The trace fossil *Zoophycos* from the Silurian of Estonia

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Abstract. Trace fossils of the ichnogenus *Zoophycos* have been described for the first time from the Silurian of Baltica. They occur in Llandovery pure limestones of middle Estonia and in Ludfordian argillaceous limestones and early Pridoli crinoid grainstones of western Estonia (Saaremaa). The occurrence of *Zoophycos* in the Silurian of Estonia was not restricted to a particular facies, though all finds come from shallow-water sediments. *Zoophycos* had a wide geographic distribution in the Silurian.

Key words: trace fossils, burrows, *Zoophycos*, carbonate rocks, Ordovician, Silurian.

INTRODUCTION

Trace fossils are an important tool for palaeoenvironmental reconstructions (Seilacher 2007). They are relatively poorly known in the Silurian of Baltica, especially the Estonian and eastern Baltic ones (Raukas & Teedumäe 1997). Recently, several hard substrate ichnofossils, such as *Trypanites* and *Osprioneides* (Vinn & Wilson 2010) and bioclaustrations were described from the Silurian of Estonia (Vinn et al. 2014). However, soft substrate trace fossils, such as *Skolithos* and *Cruziana*, have only seldom been described from the Silurian of Estonia (Kaljo 1970; Vinn & Wilson 2013; Vinn 2014).

The earliest *Zoophycos* Massalongo, 1855 occurs in the Lower Cambrian strata of the lower member of the Wood Canyon Formation in southeastern California (Sappenfield et al. 2012). *Zoophycos* is a helical spreite that marks successive, former positions of the burrow (Häntzschel 1975; Olivero 2007; Sappenfield et al. 2012). The lamellae are often composed of secondary lamellae. *Zoophycos* may be present either as simple lobes or ornate spiral structures, which are enclosed by a marginal burrow (Bromley 1991; Seilacher 2007; Sappenfield et al. 2012). The marginal burrow may not always exist or be preserved (Sappenfield et al. 2012). *Zoophycos* constitutes a feeding trace of a worm-like organism (Seilacher 2007). It has often been associated with certain water depth and facies conditions (Osgood & Szmuc 1972). It gives the name to the *Zoophycos* ichnofacies. In the Palaeozoic it is usually found in shallow-water environments, but from the Mesozoic it shifted almost entirely to deep-sea sediments (Seilacher 2007).

The aims of this paper are (1) to describe *Zoophycos* traces for the first time from the Silurian of Baltica, (2) to discuss the stratigraphic and environmental distribution of the traces and (3) to discuss the palaeogeographic distribution of the traces.

GEOLOGICAL BACKGROUND AND LOCALITY

During the Silurian, the Baltica palaeocontinent was located in equatorial latitudes and continued its journey northwards (Melchin et al. 2004). The western part of modern Estonia was covered by the shallow epicontinental Baltic Basin (Fig. 1). The tropical Baltic Basin was characterized by diverse biota and environments. Organic buildups were common, especially coral-stromatoporoid reefs (Raukas & Teedumäe 1997).

Nestor & Einasto (1977) described the palaeoenvironments of the Baltic Basin in detail. They distinguished the following facies belts: tidal flat/lagoonal, shoal, open shelf, transitional (i.e. basin slope) and basin depression. The first three facies belts formed a carbonate platform. A deep pericratonic basin with fine-grained clastic deposition formed the last two facies belts (Raukas & Teedumäe 1997).

Kalana abandoned quarry (58.713586, 26.045208 by World Geodetic System 84) (Fig. 1) is located 200 m east of Põltsamaa–Kalana road at the southern border of Kalana village. A ca 4 m thick section of pure slightly dolomitized limestones with thin lenses rich in fossil debris of the Raikküla Regional Stage (Aeronian–Telychian) are exposed (L. Põlma, unpublished field notes 1981).

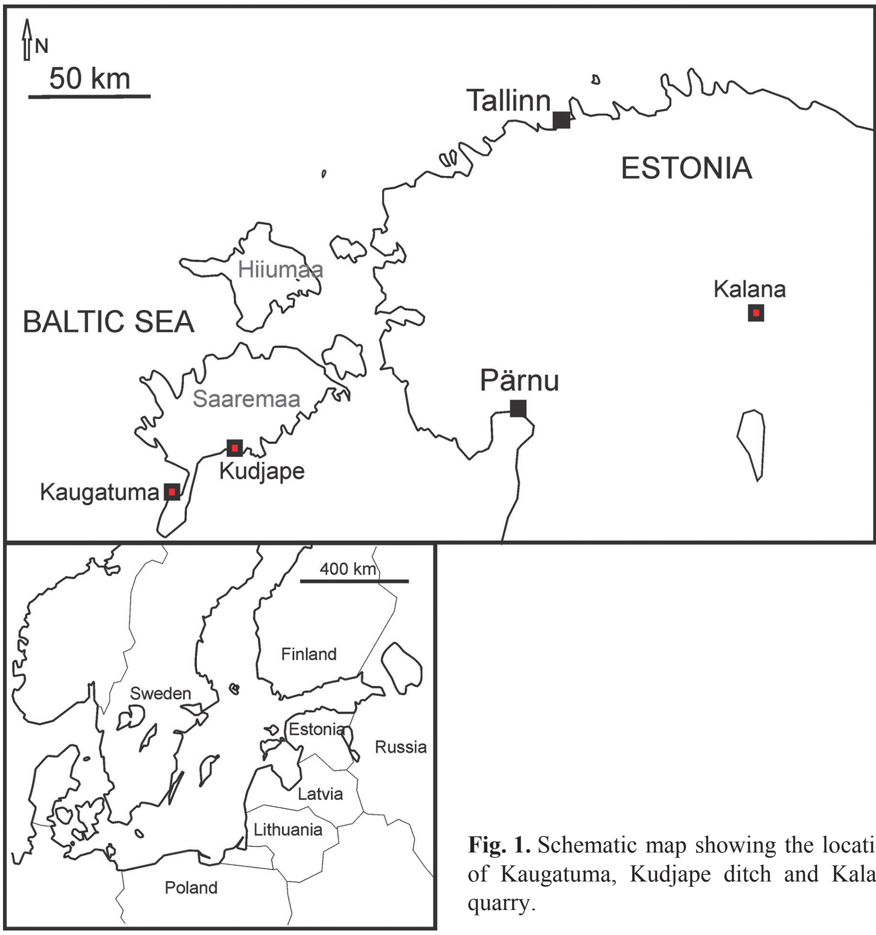

Fig. 1. Schematic map showing the location of Kaugatuma, Kudjape ditch and Kalana quarry.

Kudjape ditch (58.266500, 22.517360 by World Geodetic System 84) (Fig. 1) lies near the road from Kudjape cemetery to Kuressaare–Orissaare road. The Kudjape beds of the Kuressaare Formation (Ludfordian) are represented by nodular argillaceous biomicritic limestones containing coquinoid interlayers. *Atrypoidea* and colonial rugose corals *Entelophyllum* are numerous (Mõtus & Hints 2007).

Kaugatuma Beach (58.113890, 22.184080 by World Geodetic System 84) (Fig. 1) is located between Kaugatuma and Lõo cliffs. Dark bluish-grey slightly argillaceous to pure skeletal packstones and grey sorted crinoid grainstones of the Kaugatuma Formation (early Pridoli) are exposed on a 200 m long seashore (H. Nestor, unpublished field notes 1985).

MATERIAL AND METHODS

The authors observed *Zoophycos* in the field during several field trips and collected three specimens. The studied collection ($N = 10$) is deposited at the Institute of Geology at Tallinn University of Technology (GIT 362-43 to GIT 362-52). It contains specimens from several collectors obtained during the past fifty years but nobody had interpreted the finds before us. The trace fossil samples with *Zoophycos* burrows were photographed with scale bar using Nikon D7000.

RESULTS

Zoophycos traces are common in the Kaugatuma Formation (Fig. 2A, B) and slightly less common in the Kuressaare Formation (O. V. field observations) (Fig. 2C). They also occur in the Raikküla Regional Stage (U. T. field observations) (Fig. 2D). Complete traces have not been found in either formation. The Kaugatuma Formation traces were made in crinoid grainstone with marl interlayers, those of the Kuressaare Formation in clayey limestone containing fine fossil debris.

In the studied traces, the marginal tube, though not well preserved in all traces, corresponds to the external border of a lamina. The laminae are formed by numerous

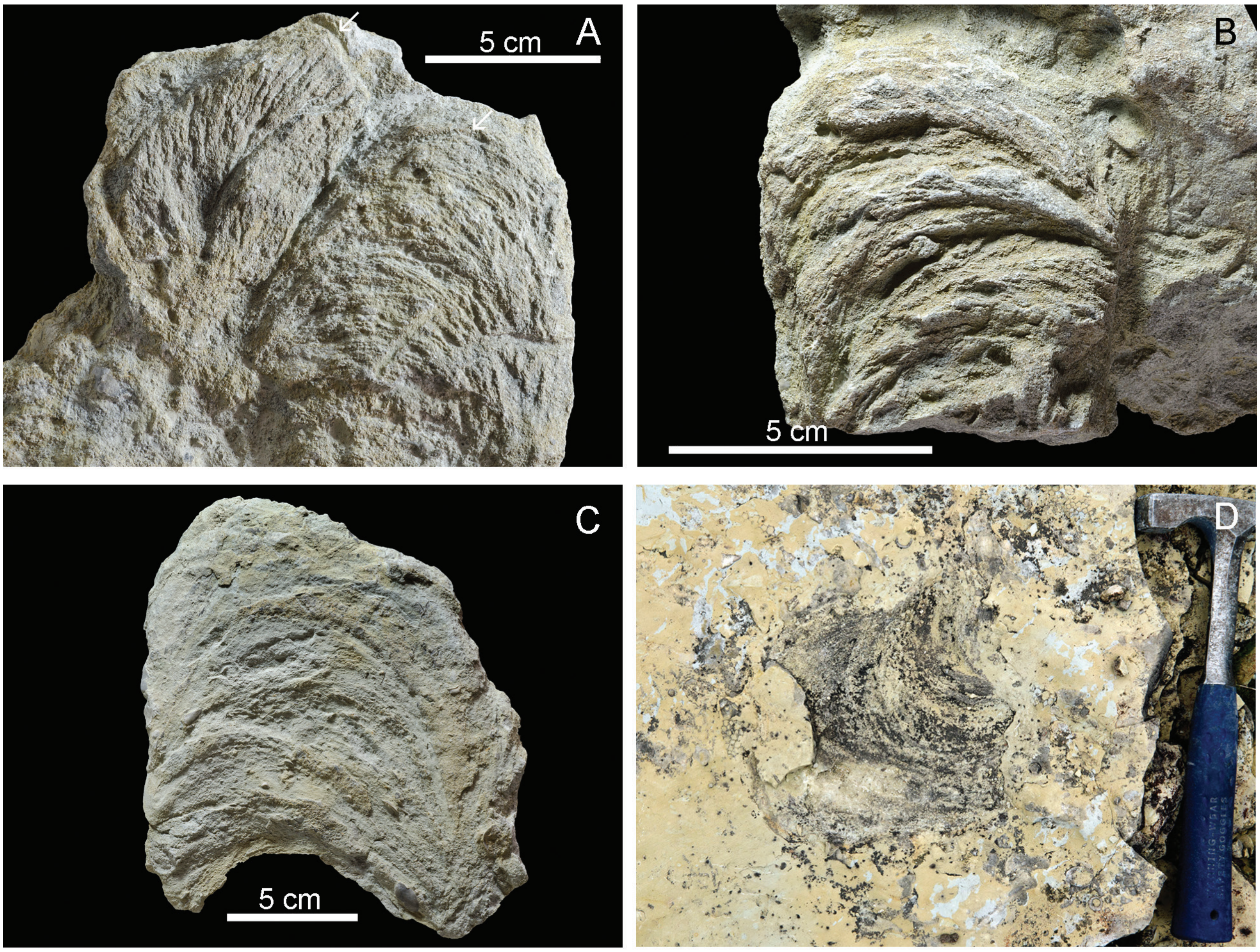

Fig. 2. **A**, **B**, *Zoophycos* isp. from the Kaugatuma Formation (lower Pridoli) from Saaremaa, Kaugatuma (TUG 362-45 and 362-50). Arrows point to the marginal tube. **C**, *Zoophycos* isp. from the Kuressaare Formation (Ludfordian) from Saaremaa, Kudjape (TUG 362-44). **D**, *Zoophycos* isp. from the Raikküla Regional Stage (Llandovery) of middle Estonia, Kalana quarry. Hammer for scale is 28 cm.

thin arched lamellae. There are up to seven lamellae per 1 cm. The lamellae are deformed, filled tunnels, which mark the previous position of the same single tunnel penetrating through the sediment. The marginal tube marks the most advanced position of this tunnel. Only this part of the burrow system remained open during the life of the trace-maker. The marginal tunnel of some Saaremaa specimens is discontinuous and does not contour the whole spreite (Fig. 2A). It seems to regularly jet-out to initiate a new lobe. The lobes are 6 to 8 cm in diameter.

DISCUSSION

Ichnotaxonomy

The transitions between *Rhizocorallium* and *Zoophycos* are known (Knaust 2013). The Estonian material differs from *Rhizocorallium* in having a proportionately much thinner marginal tube and a burrow outline in the form of a widely rounded curve. The spreite organization of one Kaugatuma specimen (Fig. 2A) resembles most the alate (wing-like) form of *Zoophycos* (Seilacher 2007). These Devonian specimens have secondary lamellae, however, we found no evidence of secondary lamellae in the Estonian material. *Zoophycos* has been interpreted as a burrow system. In these burrows the trace-maker avoids the marginal tunnel from becoming too long by making new entrances (Seilacher 2007). The spreite shape and structure of most of the studied specimens cannot be identified due to incomplete preservation of the trace. However, the preserved parts of most traces do not resemble the classical spiral form of *Zoophycos* (Seilacher 1967a, 1967b; Bromley & Ekdale 1984). The Estonian forms resemble mostly planar *Zoophycos* spreites known from the Devonian storm deposits

(Miller 1991). Their marginal curvature is similarly broadly arcuate to lobate and their marginal tunnels are weakly developed or lacking.

Stratigraphy and palaeoenvironment

In Estonia, *Zoophycos* seems to be common only in the late Silurian in the Kuressaare (Ludfordian) and Kaugatuma (early Pridoli) formations. During the late Silurian, the Baltic Basin had retreated to the southwest part of Estonia and was filled with sediments (Raukas & Teedumäe 1997). Water was relatively shallow (Raukas & Teedumäe 1997). Clayey limestones of the Kuressaare Formation were formed in the open shelf zone in deeper water and grainstones of the Kaugatuma Formation in shallower shoal conditions (Raukas & Teedumäe 1997). It seems that *Zoophycos* preferred shallow water, salinity normal marine sediments with high skeletal debris content (i.e. Kaugatuma Formation) in the Silurian of Estonia. However, *Zoophycos* also occurred in slightly deeper-water sediments of the Kuressaare Formation, thus, it was not restricted to certain facies. Several facies types similar to the Silurian of Estonia were also present in the Late Ordovician of Estonia when the climatic conditions were similar to the Silurian. In the Ordovician of Estonia, silty beds of the Variku Formation are known to contain abundant *Chondrites* and *Zoophycos* ichnofauna (Ainsaar & Meidla 2001).

Palaeogeography

Zoophycos occurred in several palaeocontinents already in the Cambrian (Doucek & Mikuláš 2014). The Ordovician records of *Zoophycos* seem to be relatively common (Mikuláš 1993; Ainsaar & Meidla 2001; Kakuwa & Webb 2007; Pak et al. 2010). Few records of *Zoophycos* are also known from the Silurian rocks. *Zoophycos* has been reported from the Rhuddanian of Saudi Arabia (Melvin 2015). It probably also occurs in the Silurian of Bolivia and in Australia (Gondwana) (Toro et al. 1990; Shi et al. 2009). Their traces are also known from the Silurian rocks of Canada (Laurentia) (Pickerill et al. 1977). The Estonian occurrences add the Baltica palaeocontinent to the Silurian record of *Zoophycos*.

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Zoophycos'e jälgede esmaleid Eesti Silurist

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Zoophycos'e jäljed on esmakordselt kirjeldatud Baltika kontinendi Silurist. *Zoophycos* esineb Raikküla lademe puhastes lubjakivides, Kuressaare lademe savikates lubjakivides ja Kaugatuma lademe krinoidlubjakivis. Jälgede levik ei ole piiratud kindla faatsiesega, kuid need esinevad madalaveelistes setendites.