LITHOLOGY OF THE KALLAVERE FORMATION ON THE NORTH ESTONIAN KLINT (Part I – Paldiski–Kunda area)

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In North Estonia the Kallavere Formation corresponds to the Cambrian–Ordovician boundary beds, the major part of which belongs to the lower Tremadoc. The stratigraphical range of the Kallavere Formation is variable: in the western part of the klint (North-Estonian cliff) it represents the lower half of the Pakerort Stage, in the east the whole stage. The Kallavere Formation is subdivided into five members: Maardu, Suurjõgi, Katela, Rannu and Orasoja. Three members – Maardu, Suurjõgi and Katela – occur in the western klint area, the eastern boundary of which coincides with the surroundings of Kunda. Part II of the article (eastern part of the klint) will be continued.

Key words: lithology, Obolus sandstone, Kallavere Formation, Cambrian–Ordovician boundary beds, Estonia.

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INTRODUCTION

In the western klint (local name for cliff of the bedrock) area the Kallavere Formation forms the lower part of the Pakerort Stage, the Türisalu Formation corresponds to the upper part. Owing to the variable lithology of the Kallavere Formation, as a result of the studies by different researchers five members – Maardu, Suurjõgi, Katela, Rannu and Orasoja – have been distinguished in it in the entire klint area (Müürisepp, 1958a; 1960; Loog, 1964; Heinsalu, 1981; 1987). The Maardu ($Є_3$-O_1*kl* M), Suurjõgi (O_1*kl* S) and Katela (O_1*kl* K) members are distributed in the western region of the North Estonian Klint, considered in the present paper. The eastern boundary of the region coincides approximately with the Toolse–Kunda district. The Rannu ($Є_3$–O_1*kl* R) and Orasoja (O_1*kl* O) members occur in the eastern part of the klint, between Kunda and Narva.

The present article bases on the data of detailed lithological investigations of 15 differently exposed sections, located on the North Estonian Klint (Fig. 1). The investigations were conducted already years ago, but the results have not been properly published yet. Field studies have been conducted by the same researchers during a short time interval and the analysis performed by the same analysts in the laboratory of the Geological Survey of Estonia, using the same methodology. All this allows of good comparability of the results. The granulometric composition of rocks was determined by the so-called quartz method, which lies in the treatment of rocks with aqua regia prior to analysis (Kazakov, 1957). In the present context this means the dissolution of phosphatic brachiopod valves and their detritus. The content of phosphatic brachiopod material in the rock, however, is revealed by the content of P_2O_5 determined by chemical analysis. Usually P_2O_5 makes one-third of the composition of brachiopod fragments (Figs. 2–5).

In the composition of the Kallavere Formation we may distinguish three major lithological components: 1. brachiopod coquina ("Obolus conglomerate"), 2. quartz sand(stone) with interbeds of dark graptolitic argillite and 3. quartz sandstone enriched with phosphatic brachiopod detritus of small size. The first two components occur in different proportions in the Maardu Member, the third component, however, is known as a "detrital layer", distinguished as the Suurjõgi Member in the section of the Kallavere Formation.

LITHOLOGICAL TYPES OF SECTIONS

Maardu Member ($Є_3$–O_1*kl* M)

In the North Estonian Klint sections the Maardu Member is generally characterized by quartz sand- or siltstone containing detritus or whole valves of inarticulate phosphatic brachiopods. There occur always also interbeds of dark kerogenous argillite (Dictyonema shale) in different numbers. In the sections east of Tallinn a layer of brachiopod coquina has been recorded on the base of the Maardu Member.

The thickness of the member ranges from 0.5 m to 5.4 m, most often from 2 to 3 m.

Detailed investigations have revealed high lateral variability of the lithology of the Maardu Member. In the western part of the North Estonian Klint, four rather distinct types of sections (I–III and III/IV) can be distin-

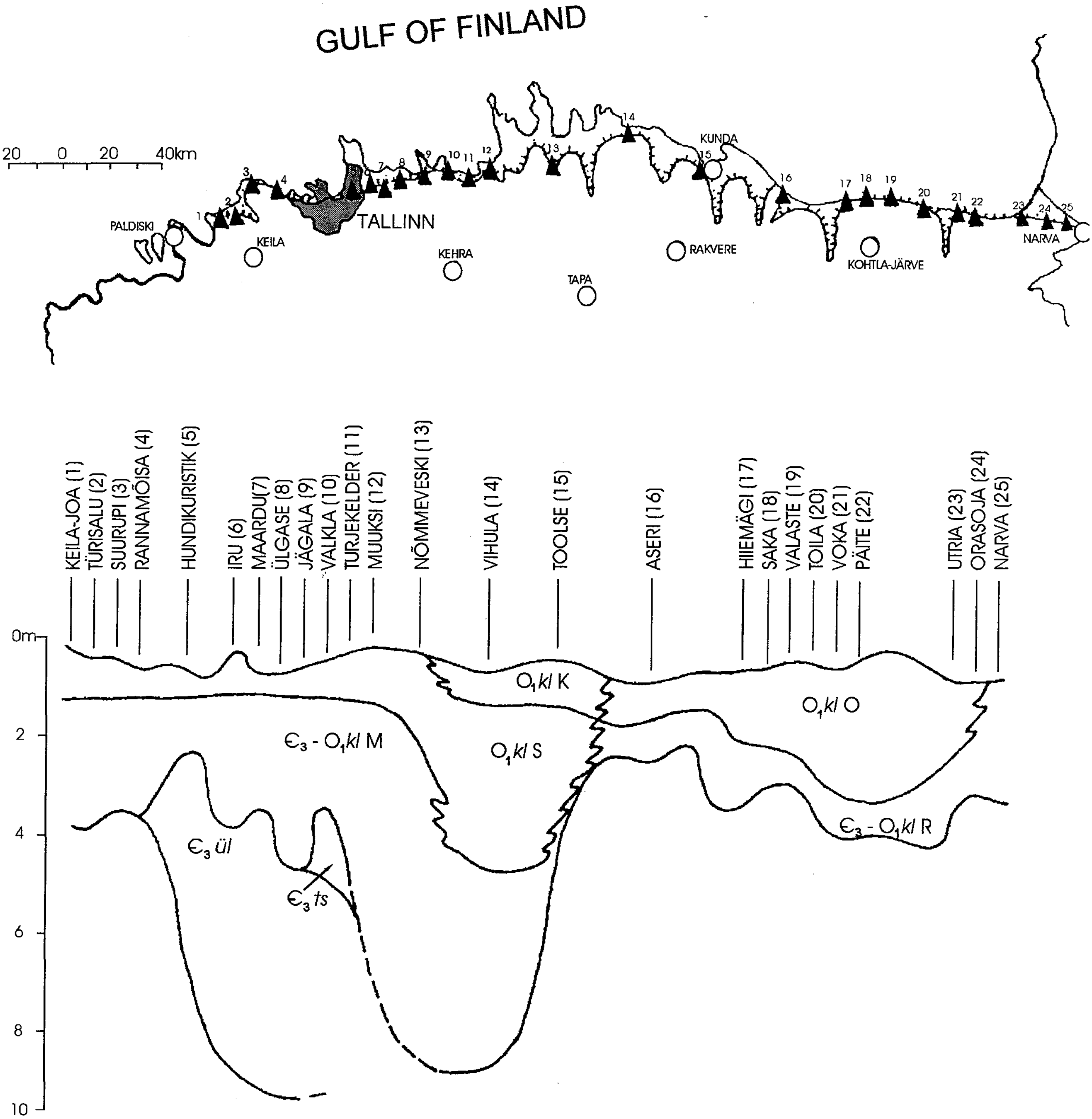


Fig. 1. Location and schematic cross-section of outcrops with lithostrathigraphical units of the Kallavere Formation.

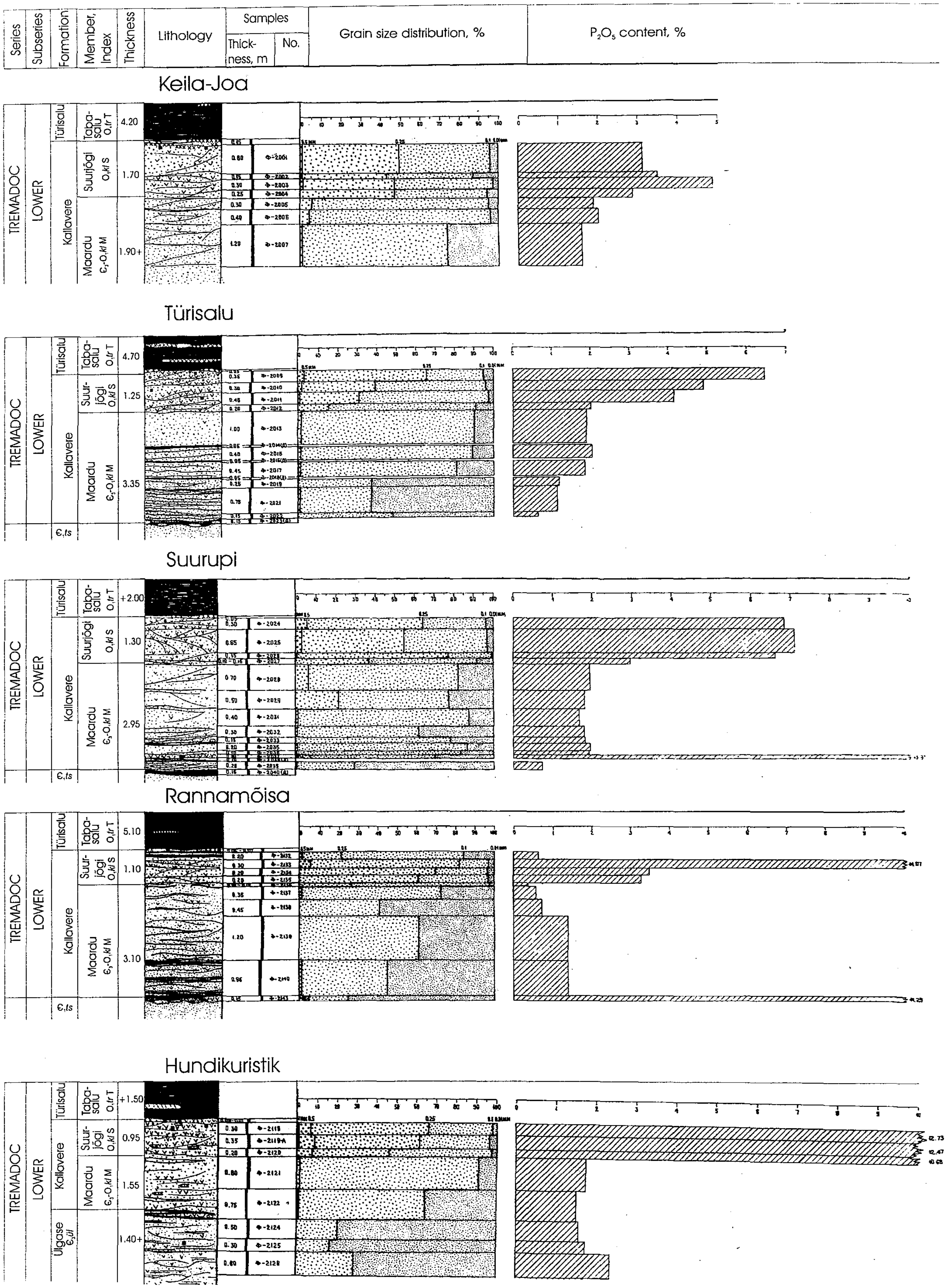


Fig. 2. The sections of type I.

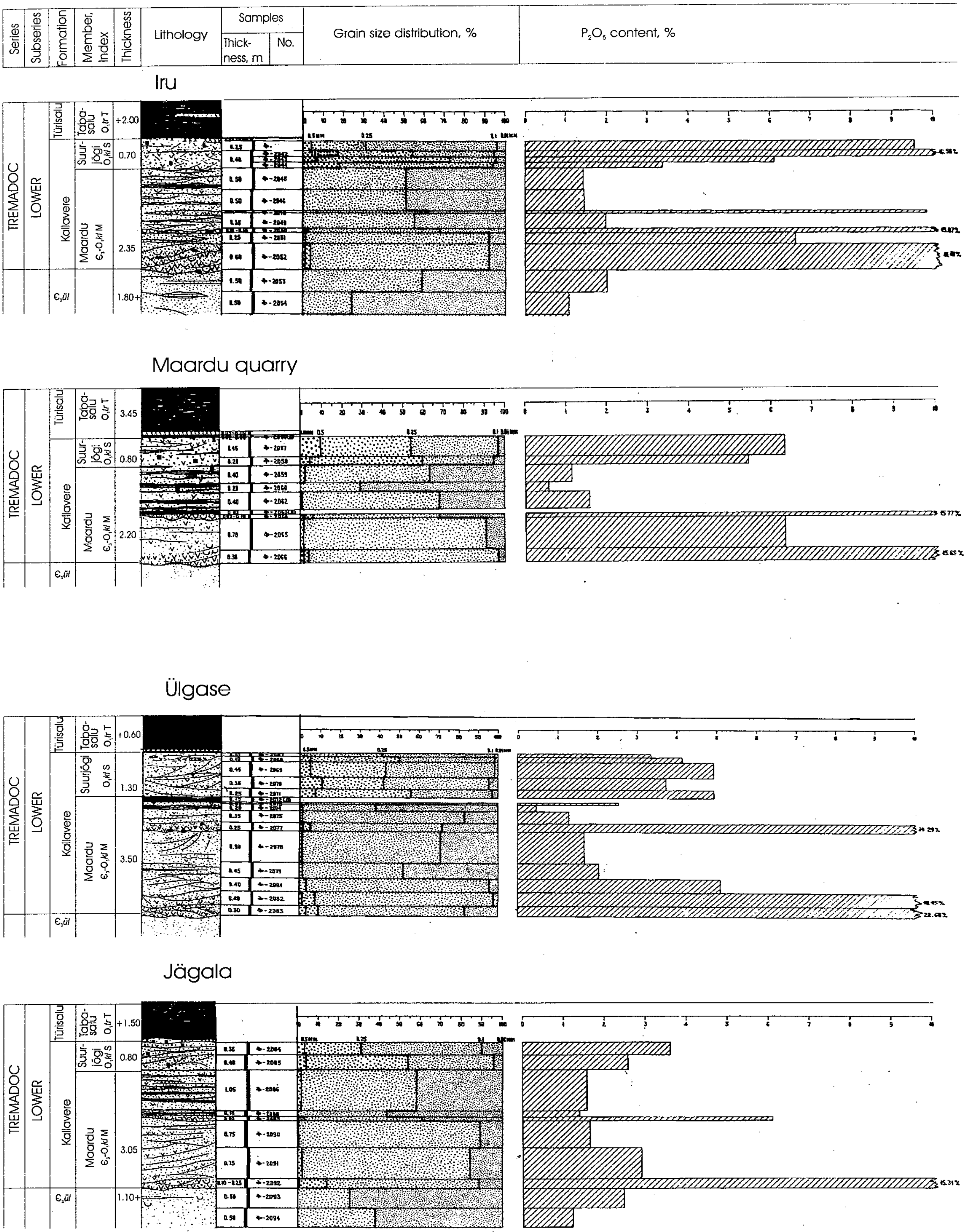


Fig. 3. The western sections of Type II.

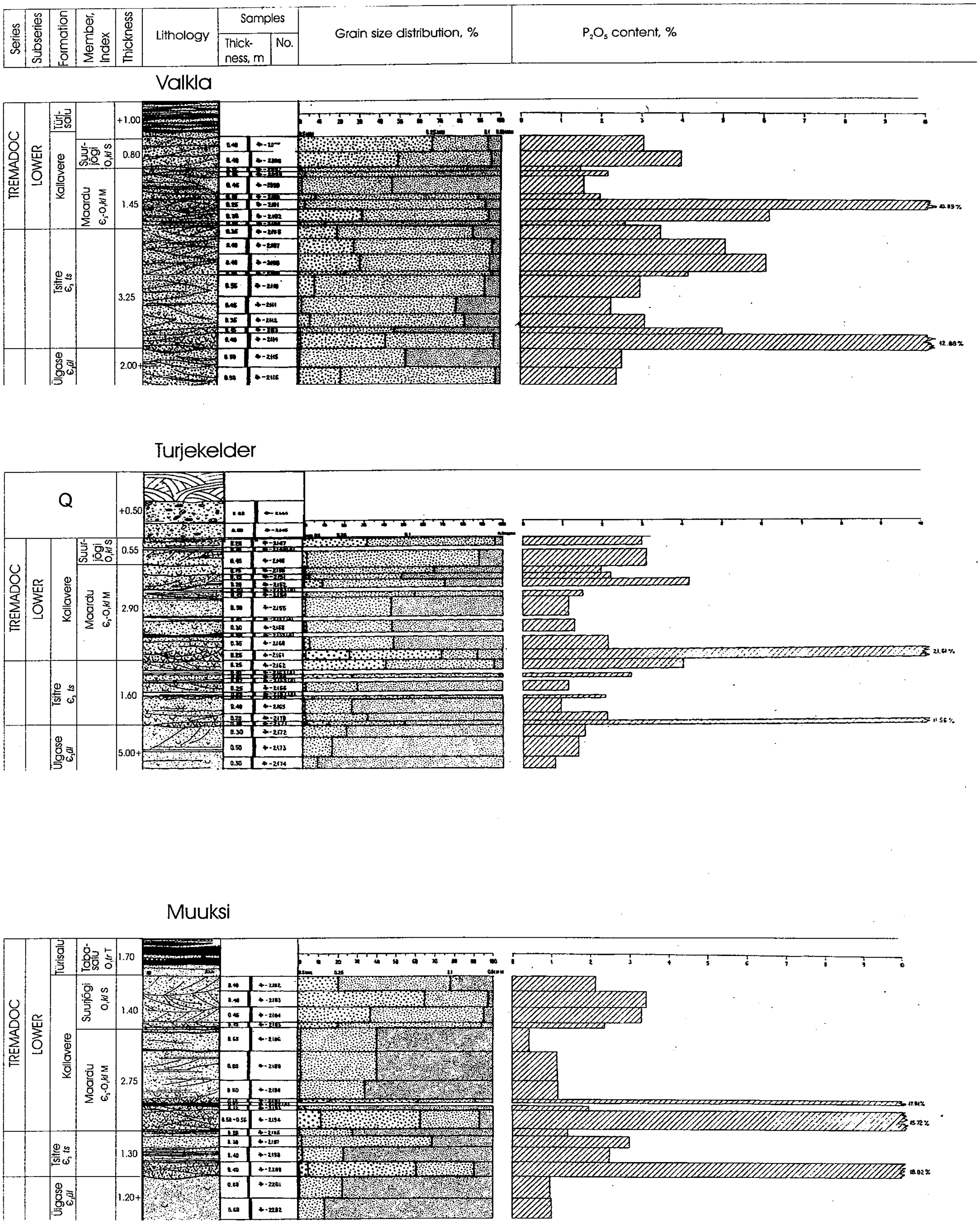


Fig. 4. The eastern sections of type II.

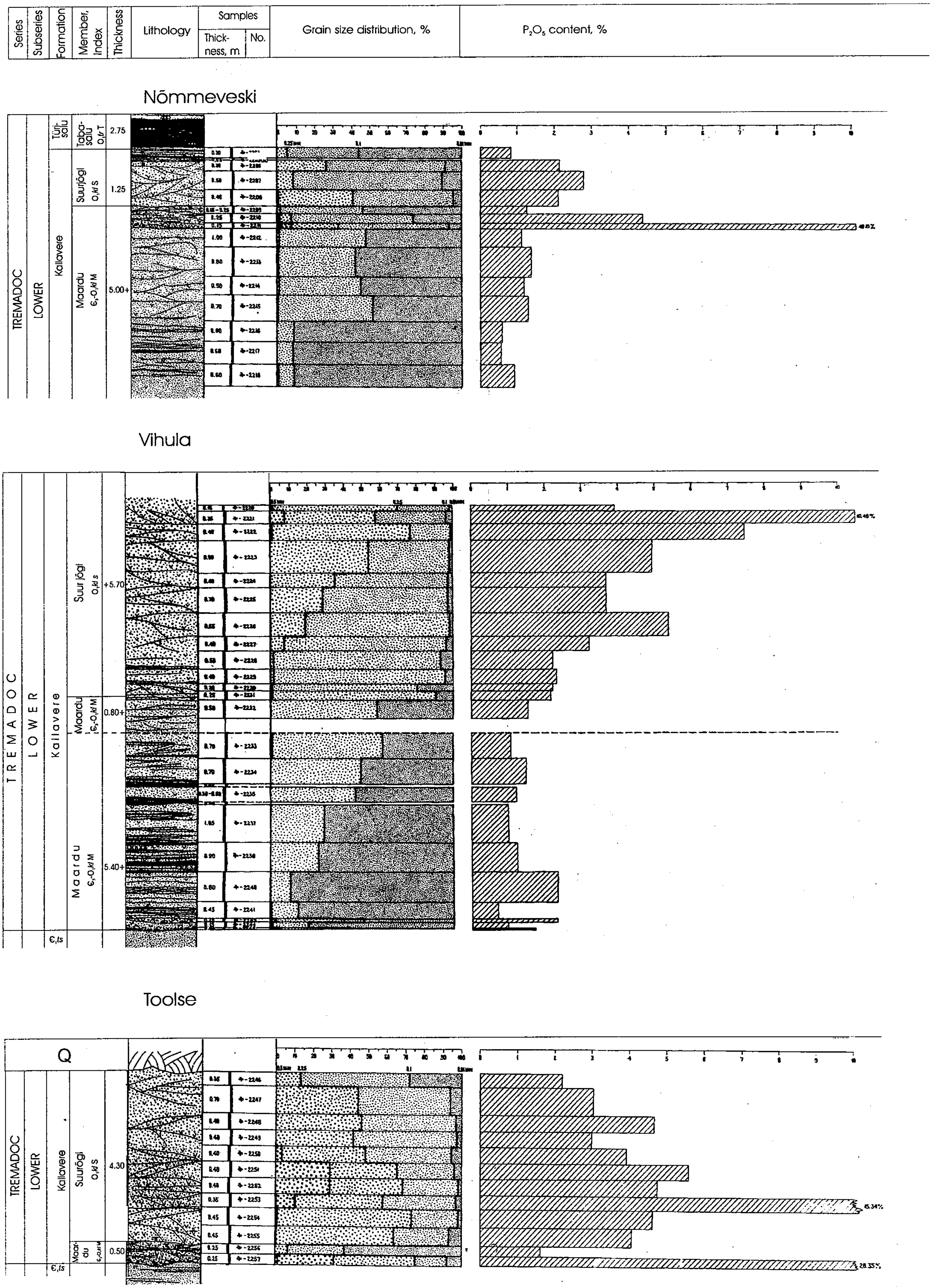


Fig. 5. The sections of Type III and of Type III/IV (Toolse section).

guished in the sections of the Maardu Member. Differences between these types are caused by changes in vertical distribution of the above-mentioned lithological components and their thicknesses.

Suurjõgi Member (O_1kl S)

The member is traditionally known as a "detrital layer" forming the upper part of the Kallavere Formation. In the area studied the Suurjõgi Member always lies on the Maardu Member. Yet, as established by the data on microfauna (conodonts), the Suurjõgi Member is locally coeval with the Maardu Member (Fig. 1). The Suurjõgi Member is characterized by fine- and medium-grained (0.1–0.5 mm) quartz sandstone with peculiar cross-bedding of predominantly dark-coloured (grey to black, brown) phosphatic brachiopod detritus. As a rule, the detritus is well sorted, 1–2 mm in size, with very rare larger fragments. Sandstone is usually poorly cemented, although on the outcrop surface cementation may be very strong.

The thickness of the member is between 0.5 and 5.7 m. In West Estonian sections the upper part of the member is pyritized to a variable degree, forming a so-called pyrite layer, from 2–3 to 15–20 cm in thickness.

Type I sections

Type I sections are distributed in the westernmost part of the North Estonian Klint west of Tallinn and are well observable in the Türisalu, Suurupi and Rannamõisa outcrops (Fig. 2). The **Maardu Member** is here represented by light-coloured, as a rule weakly cemented fine-grained (0.1–0.25 mm) and very fine (0.05–0.1 mm) quartz sandstone containing detritus of phosphatic brachiopods and dark argillite interbeds with a thickness from a few millimetres to some centimetres. This type of sections is characterized by the concentration of the argillite interbeds in the lower half of the member. Commonly, on the base of the member lies an up to 15–20 cm thick argillite layer, which in turn may contain very thin stripes or layers of fine-grained quartz sand. When the Maardu Member is underlain by the so-called basal conglomerate of the Tiskre Formation ($Є_1ts$) (Becker, 1925), the argillite covers the pebbles and fills the cracks between them (Müürisepp, 1958b).

Brachiopod coquina, which marks the lower boundary of the Maardu Member in the sections east of Tallinn, first appears in the distribution area of Type I sections in the Suurupi outcrop. It occurs there as a 10 cm interlayer not on the lower boundary of the member but ca 0.5 m higher (Fig. 2). In the Rannamõisa outcrop brachiopod coquina is found as small lenses already on the lower boundary of the Maardu Member, in places immediately on the sandstone of the Tiskre Formation or in hollows between the pebbles of the basal conglomerate, sometimes also on the lowermost dark argillite layer (Photos 1 and 2).

The argillite interbeds in quartz sandstone are horizontal or wavy, from a few millimetres to some centimetres in thickness, sometimes occurring in groups. The sections with a higher frequency of argillite interbeds always show an increase in the amount of very fine (0.05–0.1 mm) quartz grains in sandstone (Fig. 2).

The thickness of the Maardu Member in Type I sections ranges from 1.4 to 3.25 m.

The lower boundary of the Maardu Member is distinctly marked in Type I sections, but its upper boundary, the contact with the Suurjõgi Member (O_1klS) is gradual. The thickness of the transitional beds is 0.1–0.35 m.

The **Suurjõgi Member** is represented by fine- to medium-grained cross-bedded, generally weakly but on the outcrop surface often very strongly cemented quartz sandstone containing detritus of phosphatic brachiopods. The cross-bedding is caused by alternation of thin interbeds of quartz grains and detritus. Brachiopod detritus is dark-coloured, well-sorted (1–2 mm), making up to 15–35 % of total rock. Thus the rock of the Suurjõgi Member is always darker and seems coarser due to the occurrence of detritus. This makes the member visually well distinguishable in outcrops. Often the rock is rust-coloured due to the presence of iron oxide films on quartz grains.

However, all these characteristics are well observable only in klint outcrops. According to data from the drill cores 10–15 km south of the klint, one of the basic features of the Suurjõgi Member – detritus – disappears there. In this area the member can still be distinguished by coarser quartz grains. As the present study has shown, the transition from the Maardu Member to the Suurjõgi Member is always characterized by distinct coarsening of quartz grains in sandstone (Fig. 2).

The uppermost part of the Suurjõgi Member, which lies immediately below the argillite (Dictyonema shale) of the Tabasalu Member, is practically always pyritized (so-called pyrite layer). The degree of pyritization is variable, from cement of quartz sandstone to pure pyrite plate with completely or almost completely corroded quartz grains. The thickness of the "pyrite layer" is from a few centimetres to 15–20 cm.

Type II sections

Sediments of the Kallavere Formation representing this type of sections are distributed directly east of Tallinn. The easternmost point where these sections have been studied is the Muuksi outcrop, located a few kilometres west of Valgejõgi River. The Nõmmeveski outcrop examined at Valgejõgi belongs already to Type III.

Type II sections show the occurrence of a layer of brachiopod coquina everywhere in the lower part of the **Maardu Member**. In some sections it forms up to half of the member (Fig. 3). The upper part of the Maardu Member is represented by light quartz sand which contains dark argillite interbeds in variable numbers, ranging from a few millimetres to some centimetres, rarely 10–15 cm, in thickness. Thicker argillite interbeds in turn comprise very thin light sand interlayers. The argillite interbeds are predominantly horizontal, but often wavy or inclined beds occur as well. In the eastern sections of Type II (e.g. Turjekelder outcop; Fig. 4), the Maardu Member includes argillite and, as exception brownish or grey clay interbeds.

As a rule the clay interbeds characterize the Tsitre Formation which lies under the Maardu Member.

The brachiopod coquina occurring in the lower part of the Maardu Member constitutes an accumulation of different-size fragments of phosphatic brachiopods in quartz sand. In Type II sections brachiopod coquina is always represented by alternating cross-bedding of fine detritus and unbroken valves in quartz sand.

In the western sections of Type II (Iru–Jägala), the Kallavere Formation is underlain by the Upper Cambrian **Ülgase Formation** ($Є_3$*ül*) in the eastern (Valkla–Muuksi) by the **Tsitre Formation** ($Є_3$*ts*). In both cases the contact with the overlying brachiopod coquina of the Maardu Member is distinct, in places horizontal, but in places uneven, containing pockets. The lower part of brachiopod coquina may contain also quartz sandstone pebbles of different size, which are mostly flat in shape, sometimes dark-coloured, phosphatized. The upper boundary of the brachiopod coquina layer is as a rule transitional, the amount of valves and detritus gradually decreases upwards, and thus the rock becomes an "empty sandstone". This can be well illustrated on the example of the Ülgase outcrop, where the P_2O_5 content is 22.6 % on the base of the layer but only 5 % on the top. We can see that from base to top the amount of detritus and valves in brachiopod coquina decreases from 65–70 % to 15 %, still lowering upwards in the layer.

The clastic terrigenous component, mostly represented by quartz in brachiopod coquina, occurs in the western Type II sections (Fig. 3) mainly as fine-grained sand (0.1–0.25 mm) which makes up to 75–95 % of the whole quartz. Nevertheless, this rock contains always also coarser grains, although in scarce numbers. The total amount of coarser grains increases from 4–5 % in the west (Iru) to 15 % in the east (Jägala).

The quartz grains in the sandstone of the brachiopod coquina lying on the base of the Maardu Member are coarser in the eastern Type II sections than in the western sections, tending to increase to the east. For example, in the Valkla outcrop fine-grained sand is strongly dominating (60–80 % of quartz), at Turjekelder and Muuksi medium sand (0.25–0.5 mm) is already prevalent in the rock, making 45–50 % of total quartz, and in the Turjekelder section the coarse sand fraction (0.5–1.0 mm) forms up to 20 % of total quartz (Fig. 4).

The thickness of the brachiopod coquina layer lying on the base of the Maardu Member ranges from 0.1–0.2 m to 0.6–0.7 m, in places even more. The brachiopod coquina layer having sufficient thickness and P_2O_5 content is considered as phosphorite. The parameters required at the present time are 1 m and 6 % P_2O_5, respectively. The western sections of Type II namely characterize the Maardu phosphorite deposit, eastern sections – the Tsitre deposit.

As a rule, brachiopod coquina occurs as lenses of variable thickness. However, beside the basal brachiopod coquina layer described above, in the western sections of Type II the Maardu Member includes the second coquina layer, occurring also as lenses, but being less in thickness (0.1–0.25 m). The lower boundary of the second coquina layer as well is always distinct, with traces of erosion, and marks the beginning of the next transgressive cyclite in the sedimentation process.

In the eastern sections of Type II, too, another brachiopod coquina layer has been recorded, but it occurs already on the lower boundary of the Tsitre Formation below the Maardu Member (Fig. 4). Quite recently the Tsitre Formation was still ascribed to the Maardu Member, and only acritarch datings proved its upper Cambrian age (Volkova, 1989).

In the distribution area of Type II sections, the upper part of the Maardu Member above the higher coquina interbed consists of fine-grained quartz sandstone with dark argillite interlayers, whereas the frequency of argillite interlayers is greater in the western sections. In this part of the section the grain-size composition of quartz is dominated by very fine (0.05–0.1 mm) and fine (0.1–0.25 mm) sand, with one or another prevailing. These changes show no distinct regularity.

In Type II sections the contact between the Maardu and overlying Suurjõgi members is distinct, unlike the more western Type I and more eastern Type III sections, where this boundary is transitional. In the Type II sections the boundary is defined by a mostly 0.5–1 cm thick horizontal or wavy dark argillite interbed, lying on the top of the Maardu Member. In the eastenrmost outcrop of this type, Muuksi, the boundary is already gradual; the thickness of the transitional layer is ca 0.15 m.

The stratotype of the Maardu Member and the whole Kallavere Formation is the Ülgase outcrop, located in the western area of this type of sections.

The **Suurjõgi Member** is represented by cross-bedded detrital quartz sandstone which is darker in colour and coarser (medium- to fine-grained) than in the Maardu Member. Usually, in Types I and II sections the Suurjõgi Member is characterized by 2–3 series of cross bedding, which differ in colour, detritus content or inclination of layers inside the series. The amount of detritus is greater in the western sections (Iru and Maardu outcrops), reaching there up to 20–30 %, but only up to 10 % in the eastern sections. The thickness of the member ranges from 0.7–0.8 m to 1.3–1.4 m.

In western sections, from Iru to Jägala, at the upper boundary of the Suurjõgi Member lies a 5–8 cm thick "pyrite layer".

Type III sections

Type III sections of the Kallavere Formation have been studied in the Nõmmeveski outcrop on the steep right bank of the Valgejõgi River and in two Vihula outcrops: Suurjõgi and Katela members on the left bank of the Mustoja (or Suurjõgi) River and the Maardu Member in an outcrop on the high right bank, a few hundreds of metres downstream.

In this type the lithology of the **Maardu Member** is rather monotonous. The lower boundary of the member is marked by a some centrimetres thick layer of brachiopod coquina, which in the Vihula outcrop contains abundantly rounded different-size (up to 1 cm) pyrite concretions. Upward occurs light-coloured fine- to very fine-grained quartz sandstone. Throughout the member it contains generally relatively regular interbeds of dark argillite, ranging from a few millimetres to 10 cm in thickness (Photo 3). Thicker argillite beds in turn contain very thin sandstone interbeds.

In the Nõmmeveski section, west of Vihula, the lower boundary of the Maardu Member is not exposed, lying below water level. The c. 4.5 m thick part of the section above the water surface shows typical characteristics of the Maardu Member: light quartz sandstone with thin interbeds of dark argillite, the concentration of which is greater in the ca 2 m interval immediately higher the water level (Fig. 5). However, about 4.5 m above the water surface a 0.15 m interbed of brachiopod coquina appears in the section. As usual, its lower boundary constitutes a slightly uneven sharp erosional surface. Upwards the amount of detritus decreases constantly (as it usually does) and gradually the rock goes over to that of the Suurjõgi Member. The entire thickness of the described part is 0.55–0.65 m.

This interbed of brachiopod coquina in the Nõmmeveski outcrop could be considered as an analogue of the upper coquina in Type II sections, but it lies extraordinarily close to the upper boundary of the Maardu Member. Moreover, lithologically it is more similar to the coquina characterizing the Rannu Member in eastern sections (east of Aseri) than to the typical coquina of the Maardu Member. Thus, we may say that in the Nõmmeveski outcrop section the lithology of the upper 0.55–0.65 m of the Maardu Member is untypical of both the Maardu Member and the overlying Suurjõgi Member.

Basing on their studies, the geologists from St. Petersburg L. Popov and K. Khazanovich proposed a new scheme for the stratigraphic subdivision of Estonian Tremadoc (Opornye razrezy..., 1989). In their scheme they distinguished the Maardu and Lahemaa formations. The Nõmmeveski outcrop was proposed as the stratotype of the Lahemaa Formation and the above-mentioned interbed of brachiopod coquina as its lower boundary. The Lahemaa Formation comprised the part of the section upwards from the lower boundary of the brachiopod coquina layer, including the detrital sandstone and whole argillite complex of the Türisalu Formation. The Lahemaa Formation was subdivided into (from base to top) the Vihula, Orasoja, Toolse and Türisalu members. The formation was underlain by the Maardu Formation which in turn divided into (from the base) the Maardu and Suurjõgi members. We should note that in the outcrops west of Nõmmeveski the lower boundary of the Lahemaa Formation proposed by L. Popov and K. Khazanovich coincides with the lower boundary of the Suurjõgi Member of our scheme, but in the Vihula and Toolse outcrops east of Nõmmeveski it lies inside the Suurjõgi Member, ca 1 m below the upper boundary of the member.

Quartz grains of the sandstone (alternating with dark argillite) of the Maardu Member in Type III sections are mostly represented by the fine (0.1–0.25mm) and very fine (0.05–0.1mm) sand fraction. Very fine sand fraction is strongly prevailing in the lower part of the member, whereas the share of fine sand grows markedly in its upper part (Fig. 5). The quartz of brachiopod coquina contains also much coarser grains.

As compared to the more western sections, the thickness of the Maardu Member tends to increase in Type III sections, exceeding 5 m there. Unfortunately, this thickness is not observable in either outcrop.

The boundary between the Maardu and Suurjõgi members is again transitional in Type III sections like in Type I sections. The thickness of the transitional part of the section is 0.45 m in the upper (left bank) Vihula outcrop.

The **Suurjõgi Member** has been distinguished by A. Loog with a stratotype section in the upper Vihula outcrop. Like more western sections, it is lithologically represented by medium- to fine-grained, relatively weakly cemented detritic cross-bedded quartz sandstone. As usual, the sandstone is darker in comparison with the Maardu Member.

However, the thickness of the member is notably greater – almost 6 m at Vihula against 1 m in Types I and II sections. Cross-bedding can be observed as well. The more western sections usually show the presence of 2–3 more-or-less horizontal series of cross-bedding in the sequence of the Suurjõgi Member, but the stratotypic Vihula outcrop is characterized by lenticular and wedge-shaped cross-bedding.

Quartz grains of the Suurjõgi Member are dominated by the fine sand fraction in the lower two-thirds of the section, but in the upper one-third of the section the share of medium sand increases notably, becoming prevalent (Fig. 5). An increase in the size of quartz grains is accompanied by a growth in P_2O_5, i.e. the share of phosphatic detritus grows. Thus, at Vihula the Suurjõgi Member constitutes an example of a small regressive cyclite.

Due to the changed situation in the Vihula outcrop, recently part of the section was exposed above the Suurjõgi Member, which possibly resembled more the Maardu Member than the Suurjõgi Member. After similar sediments had been found in cores near Toolse and Haljala, it turned reasonable to distinguish a new, Katela (O_1*kl*K) Member (Heinsalu 1981; 1987) with the stratotype in the Vihula outrop.

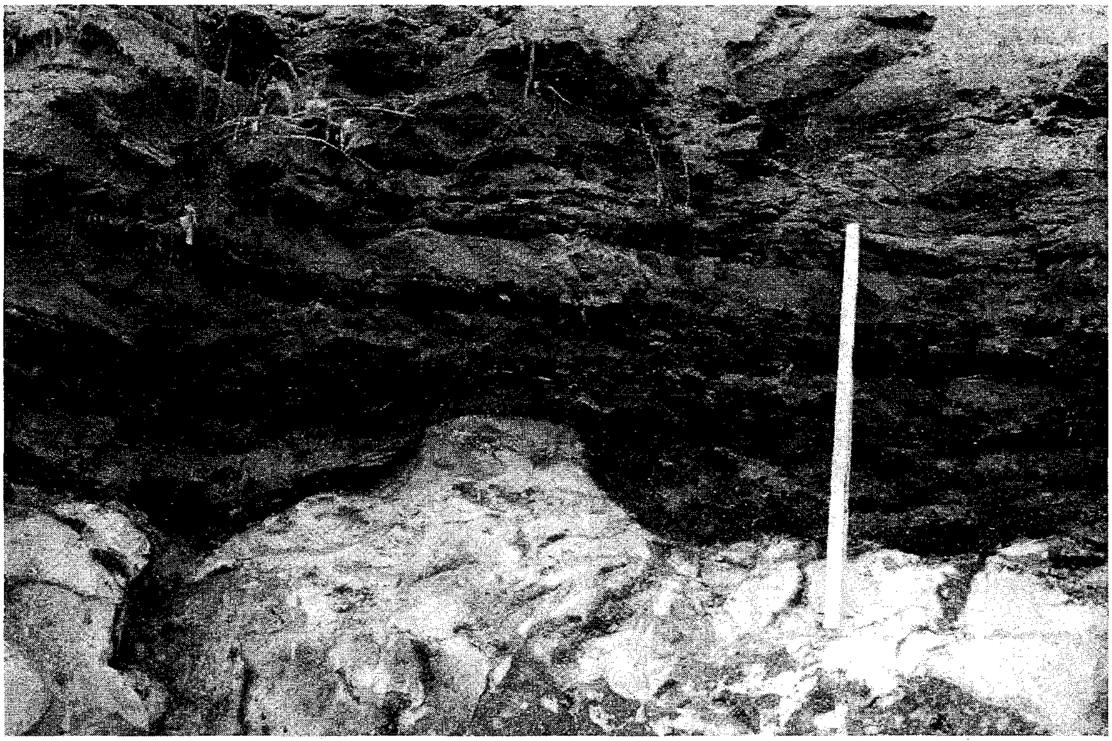
The **Katela Member** is represented by light-coloured fine- and very fine-grained weakly cemented quartz sandstone containing rare thin interbeds of dark argillite. The amount of phosphatic detritus is minimal or it is entirely lacking.

The rocks of the Katela Member are represented by very fine and fine sand fraction with slight prevalence of the latter.

The thickness of the member is 0.60 m in the Vihula outcrop.

Transitional (Type III/IV) Toolse section

The sections of the Kallavere Formation, located in the steep left bank of the Toolse River, are the easternmost sections among those considered in the present paper, and also the marginal ones on the distribution area of the



Photos 1 and 2. The lower boundary of the Kallavere Formation at Rannamõisa outcrop.
Photos by Ü. Heinsalu.

Photo 3. Maardu Member at the Vihula outcrop (right bank of Mustoja river). Photo by Ü. Heinsalu.

Photo 4. Cross-bedding sandstone of Suurjõgi Member at the Toolse outcrop (left bank of Toolse river). Photo by Ü. Heinsalu.

Maardu and Suurjõgi members. By lithology, in the studied Toolse outcrop (Fig. 5) the Suurjõgi and Katela members belong to Type III sections, but the Maardu Member is different.

In the Toolse outcrop the **Maardu Member** has similar characteristics as in Type II sections. Again, brachiopod coquina is highly significant. Still, unlike Type II sections, the thickness of the Maardu Member is small here, only 0.5 m, half of which is represented by the coquina very rich in brachiopod valves and detritus (Fig. 5). The upper half of the member is represented by lighter quartz sandstone with thin dark argillite interbeds.

At Toolse the grain-size composition of quartz in the rocks of the Maardu Member differs notably from that of Type II sections at Maardu. In Type II sections the fine sand fraction dominates in the quartz of brachiopod coquina. The share of medium to coarse sand is hardly up to 5–10 % at Maardu, but at Toolse it reaches already ca 70 %. At Toolse the upper part of the member is mostly represented by very fine sand fraction, which makes up more than 60 % of quartz in this layer. Thus, the spectrum of the grain-size composition of quartz is wider and more diverse at Toolse than at Maardu (Type II). In advance, we may say that at Toolse the Maardu Member is granulometrically more similar to the Rannu Member which occurs in more eastern sections than to the Maardu Member in the vicinity of Maardu.

The **Suurjõgi Member** at Toolse generally has the same characteristics as in the Vihula outcrop (Photo 4), the thicknesses are similar as well. However, the average grain size of the quartz sandstone of the Suurjõgi Member is coarser at Toolse than in the westward Vihula section (Fig. 5).

The **Katela Member** is absent in the Toolse outcrop. Owing to erosion, probably also the upper part of the Suurjõgi Member is missing. Still, after the discovery of the Katela Member in the Vihula outcrop it was established also in the section of a temporary ditch a few hundreds of metres north of the main outcrop. Here as well the member is represented by very fine- and fine-grained light quartz sandstone containing rare thin interbeds of dark argillite. The visible thickness of the member is here 0.9 m.

The section of the Toolse outcrop characterizes the Toolse phosphorite deposit where the commercial layer is several times thicker than at Maardu. In the Maardu deposit the commercial layer includes only the brachiopod coquina in the lower part of the Maardu Member, but in the Toolse deposit it comprises the entire Maardu Member and most of the Suurjõgi Member.

SUMMARY

In the Paldiski–Kunda area near the North Estonian Klint the Maardu and Suurjõgi members of the Kallavere Formation are distributed. Additionally, in the easternmost part of this region the Katela Member is distinguished. The rock of the Maardu Member is dominated by light, weakly cemented quartz sandstone with dark argillite (Dictyonema shale) interbeds. In the Iru–Kuusalu region the brachiopod coquina plays an important role in the lower half of the Maardu Member. In klint sections the Suurjõgi Member is always represented by cross-bedded, somewhat darker quartz sandstone containing phosphatic brachiopod detritus, known as the detrital layer. The Katela Member, which in the Viitna–Kunda area lies on the Suurjõgi Member, is again represented by lighter and more fine-grained quartz sandstone. The sandstone is very poor in detritus and contains rare thin argillite interbeds.

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