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# The early Katian (Late Ordovician) reefs near Saku, northern Estonia and the age of the Saku Member, Vasalemma Formation

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**Abstract.** Reefs developed simultaneously during the latest Sandbian/earliest Katian global Guttenberg Isotopic Carbon Excursion (GICE) in several places across Baltoscandia. Latest Sandbian/earliest Katian patch reefs are also described from the Vasalemma Formation of northern Estonia. The Saku Member of the Vasalemma Formation was previously considered as a proximal facies related to the reefs. However, the Saku Member clearly post-dates the GICE interval and ranges from the latest Keila to Rakvere in terms of regional stages. Some small reefs occur in direct proximity to the stratotype of the Saku Member. New $\delta^{13}C$ data from the stratotype section and the adjacent reefs indicate that these reefs developed before the deposition of the Saku Member during the GICE interval. The chemostratigraphic data support the hypothesis of a short-time Baltoscandian reef growth event that terminated during the GICE interval.

**Key words:** carbon isotopes, GICE excursion, Kope excursion, Ordovician reefs, Oandu Stage, Estonia.

## INTRODUCTION

Late Ordovician reefs were first reported from northern Estonia by Raymond (1916). These reefs occur as distinctive bodies with diameters of up to 50 m and thicknesses of up to 15 m within the Vasalemma Formation (Fig. 1). The Vasalemma Formation is unique within the Ordovician succession of the entire Baltic region, being mainly composed by echinoderm grainstones dominated by ossicles and thecal plates of the rhombiferan cystoid *Hemicosmites*.

Recently, the stratigraphy of the Vasalemma Formation was revised and for the first time the reefs were described in detail by Kröger et al. (2014). These authors demonstrated that the Vasalemma Formation is nearly coeval with other reef-bearing formations across Baltoscandia, and that it represents a conspicuous reef-building event at the Sandbian/Katian boundary. Reef formation culminated and terminated during the Guttenberg Isotopic Carbon Excursion (GICE) interval. However, a question remained with respect to the silty, marly 'Saku facies' (Männil 1960) of the Vasalemma Formation.

The 'Saku facies', later formalized as the Saku Member (Rõõmusoks 1970), was first recognized in the northeastern edge of the outcrop area of the Vasalemma Formation near the Saku settlement and interpreted as a lateral continuation of the echinoderm grainstone facies (Põlma et al. 1988) (Fig. 1). Kröger et al. (2014) reinterpreted the Saku Member as a younger, locally restricted post-reef deposit at the eastern and southern margins of the reef-growth area.

Reports of reefs in the Saku area (Männil 1960) seem to be in conflict with the interpretation of Kröger et al. (2014). Furthermore, a prolonged, post-GICE reef growth in the Saku area would contradict the hypothesis of a short-term Baltoscandian reef-building event during the GICE.

However, these easternmost reef occurrences have never been compared with the reefs in the Vasalemma region and their vertical range was never specified. Herein, the first chemostratigraphical correlation of the reefs in the Saku region is presented. Additionally, new $\delta^{13}C$ and conodont data allow for a refined correlation of the Saku Member.

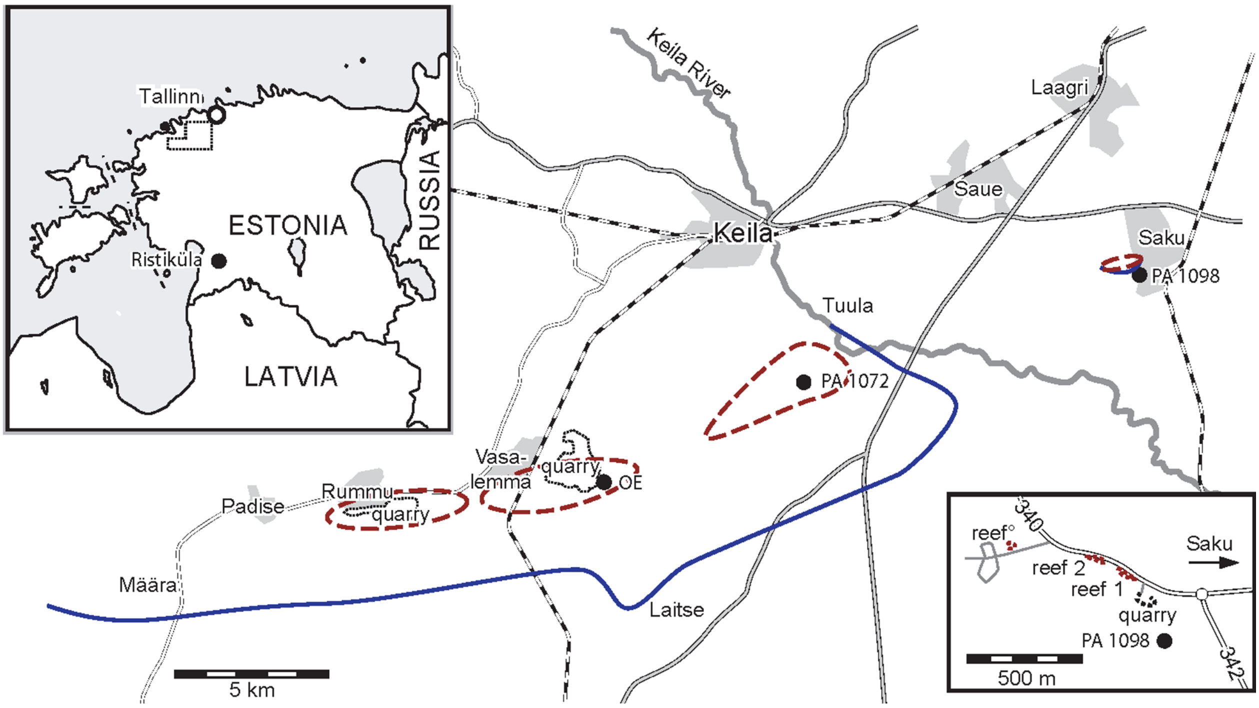


**Fig. 1.** Regional distribution of the Vasalemma Formation, Late Ordovician (solid black line), with areas of reef occurrences (dashed line). Based on Kröger et al. (2014).

## METHODS

The investigation is based on field observations on fresh road cuts of reefs at the road 340, east of the town of Saku (reef 1: 59°18′1.92″N/24°38′49.14″E; reef 2: 59°18′6.18″N/24°38′35.16″E), on the stratotype of the Saku Member in the abandoned quarry south of the road 340, east of Saku (59°17′59.58″N/24°38′56.10″E) (Fig. 1) and on a small ditch located about 10 m to the NE from the Saku type section in the same quarry (59°18′01.15″N; 24°38′48.33″E).

The $\delta^{13}C$ analysis of samples from the Saku reef 1, and from the stratotype was performed in the stable isotope laboratory of the GeoZentrum Nordbayern at the University of Erlangen (Germany). Carbonate powders were recovered by a dental drill and reacted with 103% phosphoric acid at 70 °C using a Gasbench II connected to a ThermoFinnigan Five Plus mass spectrometer. All values are reported in per mil relative to V-PDB by assigning a $\delta^{13}C$ +1.95‰ to NBS19. The accuracy and precision of the carbon isotope measurements were checked by replicate analysis of standards NBS19 and laboratory standards. Reproducibility was better than ±0.05‰.

## GEOLOGICAL SETTING AND LOCAL STRATIGRAPHY

In the Baltic, the latest Sandbian–earliest Katian interval (late Keila–Oandu regional stages) is characterized by an unusually complex regional facies differentiation and by the presence of large areas of non-deposition (Ainsaar & Meidla 2001). The Saku Member of the Vasalemma Formation is part of this complicated facies mosaic.

During the Ordovician, northern Estonia was part of the shallow Estonian Shelf of the Baltoscandian epicontinental palaeobasin (Nestor & Einasto 1997). Ainsaar et al. (1999) provided a general overview of facies transitions between the different East Baltic depositional belts in the Keila–Oandu interval. In this overview the most striking feature is the wide area of non-deposition that stretched over large parts of the Estonian Shelf at the Keila–Oandu boundary interval. Classically, the Vasalemma Formation was interpreted as the only exception in this area, with more or less continuous sedimentation ranging well into the Oandu Stage (Põlma et al. 1988; Ainsaar et al. 1999, 2004).

However, Kröger et al. (2014) demonstrated that the picture is far more complicated (Fig. 2). First of all,

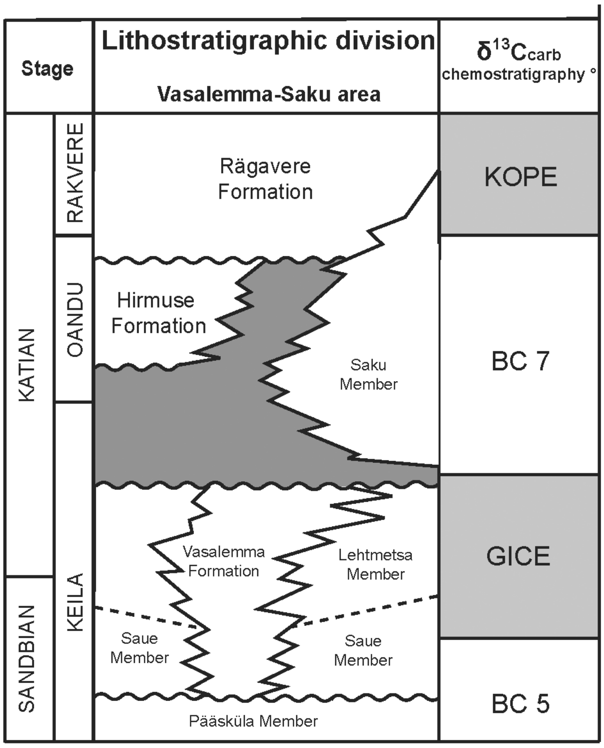


**Fig. 2.** Lithostratigraphy of the upper Sandbian–lower Katian interval in the Vasalemma–Saku region, NW Estonia. Dark grey, hiatus; light grey, positive $\delta^{13}C$ isotope excursion, °after Ainsaar et al. (2010), Kope = Rakvere excursion.

the exact position of the Keila/Oandu boundary is not defined (Ainsaar et al. 2004; Kaljo et al. 2004). A review of this problem is beyond the scope of this short paper. Therefore, and without further discussion, we follow the practice of Ainsaar et al. (2004) and consider the top of the low-diversity interval '*tetrada*-beds' (= 406.7 m in the Ristiküla-174 core) within the Variku Formation as the base of the Oandu Stage (Fig. 3).

Secondly, the Vasalemma Formation must be divided into a reef facies (Vasalemma facies *sensu* Männil 1960) and a proximal or non-reef facies (Saku facies *sensu* Männil 1960, Saku Member *sensu* Rõõmusoks 1970). The lower boundary of the Saku Member is defined by Põlma et al. (1988, p. 70) at the level of 7.10 m in the Saku-1098A core. Chemostratigraphy reveals that this level is above the GICE peak interval (Kaljo et al. 2004; Fig. 3). However, all sections of the Vasalemma facies studied for $\delta^{13}C$ data produced values indicating a deposition during the rising limb and peak interval of the GICE and display a considerable hiatus and abrupt facies change at its top (Fig. 3).

Hence, the deposition of the Vasalemma Formation (Vasalemma and Saku facies) terminated within the peak GICE interval in the Rummu and Vasalemma areas. However, it continued slightly longer in the Tuula area to the east and considerably longer in the Saku area even further east (Kröger et al. 2014) where sedimentation continued throughout the Oandu Stage.

## REEFS IN THE SAKU AREA

Reefs are exposed or have been exposed in the past in an area southwest of Saku (Männil 1950; L. Põlma unpublished data) (Fig. 1). The reefs are located 17 km east of the central region of the reef growth area, near the Vasalemma parish, and ca 11 km east of the easternmost location of the reefs of the Tuula area.

The reefs have diameters of up to 50 m, based on the present outcrop dimensions, and a thickness of at least 4 m. Their complete thickness and exact stratigraphic position are not known. The reefs are embedded in an echinoderm grainstone, identical to those known from the Vasalemma and Rummu area.

The lithology of the reefs is similar to the structures described from the Vasalemma and Rummu area further west (Kröger et al. 2014). They are composed of a relatively loose framework of *Hemicosmites* roots and encrusting bryozoans and can be classified as cluster and segment reefs according to the scheme of Riding (2002). The matrix of the reef-core limestone is composed of wackestone to mudstone, with a high probability of a similar mix of authochthonous and allochthonous micrite (Kröger et al. 2014). No quantitative analysis of the fauna is available at the moment, but field collections reveal an exceptional abundance of large (30–50 mm high) *Cyclonema*-like gastropods in the weathered upper 2–3 m of the reef cores.

An analysis of the ca top 2 m of the core of Saku reef 1 produced highly variable $\delta^{13}C$ values of 0.76–1.77‰ (Table 1). A sample of the directly adjacent beds of echinoderm grainstone shows a value of 1.11‰. These values are similar to those of the rising or falling limb of the GICE measured in the Saku-1098A section (Kaljo et al. 2004; Figs 1, 3).

The brachiopods *Sakunites luhi* (Sokolskaya), *Vellamo* cf. *oanduensis* Öpik, *Rostricellula nobilis* (Oraspõld), *Zygospira gutta* (Oraspõld) and a rhombiferan cystoid *Hemicosmites* sp. occur in a marly limestone directly overlying reef 1. These taxa are known from the middle and upper parts of the Saku Member (Rõõmusoks 1970) and from post-reef beds in the Vasalemma quarry (Kröger et al. 2014).

Additionally, field relationships show that the reefs lie below the beds exposed in the Saku type section. About a metre of echinoderm grainstones may be missing between the top of reef 1 and the lowest echinoderm grainstone levels exposed in the ditch NE of the type section.

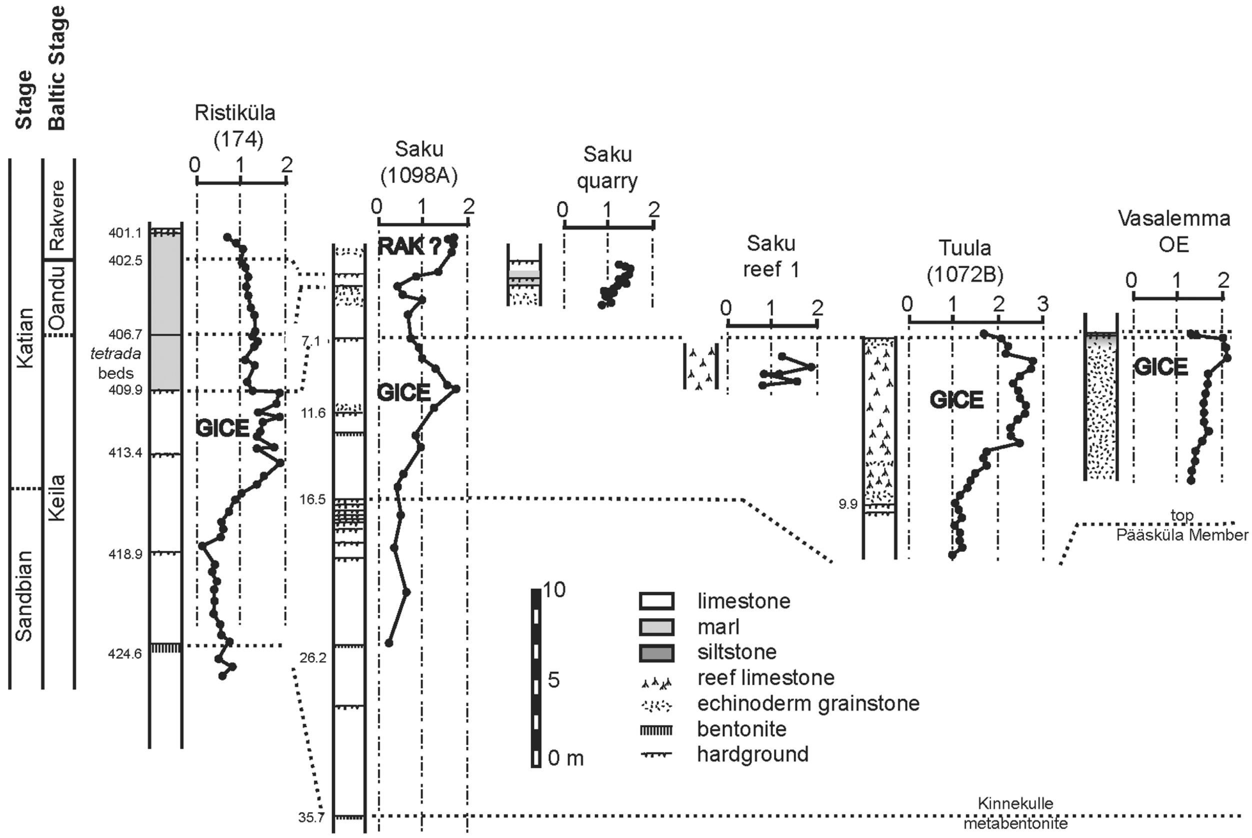


**Fig. 3.** $\delta^{13}C$ chemostratigraphy of selected early Katian outcrops in Estonia. $\delta^{13}C$ values in ‰ V-PDB. Keila/Oandu stage boundary after Põlma et al. (1988) and Ainsaar et al. (1999). Data from Saku-1098A after Kaljo et al. (2004), from Ristiküla-174 (see Fig. 1) after Ainsaar et al. (2004), from Vasalemma after Kröger et al. (2014). GICE – Guttenberg Isotopic Carbon Excursion; RAK? – questionable Rakvere/Kope Isotopic Carbon Excursion. Note the pre-Oandu occurrence of the Vasalemma facies in the Saku and Tuula reefs and in the Vasalemma quarry.

**Table 1.** $\delta^{13}C$ values of the Saku quarry type section (positions refer to the 2 m level of Põlma et al. 1988), from a ditch in the same quarry and from the section Saku reef 1 (positions measured from reef top)

| Sample | Sample level, m | $\delta^{13}C$ mean, ‰ V-PDB |
|---|---|---|
| Reef 1 | 0.0 | 0.76 |
| Reef 2 | 0.2 | 1.47 |
| Reef 3 | 0.6 (reef core) | 0.78 |
| Reef 4 | 0.6 (echinoderm grainstone) | 1.11 |
| Reef 5 | 1.0 | 1.77 |
| Reef 6 | 1.6 | 1.16 |
| Type section 1 | –1.20 | 0.90 |
| Type section 2 | –1.05 | 1.08 |
| Type section 3 | –0.65 | 0.98 |
| Type section 4 | –0.55 | 1.07 |
| Type section 5 | –0.40 | 1.13 |
| Type section 6 | –0.30 | 0.93 |
| Type section 7 | –0.20 | 1.15 |
| Type section 8 | 0.0 | 1.24 |
| Type section 9 | +0.10 | 1.44 |
| Type section 10 | +0.20 | 1.42 |
| Type section 11 | +0.40 | 1.27 |
| Type section 12 | +0.55 | 1.40 |
| Type section 13 | +0.70 | 1.48 |
| Type section 14 | +0.80 | 1.48 |
| Type section 15 | +1.05 | 1.54 |
| Type section 16 | +1.15 | 1.43 |
| Type section 17 | +1.30 | 1.28 |
| Ditch 1 | – | 0.73 |
| Ditch 2 | – | 0.49 |
| Ditch 3 | – | 0.52 |
| Ditch 4 | – | 0.65 |

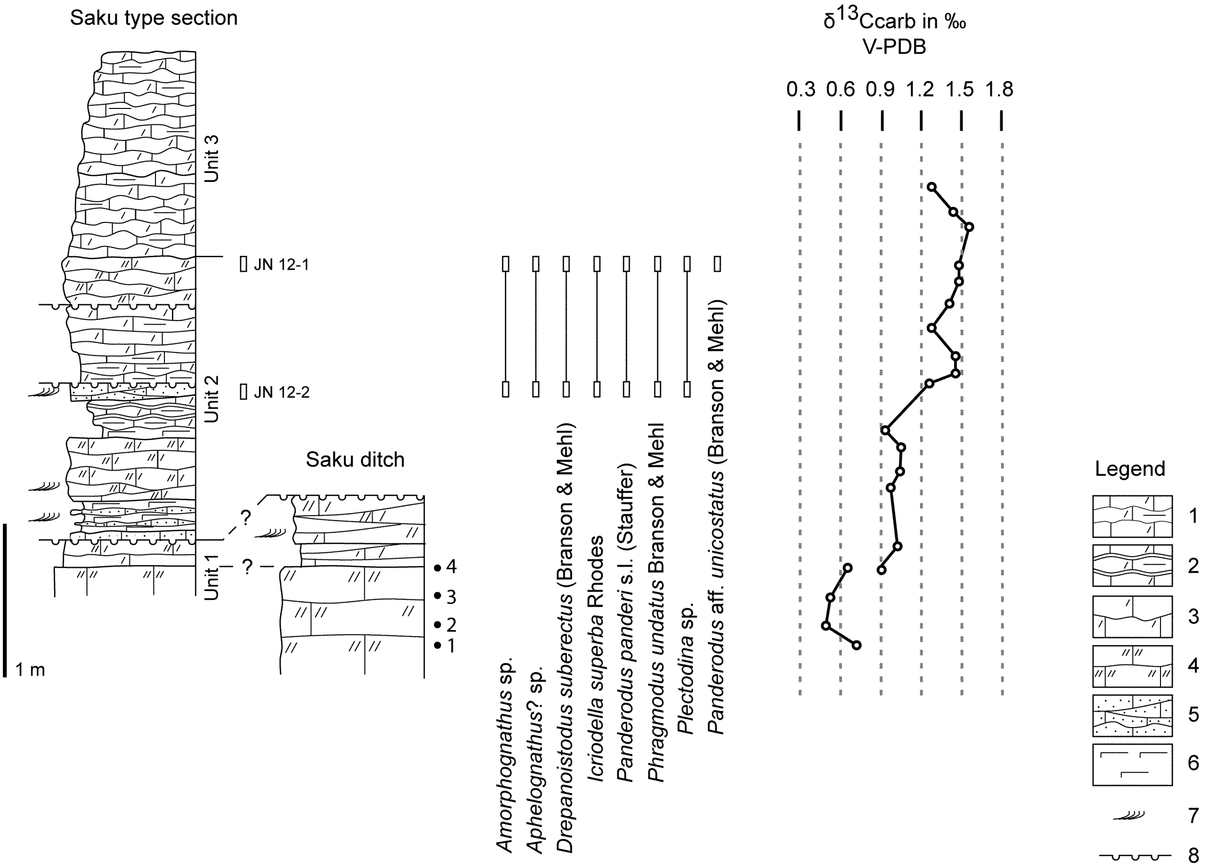


**Fig. 4.** General lithological logs of the type section of the Saku Member and a ditch in a deeper part of the same quarry. Right of the log positions of samples processed and ranges of conodonts identified are indicated. Legend: 1, argillaceous wackestone; 2, intercalation of argillaceous wackestone and marlstone; 3, mainly fine-grained wackestone–packstone; 4, coarse-grained packstone–grainstone; 5, irregularly bedded siltstone–fine-grained sandstone; 6, marlstone; 7, cross-bedding; 8, hardground.

## INTERPRETATION OF THE REEF SETTING

The stratotype of the Saku Member and the reference core section Saku-1098A are located only 120 m SE and 300 m south of the Saku reef 1, respectively. These two sections were described in detail by Männil (1960) and Põlma et al. (1988).

A general tripartite succession of the Saku Member, originally described by Männil (1960), is clearly visible in both sections, which can be subdivided into a unit with silty skeletal grainstones at its base (unit 1), lenses of partly cross-bedded, partly dolomitized siltstones and marls with several hardgrounds in the middle (unit 2) and thin-bedded argillaceous silty limestones at its top (unit 3; Fig. 4).

The combined structural, lithological, faunal and geochemical evidence suggests a position of the Saku reefs within the late GICE interval at a stratigraphic level that is equivalent to the interval below 7.1 m in the Saku-1098A core. This is below unit 1, exposed in the stratotype. Hence, the Saku Member itself is clearly overlying the reef facies in the Saku area and is not a lateral continuation of the Vasalemma reef facies as suggested by Põlma et al. (1988), but represents a younger deposit. This conclusion is supported by preliminary conodont data from the Saku and Vasalemma quarries. Two small samples processed from the middle of the Saku type section (Fig. 4) yielded *Phragmodus undatus* and *Amorphognathus* sp. Both taxa appear above the top of the reefs in the Vasalemma quarry (Peep Männik, unpublished collection). Additionally, *Semiacontiodus* sp. and *Nordiodus*? sp., characterizing the reefs in Vasalemma and disappearing at their top, have not been found in the Saku type section. The data above suggest a correlation of the middle part (unit 2) of the Saku type section with the upper Oandu Stage (time-equivalent to the topmost Variku Formation in the Mehikoorma-421 core section; Männik & Viira 2005).

The Saku Member is evidently a highly diachronic facies ranging from the Keila/Oandu boundary interval into the Rakvere Stage. Unit 1 of the Saku Member might be an equivalent of the *tetrada*-beds of southern Estonia. The silty middle unit (unit 2) can be interpreted as a lowstand deposit above a major sequence boundary, which is equivalent to the SB 7/8 of Dronov et al. (2011).

Consequently, the depositional scenario, hypothesized by Kröger et al. (2014), should be modified and the Saku Member should be considered as a distinctive post-reef unit that ranges over a major sequence boundary, up into the Rakvere Stage. Future biostratigraphical studies will help to reach a consensus for the definition of the base of the Oandu Stage.

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