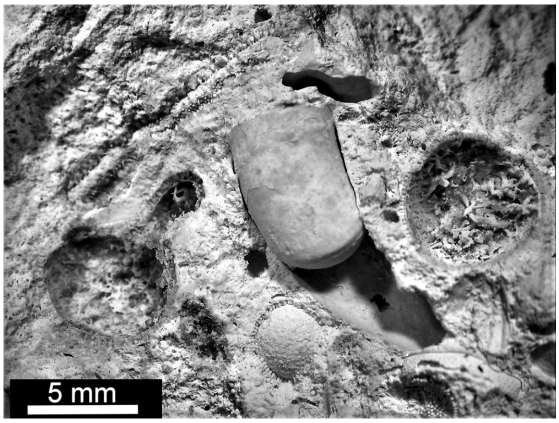

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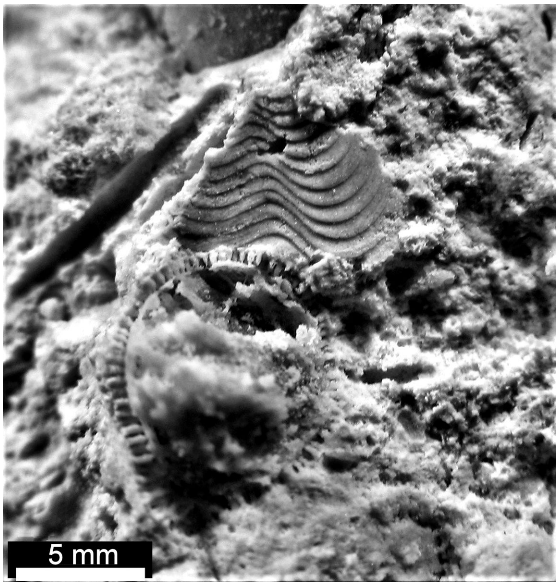

Fig. 10. A, fragment of a boulder showing an assembly of fossils characteristic of type 1. Arrows: A, *Apidium* sp. [‘claviformis’]; H, *Hoeegonites* sp. [‘elongata’]. RGM 1317647, Wilsum. **B**–**D**, details of the boulder depicted in Fig. 10A: B, left and right: two specimens of *Apidium* sp. [‘claviformis’], in the specimen to the right laterals are discernible; top left: *Hoeegonites* sp. [‘elongata’]; centre bottom: *Apidium pygmaeum*; centre: undetermined cephalopod. C, top: hypostome of *Otarozoum peri*; bottom: *Mastopora concava*. D, top: sclerite of a machaeridian, presumably *Plumulites* sp.; bottom: *Apidium pygmaeum*.

Fig. 11. Fragment of a type 1 boulder showing part of the cranidium of *Otarozoum peri* and two specimens of *Solenopora spongioides*. RGM 1317648, Wilsum.

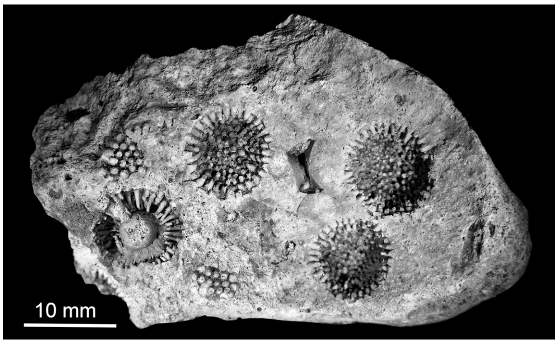

Fig. 12. Natural surface of a fragment of a type 2A boulder showing specimens of *Coelosphaeridium sphaericum* and a transverse section of a gastropod. RGM 1317649, Itterbeck.

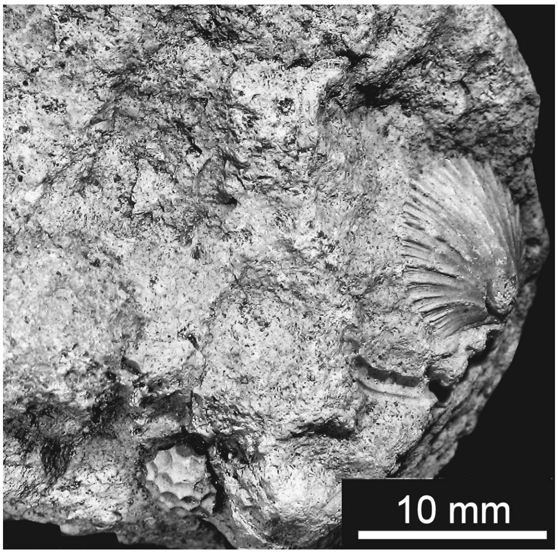

Fig. 13. Natural surface of a fragment of a type 2A boulder. Bottom: a specimen of *Cyclocrinites porosus* showing the membrane under the vanished globella; right: orthid brachiopod, interior mould of ventral valve. RGM 1317650, Wilsum.

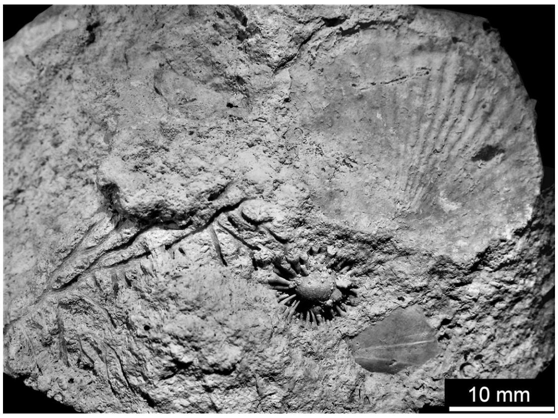

Fig. 14. Natural surface of a type 2A boulder. Left: cast of an undetermined cryptostomate bryozoan; bottom right: *Coelosphaeridium sphaericum* and a sclerite of a machaeridian; top right: *Cyrtonotella* sp., exterior mould of dorsal valve. RGM 1317651, Wielen.

The actual number of species which have left fossil remains in baksteenkalk is certainly much higher than the number of species listed here. This is due to several factors. First, part of the fossils could not be recognized for lack of the necessary expertise on our part. Second, for important groups, like crinoids and bryozoans, determination up to species level is hampered by their state of preservation: crinoids have disintegrated and bryozoans are preserved as casts which do not reveal distinctive details. Third, part of the fossils probably represent new, hitherto undescribed taxa.

Many species have a very low abundance in baksteenkalk. In the list these too have been assigned to a particular type but given the low number of available specimens, it is impossible to be definite about their distribution over the two types.

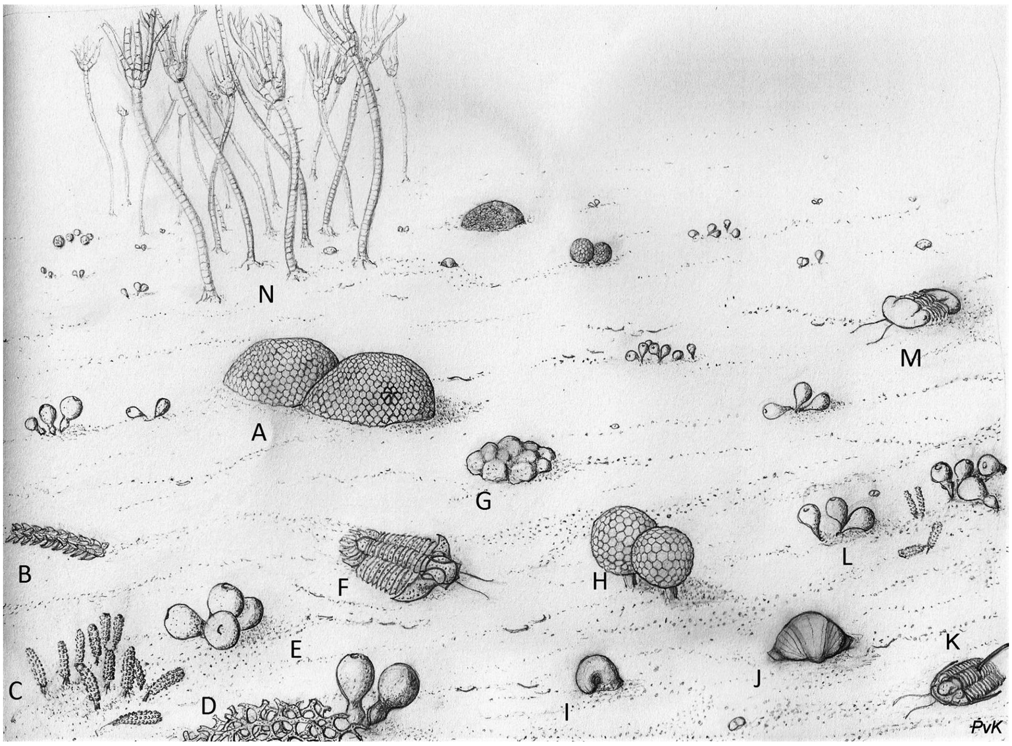

Fig. 15. Impression of the Middle–Late Sandbian marine community as represented by species characteristic of the type 1 fossil assemblage. A, *Mastopora concava*; B, *Plumulites* sp.; C, *Hoeegonites kringla*; D, *Vermiporella fragilis*; E, *Apidium* sp. ['claviformis']; F, *Otarozoum peri*; G, *Solenopora spongioides*; H, *Coelosphaeridium sphaericum*; I, *Cymbularia compressa*; J, *Bilobia* aff. *musca*; K, *Harpidella planifrons*; L, *Apidium pygmaeum*; M, *Illaenus jewensis*; N, crinoids.

Table 2. List of taxa discerned in the collections of the authors (+ rare, ++ uncommon, +++ frequent, ++++ common)

Taxa	Type 1	Type 2
Algae		
Apidium pygmaeum Stolley, 1896	++++	–
Apidium sp. ['claviformis']	+++	–
Coelosphaeridium sphaericum Kjerulf, 1865	++++	++++
Cyclocrinites porosus Stolley, 1896	–	+++
Cyclocrinites cf. *schmidti* Stolley, 1898	–	++
Hoeegonites kringla Nitecki & Spjeldnaes, 1989	+++	–
Hoeegonites sp. A ['elongata']	++	–
Hoeegonites sp. B ['bifurcata']	+	–
Mastopora concava Eichwald, 1840	++++	++++
Solenopora spongioides Dybowski, 1877	+++	+++
Vermiporella fragilis Stolley, 1893	++++	++++
Trilobita		
Achatella kegelensis (Schmidt, 1881)	++	++
Acidaspis sp.	++	++
Apianurus sp.	++	++
Asaphus (*Neoasaphus*) sp.	++	++
Atractocybeloides berneri Krueger, 1991	+++	+++
Atractopyge sp.	++	++
Bolbochasmops emarginatus (Schmidt, 1881)	+	++
Bolbochasmops bucculentus (Sjögren, 1851)	–	+
Chasmops marginatus (Schmidt, 1881)	+++	+++

Continued on the next page

Table 2. *Continued*

Taxa	Type 1	Type 2
Conolichas cf. *triconicus* Dames, 1877	+	–
Cybelella dentata (Esmark, 1833)	+	++
Harpidella planifrons (Eichwald, 1861)	++++	++++
Hemisphaerocoryphe granulata Angelin, 1854	–	+
Hemisphaerocoryphe pseudohemicranium (Nieszkowski, 1859)	–	+++
Illaenus jewensis Holm, 1886	++++	++++
Keilapyge laevigata (Schmidt, 1881)	+	+
Metopolichas squamulosus (Öpik, 1937)	–	+
Nieszkowskia ahtioides Männil, 1958	++	++
Nieszkowskia inermis Kummerow, 1927	+	++
Oculichasmops muticus (Schmidt, 1881)	++	++
Otarozoum peri (Warburg, 1939)	++++	++++
Panarchaeogonus sp.	+	++
Paraceraurus elatifrons (Krause, 1894)	–	++
Platylichas cf. *bottniensis* (Wiman, 1907)	++	++
Platylichas westergardi Kummerow, 1927	++	++
Remopleurides sp.	+	+
Stenopareia ava (Holm, 1886)	+	+
Toxochasmops macrourus (Sjögren, 1851)	–	+
Brachiopoda articulata		
Actinomena sp.	–	+
Astamena cf. *inaequalis* Rõõmusoks, 1989	–	+++
Bilobia aff. *musca* (Öpik, 1930)	+++	–
Clitambonites schmidti (Pahlen, 1877)	+	++
Cyrtonotella kuckersiana (Wysogórski, 1900)	+	++
Dalmanella testudinaria (Dalman, 1828)	+++	+++
Glossorthis? sp.	+	–
Glyptorthis sp.	++	++
Haljalanites anijana (Öpik, 1930)	+	++
Haljalanites assatkini (Alichova, 1951)	–	+
Hesperorthis sp.	+	+
Kurnamena taxilla (Oraspõld, 1956)	–	++
Nicolella sp.	++	+++
Orthis sp.	++	++
Oxoplecia sp.	–	+
Platystrophia chama (Eichwald, 1830)	–	++
Platystrophia dentata (Pander, 1830)	–	++
Platystrophia pogrebovi (Eichwald, 1830)	++	+++
Porambonites baueri (Noetling, 1883)	+	++
Porambonites schmidti (Noetling, 1884)	+	++
Septomena alliku (Oraspõld, 1956)	+	++
Septomena cf. *crypta* (Öpik, 1930)	+	++
Skenidioides? sp.	++	+++
Sowerbyella (*Sowerbyella*) *plana* (Rõõmusoks, 1959)	–	++++
Sowerbyella quinquecostata (McCoy, 1871)	–	++
Brachiopoda inarticulata		
Acanthocrania sp.	–	++
Discina? sp.	+	–
Lingula sp.	++	–
Orbiculoidea sp.	+	+
Orthisocrania depressa (Eichwald, 1840)	+	++
Orthisocrania curvicostae (Huene, 1899)	++	+++
Philhedra glabra Huene, 1899	–	+
Philhedra pustulosa? (Kutorga, 1846)	+	++
Philhedra sp.	++	+++
Pseudopholidops stolleyana (Huene, 1900)	++	+++

Continued on the next page

Table 2. *Continued*

Taxa	Type 1	Type 2
Gastropoda		
Brachytomaria baltica (Verneuil, 1845)	+	+++
Deaecheospira elliptica (Hisinger, 1829)	++	+++
Deaecheospira inflata (Koken, 1896)	–	++
Cyclonema sp.	–	++
Cymbularia compressa Koken & Perner, 1925	+++	++
Cymbularia roemeri Koken & Perner, 1925	–	++
Holopea balticus Koken, 1897	+	++
Mestoronema bipatellare (Koken & Perner, 1925)	–	+
Mestoronema marginalis (Eichwald, 1840)	+	++
Megalomphala crassiuscula (Koken, 1896)	++	++
Megalomphala contorta (Eichwald, 1856)	+	+++
Murchisonia sp.	+++	++
Salpingostoma sp.	–	++
Pachystrophia devexa (Eichwald, 1859)	–	+
Proturritella sp.	–	++
Straparollina? *norvegica* (Koken in Koken & Perner, 1925)	+	++
Subulites amphora (Eichwald, 1854)	–	++
Temnodiscus cf. *accola* Koken, 1925	+	–
Tropidodiscus planissimus (Eichwald, 1840)	+	++
Worthenia sp.	++	+++
Cephalopoda		
Adnatoceras sp.	–	+
Beloitoceras sp.	–	+
Endoceras sp.	–	++
Ephippiorthoceras sp.	+	++
Orthoceras sp.	–	++
Protocycloceras sp.	–	++
Strandoceras sp.	–	+
Pelecypoda		
Ctenodonta sp.	+++	+++
Cyrtodontula sp.	++	++
Deceptrix sp.	–	+
Rostroconcha		
Ischyrinia sp.	++	+++
Pinnocaris? sp.	+	+
Tolmachovia sp.	+	–
Monoplacophora		
Archinacella cf. *rostrata* (Eichwald, 1859)	+	+
Bryozoa		
Ceramopora sp.	++	++
Chasmatopora sp.	++	+++
Corynotrypa sp.	++	++
Diplotrypa petropolitana Nicholson, 1879	+++	+++
Graptodictya sp.	–	++
Hallopora sp.	++	+++
Lichenalia concentrica Hall, 1852	+	+++
Monotrypa jewensis Bassler, 1911	++++	++++
Nematopora sp.	++	+++
Pachydictya cyclostomoides Eichwald, 1855	++	++

Continued on the next page

Table 2. *Continued*

Taxa	Type 1	Type 2
Echinodermata		
Bothriocidaris pahleni Schmidt, 1874	+	+
Crinoidea (undifferentiated)	+++	++++
Cystoblastus sp.	–	+
Cheirocrinus sp.	–	+
Cyclocystoidea sp.	+	–
Echinosphaerites sp.	+	+
Hemicosmites extraneus Eichwald, 1840	–	++
Protocrinites oviformis Eichwald, 1840	–	+
Receptaculitida		
Ischadites sp.	–	+
Parareceptaculites biparietus? Bartholomäus, Böhmecke & Lange, 1999	–	+
Porifera		
Undetermined brachiospongioid sponge	–	+
Haljalaspongia inaudita Botting & Rhebergen, 2011	+	–
Hindia sphaeroidalis Duncan, 1879	–	+
Hexactinellid spicules	++	++
Monaxonoid spicules (‘root-tuft’)	+++	++++
Undetermined chiastoclonellid sponge	–	+
Hyolitha		
Hyolithida (undifferentiated)	–	++
Orthothecida (undifferentiated)	++	+++
Machaeridia		
Deltacoleus sp.	+	–
Lepidocoleus sp.	+	–
Mojczalepas sp.	+	–
Plumulites sp.	+++	++
Conularia		
Conularia orthocerathophila (Roemer, 1880)	++	++
Conularia sp.	++	++
Ostracoda (undifferentiated)	++++	++++
Graptolithina		
Dendrograptus sp.	++	++
Melanostrophus fokini Öpik, 1930	+	+
Pseudoclimacograptus sp.	+	–
Varia		
Cornulitidae (undifferentiated)	+	+++
Tentaculitidae (undifferentiated)	+	++
Ancientia sp.	+++	+++
Tomaculum problematicum Groom, 1902	+	+++
Ichnofossils		
Arachnostega gastrochaenae Bertling, 1992	+	+++
Chondrites von Sternberg, 1833	+++	+++
Conichnus conicus Männil, 1966	+	–

INTERPRETATION

Palaeoecology

The fossil assemblages are dominated by calcareous algae, bryozoans, crinoids, brachiopods and gastropods. These organisms represent benthic biotic communities. The prominence of calcareous algae implies that the seafloor was in the euphotic zone. The lithological differences between types 1, 2 and 3 of baksteenkalk reflect slightly different environmental conditions.

Type 1

This type formed from a seafloor composed of fine-grained bioclastic calcareous mud. The unevenly shaped, unstratified blocks, with small fossils either being concentrated in nests or disorderly dispersed over the matrix, indicate a repeated shift of sediment. Fossils consist of seafloor debris because trilobites, crinoids and machaeridia are nearly always disintegrated. *Post mortem* overgrowth of fossils and marks of etching and burrowing organisms, which are abundant in type 2, are less frequent in type 1. Trace fossils (e.g., *Chondrites*) and other signs of bioturbation are common but do not occur as strongly concentrated as in type 2. All this suggests that high-energy conditions, with periodical minor mud flows burying the seafloor, prevailed (Botting & Rhebergen 2011). There are no signs of winnowing. Interesting are occasional finds of *Lingula*; these suggest proximity of the tidal or littoral zone, where this inarticulate brachiopod is at home.

Type 2

In the flat slabs of type 2A fossils tend to be concentrated in thin layers or lenses. Often large fossils are clustered. Overall, slabs consist of bioclasts which are more coarse-grained than in type 1. These phenomena imply that the seafloor was subject to winnowing. Although cryptostomate bryozoans, crinoids and large calcareous algae like *Mastopora concava* are never preserved in full, sizable fragments of these organisms may be found. Also shells of gastropods, brachiopods and occasionally even trilobites may occur undamaged. This renders it likely that moderate energy conditions prevailed. *Post mortem* phenomena in type 2 indicate that calcareous organic remains rested for a prolonged period of time on the seafloor (or inside the upper, well oxygenated part of it) before being covered by sediment, otherwise it would have been impossible for other organisms to leave their marks on them. The sediment was constantly reworked and churned up by burrowing organisms; this is indicated by vague spots, filled burrows and lack of stratification (Van Diggelen 1983). The high degree of bioturbation in conjunction with the prolonged stay of organic remains on the seafloor indicates a low sedimentation rate. The flat bottom of slabs might be indicative of an interruption in depositional patterns.

Such discontinuity surfaces are especially pronounced in hardgrounds (type 2C). Hardgrounds may have been attachment surfaces for trepostomate bryozoans and algae (Vinn & Toom 2015). It is possible that the layer of fossil remains in certain hardgrounds results from winnowing. The coquinites (type 2B) are genuine storm depositions. The obvious variation in energy conditions which is manifested in type 2 and its subtypes implies that the seafloor lay under the fair-weather wave base and above the storm wave base.

Type 3

Blocks of this type are penetrated by evenly distributed, hollow burrows. Although burrows may run in all directions, a preference for one orientation can be observed, suggesting bedding. In specimen A of Fig. 6 one straight side is actually covered by a thin crust without burrows. The fact that burrows are intact and some burrows can be seen to penetrate the entire bed perpendicular to the bedding plane implies that these boulders represent some kind of 'snapshot'. Sudden deposition of sediment may have abruptly stopped the activity of burrowing organisms.

Biostratigraphic implications

The fossil fauna and flora of baksteenkalk as a whole firmly points to the Haljala Stage (Idavere C_{III}–Jõhvi D_I). Our collections do not contain species whose latest occurrence recorded is C_I or C_{II}. The upper boundary of baksteenkalk is more difficult to determine because the evidence for the presence of D_{II} is debatable.

Type 2 contains many species which in Estonia have not been recorded for earlier stages than D_I, like *Cyclocrinites porosus* (Rõõmusoks 1970; Kõrts et al. 1990), *Brachytomaria baltica*, *Mestoronema marginalis*, *Megalomphala contorta*, *Achatella kegelensis*, *Nieszkowskia ahtioides*, *Protocrinites oviformis*, *Conularia* sp., *Hyolithes* sp., *Bothriocidaris pahleni* (D_Ia; Jaanusson 1945). According to Rõõmusoks, *Bolbochasmops emarginatus* occurs only from C_{III}b onwards. *Hemisphaerocoryphe pseudohemicranium* has not been recorded from stages later than Lower Jõhvi (for references, see Krueger 1994: 480). The same applies to *Nieszkowskia ahtioides* (Männil 1958: 184, 185; Krueger 1995: 670; cf. also Dolgov & Meidla 2011: 625). Overall, the fossil assemblage is typical of D_I.

Two or three species of trilobites, only a few specimens of which have been found in type 2, seem to indicate the Keila Stage: *Bolbochasmops bucculentus* type 1 (D_{II}a, Krueger 2013: 33, but D_I according to Jaanusson 1945: 221, 222), *Hemisphaerocoryphe granulatus* (D_{II}bp, Krueger 1994: 483, 484; cf. Dolgov & Meidla 2011: 628); *Toxochasmops macrourus* (D_{II}b, Krueger 2013: 41). The possibility should be considered that these rare specimens are early (possibly, the earliest) representatives of the species involved. In that instance, their stratigraphical range would have to be brought down to (late) D_I.

Type 1 is characterized by species of *Apidium* and *Hoeegonites*, but as these algae are not known from Estonia and Sweden, their occurrence cannot be correlated with regional stratigraphy. The trilobites observed together with *Apidium pygmaeum* provide diverging dates: *Conolichas triconicus*, C_{III}a (Rõõmusoks 1970: 220); *Nieszkowskia inermis*, latest C_{III}–earliest D_I (Krueger 1995: 670); *Nieszkowskia ahtioides*, early D_I; *Achatella kegelensis*, D_I (Rõõmusoks 1970: 247); *Atractocybeloides berneri*, D_I (Krueger 1991: 225); *Chasmops marginatus*, *Oculichasmops muticus* and *Illaenus jewensis*, C_{III}–D_{II} (Rõõmusoks 1970: 247); *Otarozoum peri*, C_{III} (Rõõmusoks 1970: 220). It is to be noted that allegedly 'late' elements, like the trilobite species assigned by Krueger to D_{II}, are lacking in type 1. Overall, the fossil assemblage of type 1 indicates a stratigraphical range falling within the Haljala Stage, but not going beyond C_{III}–early D_I.

The differences in lithology and ecology noted above imply that the various types of baksteenkalk originated in slightly different environments on the open shelf (see above). Here the question presents itself whether the differences between types 1 and 2 are to be understood in terms of different environments only or whether they also reflect a chronostratigraphical difference.

Many species found in baksteenkalk are known from the Idavere and Jõhvi stages in Estonia and their fauna and flora supply the best reference material available for establishing the chronostratigraphical range of baksteenkalk. Jaanusson (1995) noted that in Estonia the boundary between these stages does not coincide with a distinct change in macro- and microfauna and moreover is situated within a lithologically uniform sequence. For that reason, he erected the Haljala Stage encompassing both the Idavere (C_{III}) and Jõhvi (D_I) stages. A substantial part of the Idavere Stage and the lower part of the Jõhvi Stage, the so-called Aluvere Zone (D_Ia), belongs to the same 'mittelordovizische Grundfauna' (Jaanusson 1945: 221, 222). Changes in the faunal composition between these stages are moreover continuous (Hints 1997). This does not alter the fact that many species in D_I are 'new' in comparison with C_{III}. Rõõmusoks (1970) listed 206 species for D_I, of which 84 are not known from C_{III}.

This picture of gradual change within the framework of overall continuity also applies to baksteenkalk. As shown by the fauna list, the large majority of species is recorded for both type 1 and type 2. In rare instances, blocks of baksteenkalk hold a fossil assemblage combining species which are otherwise exclusive to one type. Thus, one block holds a specimen of *Apidium pygmaeum* alongside *Hemisphaerocoryphe pseudohemicranium*. Unusual combinations like these indicate that the transition in flora and fauna between types 1 and 2 occurred gradually.

Thus, against the background of the Estonian biostratigraphy in the Viruan, it may not seem inappropriate to differentiate chronologically between type 1 and type 2. As it is, type 1 appears to be slightly older than type 2. The fossil assemblage suggests a C_{III}–D_Ia date for type 1 and, overall, a D_I date for type 2.

Remarks on diagenesis

Various aspects of the diagenetic processes that gave shape to baksteenkalk are poorly understood. This is in particular true of the mechanisms of silicification and leaching. The complexity of these processes is aptly demonstrated by the variety of forms in which fossils, in particular the algae *Apidium*, *Cyclocrinites* and *Coelosphaeridium*, have been preserved (Van Keulen 2011, 2014). Specimens may show exceptional details in anatomy defying a simple explanation in terms of linear silicification and leaching processes.

All the same, the mode of preservation of most algae is such that it enables us to reconstruct the main stages of the diagenetic process. These stages are best exemplified by *Coelosphaeridium sphaericum*. In comparison with other species, specimens of this calcareous alga show a rather uniform manner of preservation and are common to both type 1 and type 2.

Coelosphaeridium sphaericum consists of a central axis with a bulbous end, bearing whorls of laterals which expand distally to form the surface of a sphaerical thallus (Fig. 12, specimen on the left). The central axis and, probably, the laterals were filled with soft organic matter (cytoplasm). At a late stage of growth, the void between the central axis and the laterals became calcified (Spjeldnaes & Nitecki 1990; Rhebergen 1994). All specimens preserved as fossils were originally calcified.

Specimens in baksteenkalk are mostly preserved as casts of the cavities that originally contained organic matter. Thus, an initial stage in the diagenetic process involves the decomposition of soft organic parts of dead organisms (1). The cavities that resulted were filled by fine-grained sediment (2). In our specimens the intralateral calcified parts have all been dissolved; roughly coeval specimens from impure limestones of the Oslo region in

Norway (Furuberg Formation) show the same mode of preservation. As a consequence, the surrounding sediment must have solidified as limestone (3) before calcareous skeletal parts (aragonitic: brachiopods, hyolitha; calcitic: trilobites, bryozoans; both: algae, molluscs) dissolved (4). Otherwise the cavities mimicking the shape of the skeletal parts would not have survived. In a subsequent stage, the limestone became silicified (5). A mechanism of transport and accumulation of silica at low temperatures has been proposed by Landmesser (1995). The wide variety of modes of silicification of baksteenkalk fossils, in particular algae, points to a complicated process. We confine ourselves to stating that in the hard, unweathered cores of boulders and hardgrounds all specimens of *Coelosphaeridium sphaericum* are massively silicified, whereas in the weathered, soft and porous boulders they are invariably preserved as casts of fine-grained sediment due to the secondary dissolution of the intralateral silicifications (Figs 8, 12, 14). This indicates that boulders were subjected to leaching (6).

Geochemical analysis might help unravel the intricate mechanisms of the silicification and leaching processes during the formation of baksteenkalk. It is to be hoped that this analysis will be carried out in future.

Provenance and palaeogeography

In Baltoscandinavia, Ordovician bedrock is mainly preserved in intracratonic basins: Vänern, Vättern, the Southern Bothnian basin and the Central Baltic basin (e.g. Van Balen 1996). Part of the Ordovician bedrock is well exposed on the Swedish mainland, on Öland, Estonia and in the area around St Petersburg. Another part lies buried below the seafloor of the Baltic and the Bothnian Sea, and these Ordovician beds are only known from drill cores. To date, no silicified sediments with fossil assemblages akin to those of baksteenkalk have been reported from the intracratonic basins.

It is generally assumed that Ordovician sediments originally covered a much larger area. Large stretches of Ordovician deposits have vanished as a result of prolonged fluvial erosion by the Eridanos river system and by subsequent glacial erosion caused by the Pleistocene glaciations (Zeck et al. 1988). Thus, the slightly tilting Ordovician beds along the northern and northwestern edge of the Central Baltic Basin probably extended further northwards. There is even evidence that Middle Ordovician beds extended well into Northwest Finland (Uutela 1998). It is possible that baksteenkalk originates from deposits which nowadays have completely disappeared due to erosion.

Information about the probable source area of baksteenkalk may be derived from the distribution of erratics (geschiebes) in Baltica. Erratic boulders of massively silicified limestone containing remains of dasyclad algae and bryozoans are known from Gotland. The algae comprise *Coelosphaeridium sphaericum*, *Mastopora concava* and, rarely, *Apidium* sp., species which are common in baksteenkalk (Fig. 16). The boulders closely resemble hardgrounds of baksteenkalk (type 2C; Fig. 17).

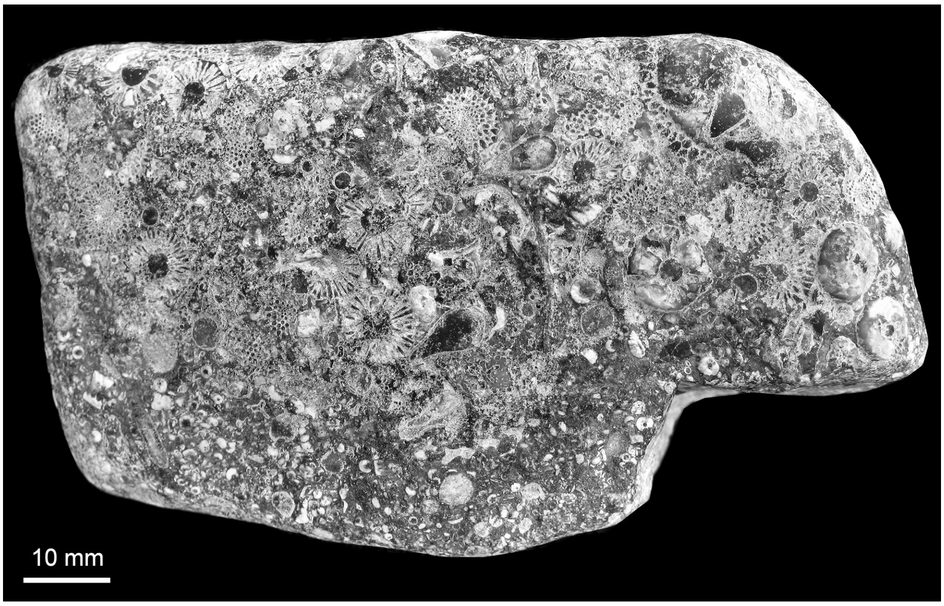

Fig. 16. Boulder of silicified limestone showing transverse sections of *Coelosphaeridium sphaericum*, *Apidium* sp. and *Mastopora concava*. PMU 31615, Tofta (beach), Gotland.

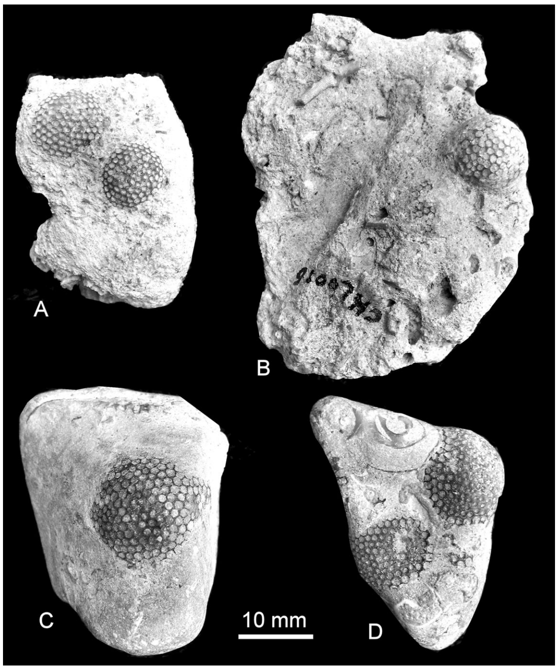

Fig. 17. **A**, **B**, fragments of hardgrounds (type 2C) showing massively silicified specimens of *Coelosphaeridium sphaericum*: A, RGM 1317652, Itterbeck; B, RGM 1317653, Itterbeck. **C**, **D**, similar fragments from Björkume, Gotland: C, PMU 31616; D, PMU 31617.

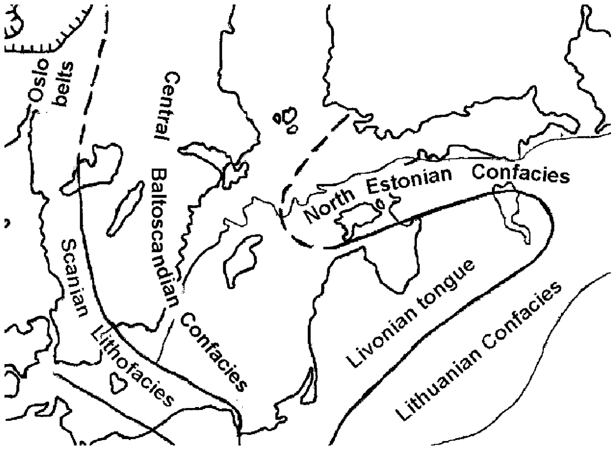

Fig. 18. Ordovician confacies belts in Baltoscandia. After Jaanusson (1995).

Although the exact relationship of boulders to baksteenkalk is difficult to establish, there is an obvious affinity. As the direction of the ice flows by which they were transported was south to southwest, both the Southern Bothnian and the Central Baltic Basin come into consideration as source areas. These boulders may be identical with the numerous Backsteinkalkgeschiebe of the Baltic type which Schallreuter (1989) reported from Gotland.

Another clue as to the probable provenance of baksteenkalk is provided by lithology, and in particular by the fossil assemblage. Outcrops and borings led Männil (1966) and Jaanusson (1976) to distinguish various lithofacies, arranged in belts, in the sediments deposited in the epicontinental sea of Baltica. These 'confacies belts', a term coined by Jaanusson, are each 'defined by a combination of litho- and biofacial characteristics' and have 'a fairly stable relative position within the depositional area' (Jaanusson 1976: 308) (Fig. 18).

The Central Baltoscandian Confacies Belt has a varied lithology and was in general deposited in deeper water than the eastern confacies belts (Jaanusson 1976: 309). The lithology of the North Estonian Confacies Belt is more uniformly characterized by shallow-water carbonate and fine-clastic sediments (Nestor & Einasto 1997). New data from borings in eastern Sweden caused Jaanusson to reduce the area covered by this belt by moving its western boundary eastwards (Jaanusson 1995). Given the lithological and faunal characters of this confacies belt, it constitutes a probable source area of baksteenkalk.

The fossil assemblage of baksteenkalk appears to have a strong affinity with the Haljala Stage in Estonia, without completely coinciding with it. There is no such strong affinity with fossils from coeval formations in Sweden. With the exception of *Apidium* and *Hoeegonites*, algae typical of baksteenkalk (*Coelosphaeridium sphaericum*, *Mastopora concava*, *Cyclocrinites porosus*) have been recorded from Estonia (Kõrts et al. 1990). Among the gastropods and brachiopods in baksteenkalk, many genera and species have been reported from the Haljala Stage of Estonia, such as *Brachytomaria*, *Megalomphala*, *Salpingostoma*, *Temnodiscus*, *Cymbularia*, *Mestoronema*, *Deaecheospira*, *Subulites* (Rõõmusoks 1970; Isakar 1997) and *Astamena inaequalis*, *Bilobia* aff. *musca*, *Cyrtonotella kuckersiana*, *Haljalanites anijana*, *H. assatkini*, *Kurnamena taxilla*, *Orthisocrania depressa*, *O. curvicostae*, *Philhedra* sp., *Platystrophia chama*, *P. pogrebovi*, *Porambonites schmidti*, *P. baueri*, *Septomena alliku*, *Sowerbyella plana* (Rõõmusoks 2004). The trilobite fauna of baksteenkalk, too, shares several species with the Idavere and Jõhvi stages in Estonia (Rõõmusoks 1970; Neben & Krueger 1973), such as *Chasmops marginatus*, *Bolbochasmops emarginatus*, *Oculichasmops muticus*, *Otarozoum peri*, *Illaenus jewensis*, *Atractopyge dentata*, *Hemisphaerocoryphe pseudohemicranium*, *Nieszkowskia ahtioides*, *Achatella kegelensis*, *Asaphus* (*Neoasaphus*) sp. It is also to be noted that the echinoid *Bothryocidaris pahleni*, which rarely occurs in baksteenkalk, is known from Estonia but not from Sweden (Schallreuter 1989).

An important clue for an East Baltic origin of baksteenkalk is provided by the ostracod fauna. Although we have not carried out a systematic inventory of the ostracods occurring in baksteenkalk, we were able to determine *Tetrada memorabilis*, *Bolbina ornata*, *B. minor*, *Oepikium tenerum*, *Kiesowia frigida*, *Pentagona pentagona*. These species are characteristic of one particular ostracod fauna among the seven faunas Schallreuter (1970) distinguished in glacial Backsteinkalk. This fauna, type 1B13, contains several species which are only known from Estonia and which are restricted to the C_{III} and D_I stages. Schallreuter also noted that the ostracod *Steusloffia costata*, which in Sweden belongs to the common ostracods of D_I sediments, is completely lacking in 1B13. All this led him to locate the origin of the 1B13 Backsteinkalk in the Baltic in the vicinity of Estonia (Schallreuter 1970, 1993). In baksteenkalk, species characteristic of 1B13 are recorded from both type 1 and type 2, whereas *Steusloffia costata* has not been observed in either type.

The nature of the relationship between the East Baltic 1B13-type Backsteinkalk and baksteenkalk can only be established by a full comparison of their fossil assemblages. This lies beyond the scope of the present study. Nevertheless, the character of the ostracod fauna lends forceful support to the view that baksteenkalk originates from the Baltic region to the west of Estonia.

Conditions in this region were probably similar to those described by Nestor & Einasto (1997) for the west of Estonia. During the Haljala and Keila stages, bioclastic calcareous muds were deposited on the open shelf. The production of skeletal material, which was the main source of the carbonate, was slow. Accordingly, the rate of sediment accumulation in the Baltic epicontinental basin was extremely low. Estimates vary from 1 to 3 mm per 1000 years. In line with these figures, the beds represented by our C_{III}–D_I baksteenkalk cannot have exceeded 6 m thickness, since the Haljala Stage lasted ca 2 Ma. In Estonia, however, the thickness of the Haljala Stage varies from 10 to 20 m (Jaanusson 1945; Hints 1997), which seems to indicate a somewhat higher rate of sedimentation.

Several interbeds of volcanic ash (metabentonites) have been reported from the Haljala and Keila stages throughout the Baltic. Drill cores in the west of Estonia (including Saaremaa and Hiiumaa) have revealed a thickness of 0.4–0.6 m for the Kinnekulle bentonite (K-bentonite) lying on top of the Haljala beds (Huff et al. 1992; Bergström et al. 1995). The Jõhvi and Idavere successions of these drill cores were found to contain other bentonite beds of varying thicknesses. Backsteinkalk from Sweden and the Baltic Sea is thought to have formed by the silicification of limestone under bentonite beds (Neben & Krueger 1973; Schallreuter 2005). A similar process might be assumed for baksteenkalk.

In Estonia, coeval carbonates under bentonite beds do not exhibit the same measure of silicification. Jaanusson (1945) reported silicified fossils from the Idavere and Jõhvi beds. Yet continuous beds of silicified Ordovician sediments do not seem to occur in Estonia. Towards the east of Estonia, bentonite beds gradually decrease in thickness, but this alone does not sufficiently explain the difference between the largely unsilicified limestone beds in Estonia and the completely silicified Backsteinkalk/baksteenkalk. Apparently, variations in environmental conditions played a part as well. Recently Bartholomäus et al. (2014) have pointed to the occurrence of 'cauliflower cherts', i.e., siliceous concretions, in Haljala limestone from Põõsaspea Cliff. They interpret these cherts as diagenetically silicified anhydritic nodules which originated in Sebkha-like conditions. According to Landmesser (1995), locally high $Si(OH)_4$ concentrations may form by evaporation. Conditions may have been favourable for the formation of an evaporitic environment during the Keila age, when the sea level dropped (Nestor & Einasto 1997). As the sea retreated to the south, areas to the north and northwest of Estonia were uncovered and possibly became evaporitic. Regional differences with respect to the duration of the regression phase were probably of influence on the silicification process. Yet, baksteenkalk itself does not yield evidence that it formed in Sebkha-like conditions. All we can say is that environmental conditions in the area where baksteenkalk originated seem to have been more favourable for the silicification of limestones than in the north of Estonia.

Besides bentonite, biogenic sources of silica have been considered. Jaanusson (1945) supposed a relationship between the silicified fossils from the Idavere and Jõhvi beds and the distribution of the so-called 'Kieselspongienfazies'. Bartholomäus et al. (2014) reckon with the possibility that the silicification process derived most SiO_2 from siliceous spicules of sponges, in particular of hexactinellids. However, it seems improbable that siliceous spiculae could have supplied the amount of SiO_2 required for the silicification of such a large volume of limestone. Genuine beds of spiculite have not been observed in the Middle and Upper Ordovician of Baltica. In baksteenkalk and other erratic Ordovician silicifications, spiculae, mostly monaxons and hexactines, are common but never occur in massive quantities.

During the Ordovician, the Baltica continent drifted from southern high latitudes to the equator. In Haljala and Keila times, the epicontinental cratonic sea was still in the temperate climatic zone (at ca 35° S). Tabulates and stromatoporoids, which are bound to high water temperatures, had not yet made their appearance. As a consequence, these groups are not represented in baksteenkalk.

Comparison with Backsteinkalk fossils

Fossils from eastern German Backsteinkalk have been depicted by Kiesow (1893), Krause (1895), Kummerow (1937), Hucke (1967), Schallreuter (1970, 1984, 1985, 1989, 1993, 2005), Hergarten (1988), Rudolph (1997), Jänicke (2000), Bilz (2001), Schulz (2003), Rudolph et al. (2010) and in particular by Neben & Krueger (1971, 1973). Krueger moreover published various studies of trilobites in both Backsteinkalk and baksteenkalk in which he mentioned accompanying flora and fauna elements (1991, 1992, 1994, 1995, 2013). Yet, these publications, even the extensive overviews by Neben & Krueger (1971, 1973), only deal with a selection of Backsteinkalk fossils and leave important groups such as bryozoans and machaeridians out of consideration. To date, a comprehensive list of species determined in Backsteinkalk is wanting. Nor have attempts been made to design a typology of Backsteinkalk which takes both the lithological and palaeontological aspects into account. Based on ostracod assemblages, Schallreuter (1970) distinguished seven types of glacial Backsteinkalk, but he did not list the accompanying fauna and flora. Thus, the question whether the affinity of baksteenkalk with type 1B13 extends to other groups than ostracods cannot be answered at present.

Given this state of affairs, a sophisticated palaeontological comparison between the various types of baksteenkalk and Backsteinkalk is impossible. Yet, on the basis of the information that can be gathered from the above-mentioned publications and from personal communications, it is possible to make the following observations.

The majority of the species determined in Backsteinkalk have also been recognized in baksteenkalk. The species found in Backsteinkalk but not in baksteenkalk include *Allolichas longispinus*, *Chasmops wrangeli*, *Sinuites* sp. Conversely, the fauna and flora of baksteenkalk may comprise species which do not occur in Backsteinkalk. Although the absence of evidence is no evidence of absence, it may be telling that *Hoeegonites kringla*, *Solenopora spongioides* and *Vermiporella fragilis*, species which are frequent in type 1 baksteenkalk (cf. Rhebergen 1997), have never been reported from Backsteinkalk.

Several taxa are known to have a different abundance in Backsteinkalk and baksteenkalk. The trilobites *Keilapyge laevigata* and species of *Lonchodomas* and *Neoasaphus* are more frequent in the former than in the latter (Rhebergen 2001). Conversely, *Atractopyge berneri* (Rhebergen 2001) and *Nieszkowskia ahtioides* (Krueger 1995) are rather frequent in baksteenkalk but rare in Backsteinkalk. The same seems to apply to the brachiopod *Platystrophia chama* (H.-H. Krueger pers. comm. 1995). As to the algae, *Apidium pygmaeum* is depicted in Neben & Krueger (1979: 44), but the fact that it is mistaken for *Cyclocrinus* (= *Cyclocrinites*) strongly suggests that this alga, which is ubiquitous in type 1 baksteenkalk, is not common in Backsteinkalk. This raises the question of whether *Apidium pygmaeum* is tied to the Baltic types of Backsteinkalk, which according to Schallreuter (1984) are rare west of the Oder.

Questions like these can only be answered on the basis of a typology of Backsteinkalk and a systematic inventory of its fossils. It is to be hoped that these will be carried out in future.

Comparison with Lavender-blue Hornstein

Another group of silicified erratics comprises boulders of Lavender-blue Hornstein (LBH), as mentioned in the Introduction. They fall into two different components, one of Sandbian age, the other of Katian (Pirgu to Porkuni) age. The Sandbian component ranges from the Jõhvi Stage to the Keila Stage. Van Keulen et al. (2012) described several aspects of LBH, such as typology, fossil assemblage, distribution in Europe and provenance. This study also includes a brief comparison between Sandbian LBH and baksteenkalk erratics. The results are not repeated here, but two aspects may be worthwhile mentioning.

The first aspect concerns a marked difference in the composition of the algal flora and the fauna of sponges. In coeval erratics of LBH, *Apidium pygmaeum* is absent, whereas *Cyclocrinites* is represented by more species than in baksteenkalk. Conversely, several genera of astylospongiid sponges which are frequent in LBH of Sandbian age, such as *Astylospongia*, *Carpospongia* and *Caryospongia*, are not found in baksteenkalk. Astylospongiid species characteristic of the ‘blue’ Lausitz-Sylt sponge association sensu Rhebergen & von Hacht (2000) occur in situ in the Haljala beds of the St Petersburg region and Keila beds of the Ristna Klint in Northwest Estonia. The former location has yielded *Carpospongia pogrebowi*, *C. conwentzi* and *C. roemeri*, the latter *Syltrochos syltensis* (Rhebergen 2009) and *Carpospongia castanea* (Krueger 2003). Also in other respects, the fossil assemblage of the D_{II}a strata of the Ristna Klint bears resemblance to that of erratic LBH of Sandbian age (Krueger 2003).

The second aspect concerns the geographical distribution of the Sandbian LBH erratics. The majority derive from Miocene and Pliocene fluvial deposits of the Eridanos. Lavender-blue Hornstein erratics are not known from Gotland and the mainland of Sweden. As a consequence, their provenance is likely to differ from that of baksteenkalk and Backsteinkalk. Considering the similarities between the 'blue' erratic sponges and the coeval sponge assemblages in the St. Petersburg area and Ristna Klint, the Haljala/Keila LBH erratics may originate from strata which during the Neogene have been subjected to massive erosion by a tributary of the Eridanos, the Pra-Neva (Suuroja 2007).

Acknowledgements. We are grateful to the following collectors for donating us some of the specimens of baksteenkalk depicted in this paper: Norbert Huuskes, Henri Jansen, Jannie Jonkman (†), Peter and Karin de Vries. The last mentioned collectors are also thanked for their willingness to hand over PMU 31615-31617 to the Museum of Evolution, Uppsala (Sweden). We are much indebted to Axel Munnecke (Friedrich-Alexander University Erlangen-Nürnberg) and an anonymous reviewer for providing useful comments. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

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Sandby (Ordoviitsium) *Baksteen*-lubjakivi tüpoloogia ja fossiilikooslus: Balti päritoluga ränistunud lubjakivi Kirde-Hollandist ning Saksamaalt

Percy van Keulen ja Freek Rhebergen

On kirjeldatud *Baksteen*-lubkjakivi (*Baksteenkalk*), Hollandi idaosas leiduvat Hilis-Sandby vanusega karbonaatset bioklastilist rändkivi. Seniajani on paleontoloogid *Baksteen*-lubjakivile vähe tähelepanu pööranud, mis on kahetsusväärne kahel põhjusel. Esiteks sisaldab *Baksteen*-lubjakivi rikkalikku fossiilset floorat ja faunat, millest mitmed liigid on teistes samavanuselistes kivimites haruldased. Teiseks on tänu keerukale ränistumisprotsessile fossiilid, eriti vetikad, säilinud ainulaadsete anatoomiliste detailidega. Käesoleva töö üheks eesmärgiks ongi äratada professionaalsete paleontoloogide, eriti Eesti uurijate huvi *Baksteen*-lubjakivi vastu. *Baksteen*-lubjakivi esindab lähistroopilise epikontinentaalse madalmere keskkonda, rändkivide levik ja sisalduvad fossiilid viitavad päritolule Põhja-Eesti konfaatsiesest, arvatavasti Lääne-Eestist. Tõenäoliseks räniallikaks olid Ülem-Ordoviitsiumi bentoniidikihid. Artiklis on võrreldud *Baksteen*-lubjakivi kahe teise Balti päritolu Sandby-vanuse ränistunud karbonaatse ränikiviga: Saksa *Backstein*-lubjakivi ja lavendlisinise sarvkiviga (*Lavender-blue Hornstein*).