Stop 2: Kalana quarry

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Location: Latitude 58°43´15.8˝N, longitude 26°01´53˝E; Jõgeva County, Estonia.
Stratigraphy: Aeronian, Raikküla Fm, Jõgeva and Imavere beds, Raikküla RS.
Status: Active quarry; please follow safety instructions. Sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/15417

The new Kalana quarry (officially known as the Otisaare limestone quarry) is located about 8 km to NNE from the small town of Põltsamaa and approximately 1 km west of Kalana village. It has an area of 16.34 ha and is operated by AS Kaltsiit, producing crushed stone. The smaller old Kalana quarry is located 1–1.5 km southeast of the new quarry.

Fig. 2.1. The western wall of the Kalana quarry (height about 15 m). Beds 1–5, Jõgeva Beds. **1** – fine-grained limestone (packstone, grainstone) with marl intercalations, 2.4+ m; **2** – massive grainstone ("Kalana Marble"), 0.8–1.2 m; **3** – grainstone with marl intercalations, 1–2 m; **4** – massive grainstone ("Kalana Marble"), with a bed of thin laminated grainstone-marl at the base, 0.5–1.0 m; **5** – grainstone intercalating with argillaceous limestone (wackestone, packstone) and marl, 3 m. Bed **6**, Imavere Beds – argillaceous limestone and marl (wackestone, mudstone), 3.5+ m.

General information

In Central Estonia, in the surroundings of Põltsamaa, the cover of Quaternary sediments is thin and Silurian limestones and dolostones lie close to the surface. This is why local people have used these rocks for building and lime burning for centuries (Perens 2006). The region is dotted with numerous small old quarries, which are mostly out of use and hardly distinguishable in the modern landscape. However, several large quarries, such as Rõstla, Kalana and Sopimetsa, are actively operating and producing crushed stone for various uses.

The Kalana quarry has caught the attention of geologists for several reasons. First, it is one of the few localities in a confined area where a distinctive type of grainstone, known as Kalana marble, can be observed. Second, in

2006, Tõnu Pani, then the curator of geological collections at the Natural History Museum of the University of Tartu, discovered the first exceptionally preserved algal fossils. Over time, it became clear that the number, preservation, and quality of these fossils is truly remarkable, and has led to the description of the biota as the Kalana *Lagerstätte* (Tinn *et al.* 2009). Finally, certain levels and parts of the quarry reveal an uncommon amount of mineralisation, mostly barite, various sulfides and variable degrees of silicification.

Lithology and stratigraphy

In the Kalana quarry (Fig. 2.1), an interval of the shallow shelf carbonates of the Raikküla Regional Stage is exposed. The succession includes a series of shallowing-upward sedimentary cycles of the Aeronian age. In general, the cycles consist of open shelf argillaceous carbonates in their lower parts and of shoal and restricted shelf carbonates with interbeds of cross-bedded bioclastic grainstone and micritic limestone in their upper parts (Tinn *et al.* 2009). In micritic intervals, tempestites and organic-rich laminae are common. Five major sedimentary cycles, the Järva-Jaani, Vändra, Jõgeva, Imavere and Mõhküla beds, are described in the Raikküla Stage (Perens 1992). The upper part of the Jõgeva Beds and the basal Imavere Beds are exposed in the Kalana quarry. The strata are slightly deformed and dipping westwards; therefore, the oldest part of the interval is exposed on the eastern side of the quarry.

Mining in the Kalana quarry has been intensive, and the fossil-rich strata of the Jõgeva Beds (Ainsaar *et al*. 2014;

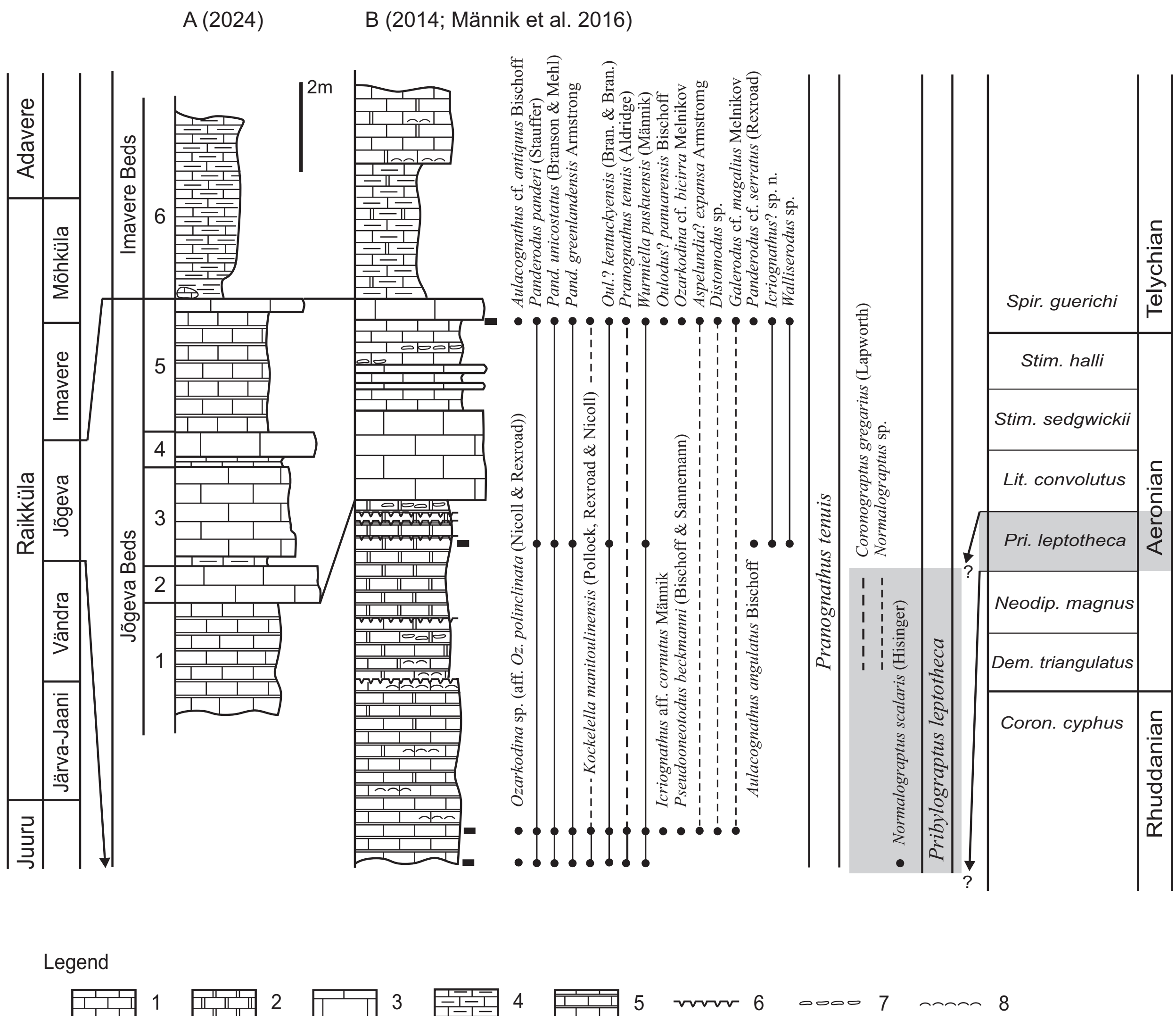

Fig. 2.2. Section of the Kalana quarry in 2024 (A) and 2014 (Ainsaar *et al*. 2014) with conodont distribution and biostratigraphy after Männik et al. (2016). From left to right: regional stages; beds in the Nurmekund Formation; beds of the 2024 quarry wall description (Fig. 2.1); lithology; section published in Männik *et al*. (2016); distribution of conodonts; conodont biozone recognised; distribution of graptolites; graptolite biozone recognised; Aeronian graptolite biozonation. Grey interval marks the identified graptolite biozone. Legend: 1, limestone (wackestone and packstone); 2, dolomitised wackestone and packstone; 3, limestone (grainstone); 4, argillaceous limestone (wackestone); 5, intercalation of different limestones and dolomitised limestones (mainly wackestone and packstone) with kerogenous laminae and thin interbeds; 6, pyritised discontinuity surfaces; 7, lithoclastic tempestites; 8, coquinal interbeds. Abbreviations: *Coron*., *Coronograptus*; *Dem*., *Demirastrites*; *Lit*., *Lituigraptus*; *Neodip*., *Neodiplograptus*; *Pri*., *Pribylograptus*; *Spir*., *Spirograptus*; *Stim*., *Stimulograptus*; Bran. & Bran., Branson & Branson.

Tinn *et al*. 2009) are not exposed any more, lying below the quarry floor (Fig. 2.2). These beds are described as dolomitic limestone, which originally might have been wackestone and/or packstone. This interval contains numerous 1–20 mm thick lenses and irregular interbeds of light to dark brown organic-rich, microlaminated, dolomitised limestone, which contains abundant non-calcified algae. Fauna in these kerogenous interbeds is represented by monograptid and diplograptid graptolites, scolecodonts, bryozoans, sponges and crinoids. The succession also contains lithoclastic and bioclastic tempestites, the latter yielding abundant gastropods, ostracods and brachiopods (Tinn *et al*. 2009). Small rugose corals are also common, and cephalopods can be found.

The top of the Jõgeva Beds is well exposed, and it is represented by a series of beds of pure hard light grey cross-bedded fine-grained grainstone in a thickness of 1–4 m. This rock is known as a good building limestone and, historically, is called the “Kalana Marble”. Interbeds of micritic limestone in grainstone often contain lithoclastic tempestites, formed from lithified pebbles of the same micritic limestone. The Imavere Beds are represented by partly dolomitised greenish-grey argillaceous micritic limestone. The exposed thickness of these beds increases westwards, where an increase in carbonate content is visible upwards in the succession (Ainsaar *et al*. 2014).

Stratigraphically, the section with the highest concentration of exceptionally preserved fossils is of mid-Aeronian age and corresponds to the *Pribylograptus leptotheca* graptolite Biozone that is not exposed in the new (2024) section. In terms of conodont biostratigraphy, the strata correlate with the middle of the *Pranognathus tenuis* conodont Biozone (Männik *et al*. 2016).

The Jõgeva and Imavere beds have been considered to be of early and middle Aeronian age, respectively (Nestor 1997). All samples processed for conodonts from the Kalana quarry come from the Jõgeva Beds, and three of them yielded specimens of *Pranognathus tenuis* (Aldridge), indicating the *P. tenuis* conodont Zone for this interval (Männik *et al*. 2016). *P. tenuis* occurs in the Jõgeva Beds also in several other sections in Estonia (Nestor *et al.* 2003). Based on co-occurrences of conodonts and chitinozoans in these sections, and chitinozoans and graptolites in others (e.g., Loydell *et al.* 2003), the level of its appearance in the region has been dated as early Aeronian. However, this does not agree with data from elsewhere where *P. tenuis* seems to occur in the upper Aeronian, in the *Lituigraptus convolutes* graptolite Zone (Cramer *et al.* 2011). The sample from the middle part of the Jõgeva Beds in the Kalana section shows the appearance of *Aulacognathus angulatus* Bischoff and the sample from its uppermost part of *A.* cf. *antiguus* Bischoff both of which were stated to occur in the uppermost Aeronian *Stimulograptus sedgwickii* graptolite Zone in Australia (Bischoff 1986), although this has not been proved by the finds of graptolites. Hence, when comparing with data from elsewhere, both samples indicate a younger age for the Jõgeva Beds than the data from the northern Baltic area. The explanation for this discrepancy might be that, as *P. tenuis* and *A. angulatus* are both known from very few regions, their specimens are rare in the sections and occur sporadically, the real FADs and distribution intervals of these taxa have been poorly known, and they appeared earlier than suggested before. However, problems in regional stratigraphy cannot be excluded as well.

Fossils

The studies have revealed a high abundance and remarkable diversity of noncalcareous algal fossils of exceptional preservation in the Kalana section. About a dozen morphological groups of algal fossils that have been distinguished represent either distinct species or different growth stages. The most abundant in this flora is *Leveilleites hartnageli* Foerste (Fig. 2.3: A), a species that is morphologically indistinguishable from the specimens described from the Hirnantian strata of Canada. From the palaeoecological perspective, this indicates a wide distribution of the species in two palaeobasins, its long temporal range in the Iapetus Ocean, and survival of the Late Ordovician Mass Extinction (Mastik & Tinn 2017). Based on the distinctive architecture of its thallus and the position of the reproductive structures, *L. hartnageli* has been assigned to the Division Rhodophyta.

Many of the algal fossils in Kalana can be assigned to the Order Dasycladales (Division Chlorophyta), which is an extant group of large unicells generally dominated by calcareous forms and having a long and highly diverse geological history (Berger & Kaever 1992). The dasyclade flora in Kalana includes *Paleocymopolia silurica* (Mastik & Tinn 2015) (Fig. 2.3: B, C), a species with serially segmented dichotomously branching non-calcified thallus, *Kalania pusilla* (Tinn *et al*. 2015) (Fig. 2.3: D), and several yet undescribed species.

Crinoid fossils often occur as disintegrated fragments or short columnals. However, the section has also yielded well-preserved, almost complete specimens of stalked crinoids with fine pinnules attached to slender brachials on calyces. Two species, *Kalanacrinus mastikae* (Fig. 2.3F) and *Tartucrinus kalanaensis* (Fig. 2.3E), have been described from Kalana (Ausich *et al*. 2019).

In addition to common normal marine Silurian skeletal fossils like rhynchonelliformean brachiopods and gastropods, which often occur in well-sorted lenses (lithoclastic and bioclastic tempestites), occasional rugose and tabulate corals, nautiloid cephalopods, bryozoans, sponges and trilobites can be found. Certain levels show thin lamination with abundant leperditiid crustaceans and infrequent eurypterid remains, suggesting short periods of shallow lagoonal environments (Mastik 2019).

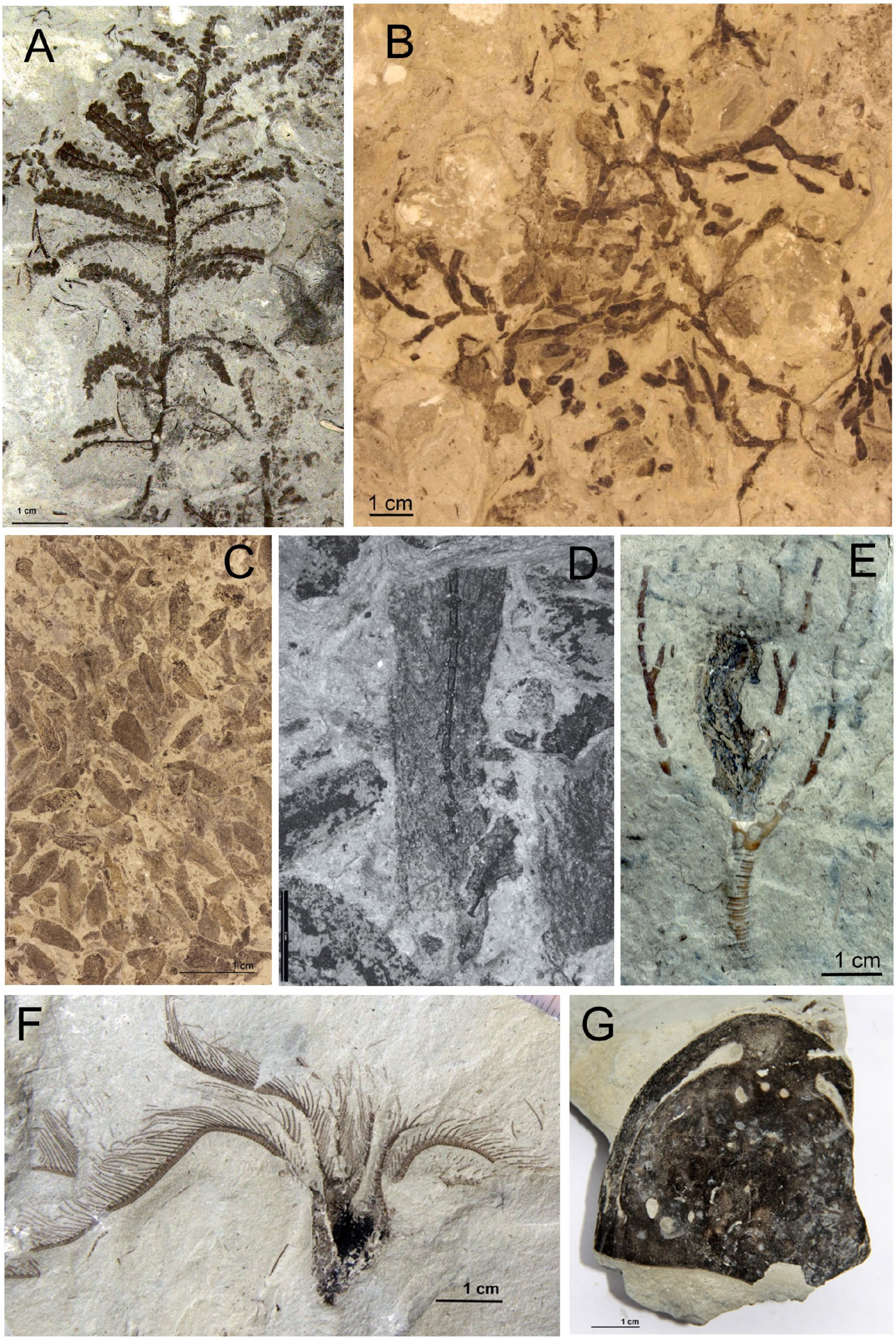

Fig. 2.3. Selected fossils of exceptionally preserved algae, crinoids and an agnathan from the eastern part of the Kalana quarry (now covered). **A** – Rhodophyte alga *Leveilleites hartnageli* Foerste, TUG 1269-1; **B** – dasyclad alga *Palaeocymopolia silurica* Mastik & Tinn, TUG 1269-9; **C** – disintegrated fragments of dasyclad alga *P. silurica* Mastik & Tinn, TUG 1269-12, on the rock surface; **D** – fragment of a dasyclad alga *Kalania pusilla* Tinn, Mastik, Ainsaar & Meidla, TUG 1269-247 demonstrating well-preserved central axis and gametophores; **E** – crinoid *Tartucrinus kalanaensis* Ausich, Wilson & Tinn, TUG 1376-2; **F** – *Kalanacrinus mastikae* Ausich, Wilson & Tinn, TUG 1736-6 with open arms; **G** – head shield of an agnathan *Kalanaspis delectabilis* Tinn & Märss, TUG 1708-1-1.

A single osteostracan fossil *Kalanaspis delectabilis* proved that the ecosystem also comprised vertebrates (Tinn & Märss 2018). However, its anomalous type of preservation – carbonaceous instead of phosphatic – could be the key to the complex taphonomic history of the whole Kalana *Lagerstätte*. According to the current hypothesis (Tinn *et al*. 2021), microbial activity has played a major role in the extraordinary preservation of the Kalana fossils.

Mineralisation

The low-temperature hydrothermal fluid-driven mineralisation in a fracture-controlled cave and vein systems in Kalana quarry carbonate succession is characterised by sphalerite, barite, pyrite, and ^{13}C-depleted speleothem calcite (Eensaar *et al*. 2017a). The earliest calcite-sphalerite veins contain two generations of sphalerite, whose primary fluid inclusions suggest formation in a NaCl-$CaCl_2$-H_2O composition fluid with 24–28 wt% $CaCl_2$eq salinity at temperatures 192–220 °C and 60–120 °C for the first and second sphalerite generation, respectively.

The cave-like structures at the quarry floor exploit pre-existing fractures and are filled with botryoidal calcite, barite, and pyrite aggregates. The calcite from speleothem-like aggregates is depleted in ^{13}C, with $\delta^{13}C$ PDB values as low as −56‰, indicating anaerobic methane oxidation providing the DIC. The $\delta^{18}O$ PDB values range from −10 to −12‰, suggesting precipitation at elevated temperatures, while variations in $\delta^{13}C$ PDB and $\delta^{18}O$ PDB values imply a shift from biogenic methane to thermogenic methane or hydrocarbons as carbon sources in the hydrothermal fluid with the time (Eensaar *et al*. 2017b). The cave structures also contain barite aggregates with individual barite crystala reaching 5-10 cm that likely formed at the mixing front of sulphate-rich seawater/groundwater and methane-bearing hydrothermal fluids in a hypogenic-hydrothermal karst system, facilitating abundant barite and pyrite precipitation under varying redox conditions (Gaškov *et al*. 2017). The timing of the mineralisation is unclear but could be tied to the continental-scale fluid flow induced by the buildup of the Scandinavian Caledonian Orogen in late Silurian–early Devonian.

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