ISOS-14 Field Guide
The Ordovician of Estonia

Edited by Olle Hints and Ursula Toom

14th International Symposium on the Ordovician System, Estonia, July 19-21, 2023
Pre-conference Field Excursion: The Ordovician of Estonia, July 15-18, 2023

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Tallinn, 2023

Excursion Day 3

Stop 9: Põhja-Kiviõli II open-pit mine

Heikki Bauert and Olle Hints

Location: Latitude 59.365394°N, longitude 26.842046°E; Ida-Viru County, NE Estonia.
Stratigraphy: Sandbian, Kukruse Regional Stage, Viivikonna Formation.
Status: Active open-pit mine; please follow safety regulations; sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/23669

Kukersite oil shale has been Estonia's most important mineral resource for over a century, with the first test mining site opened in NE Estonia in 1916. Oil shale has been used primarily for energy production in power plants and producing shale oil and other chemicals. Oil shale production peaked in the 1970-1980s, with over 30 million metric tonnes excavated in Estonia annually. As of 2022, the annual production slightly exceeded 10 million tonnes. However, due to the high environmental impact of oil shale mining and utilisation, the production is expected to decrease gradually, even though carbon capture, utilisation and storage technologies (CCUS) could make its impact on climate much smaller.

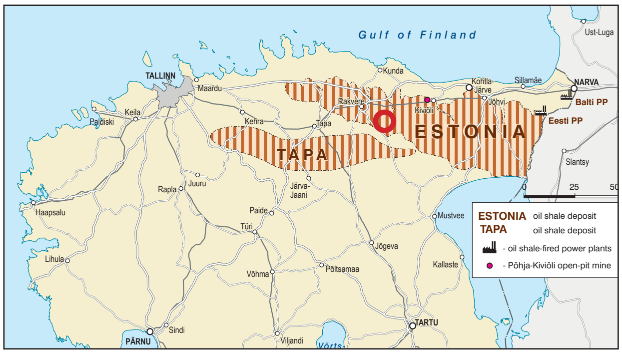

Fig. 9.1. Locality map showing the oil shale deposits in Estonia (from Bauert & Nõlvak 2014).

The Põhja-Kiviõli II open-pit mine (Fig. 9.2, 9.4) is owned and operated by Kiviõli Keemiatööstus (KKT, https://www.keemiatoostus.ee/en). It is located in NE Estonia, along the northern edge of the central part of the main oil shale deposit (Fig. 9.1).

Characteristics of the kukersite oil shale

Oil shale is commonly defined as a fine-grained sedimentary rock containing organic matter (OM) that yields substantial amounts of oil and combustible gas upon destructive distillation. The kukersite OM deposited in argillaceous marine limestones and as many as 50 beds of kukersite and kerogen-rich limestone, alternating with biomicritic limestones (wackestones), have formed during the main phase of kukersite OM deposition in northeastern Estonia during the latest Mid to earliest Late Ordovician time span (Fig. 9.8).

Fig. 9.2. Oil shale succession in the Põhja-Kiviõli II open-pit mine. Photo: Gennadi Baranov, 2019.

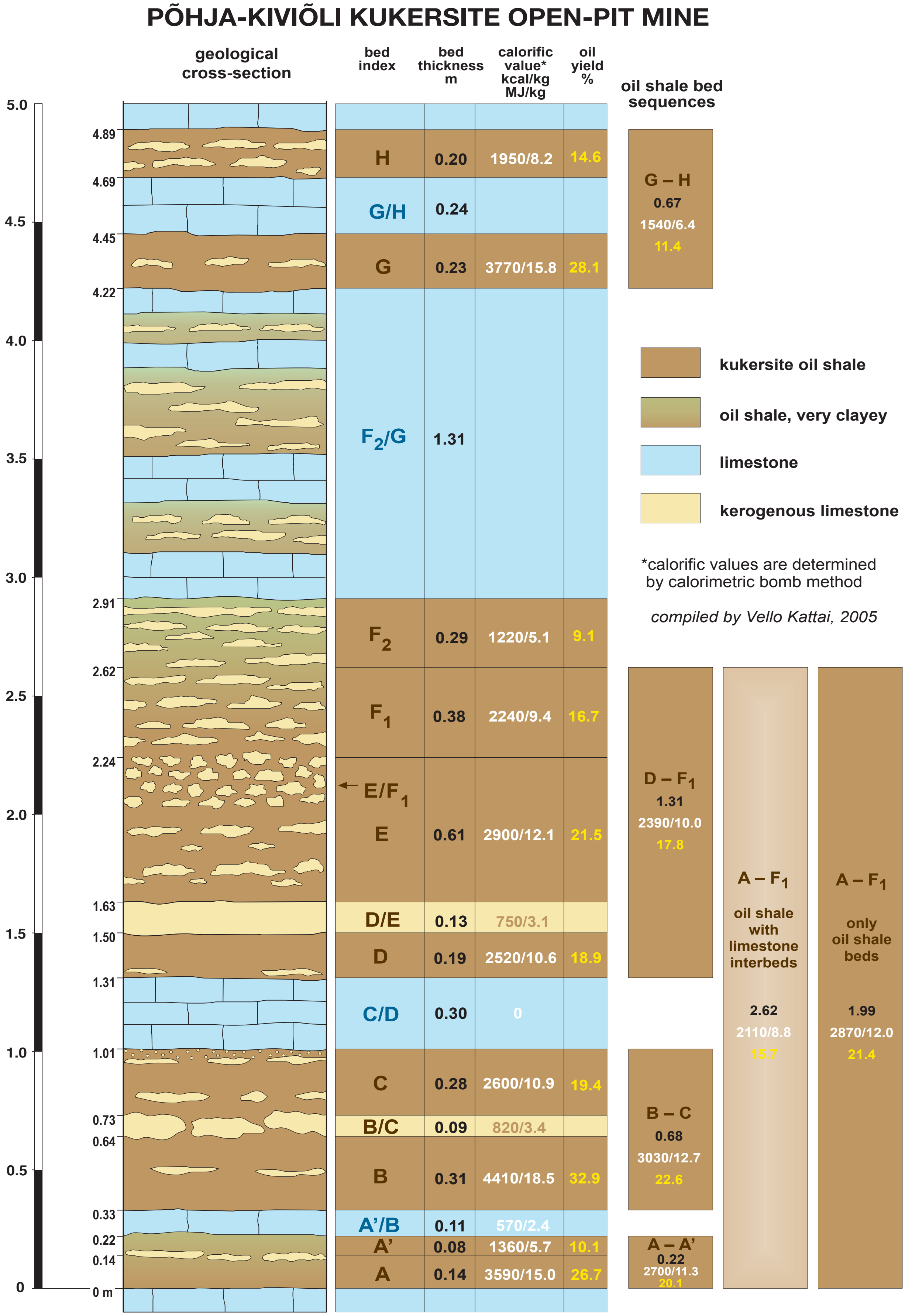

Fig. 9.3. Succession and properties of the oil shale seams in the Põhja-Kiviõli opencast mine (from Bauert & Nõlvak 2014).

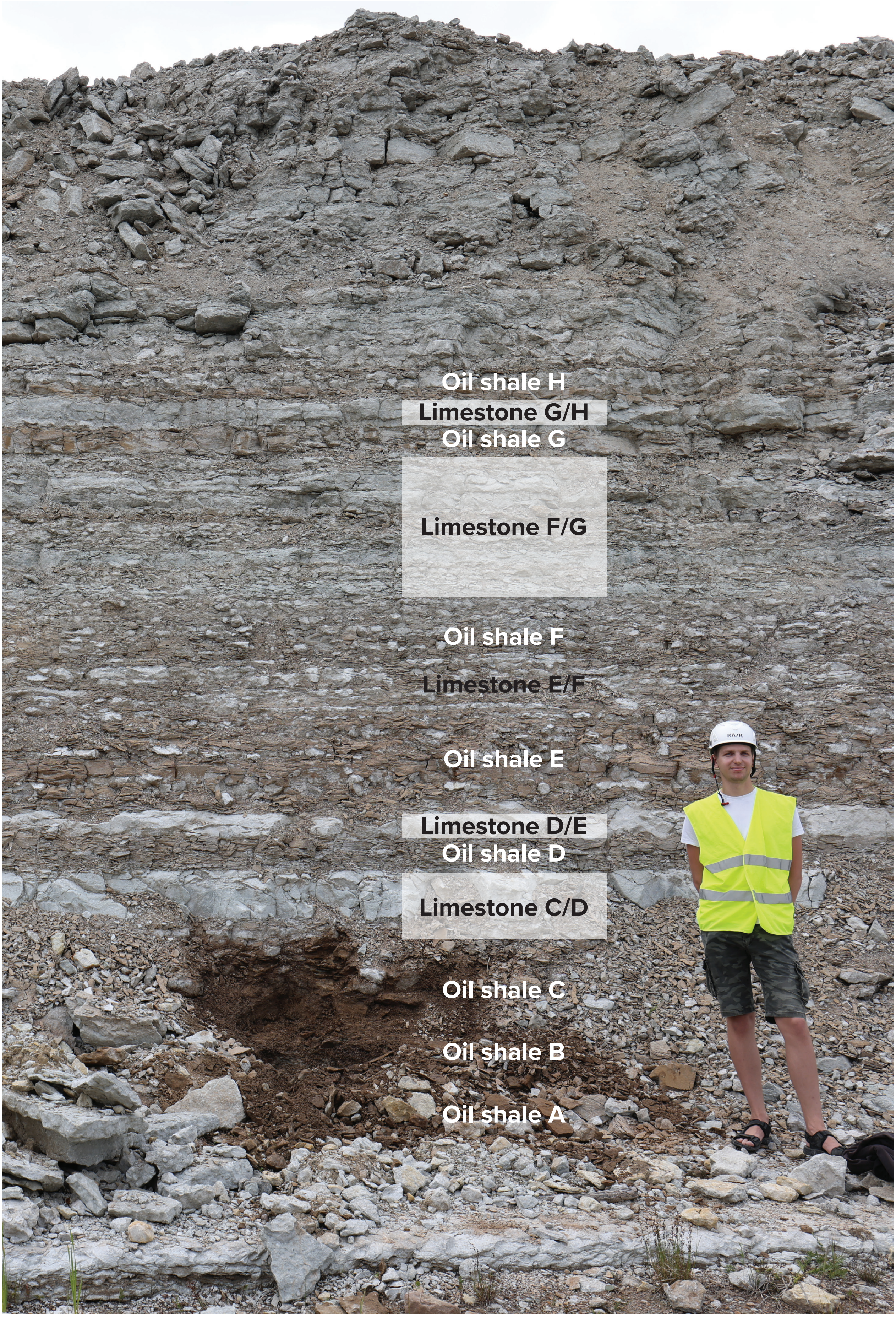

Fig. 9.4. Succession of the oil shale seams in the Põhja-Kiviõli II opencast mine. The lowermost beds are covered by debris, their appriximate position is indicated. The subdivition of beds E to F is complicated on weathered walls. Photo: Olle Hints, 2023.

The kukersite oil shale beds (seams) form an up to 20–30 m thick succession. However, individual kukersite beds of chocolate-brownish colour are commonly 10–40 cm thick and may reach as much as 2.4 m (bed III in the Kerguta-565 drill core; Põldvere 2006) in thickness. The beds designated from "A" to "F2" are feasible for mining and are currently mined in three open-pit mines (Narva, Põhja-Kiviõli, Ubja) and two underground mines (Estonia, Ojamaa).

The main characteristics of individual kukersite beds in the Põhja-Kiviõli mine are shown in Fig. 9.3. The OM content of kukersite oil shale beds varies considerably, reaching as high as 50% TOC in beds B and E in the central area of the Estonia deposit (Foster et al. 1989). Rock-Eval pyrolysis analyses (Dyni et al. 1989; Foster et al. 1989) indicate that kukersite oil shales have a significant hydrocarbon potential [S1 & S2 = 300–350; S1 – kg of hydrocarbons (extractable) per tonne rock; S2 – kg of hydrocarbons kerogen pyrolysate) per tonne rock] and are characterised by a high hydrogen index [HI = 675–960; mg hydrocarbons (S2) per gram of total organic carbon]. These data suggest the prevalence of Type I kerogen in kukersite OM. The elemental composition of kukersite kerogen is as follows: C – 67%, H – 8.3%, O – 12.8%, N – 2.2%, S – 3.5%, H/C – 1.48, O/C – 0.14, S/C – 0.02 (Derenne et al. 1989).

The matrix minerals in Estonian kukersite oil shale beds and interbedded more or less argillaceous limestones (Bauert & Kattai 1997) include mainly low-Mg calcite (usually >50%, but less in kukersite beds), dolomite (generally less than 15%) and siliciclastic minerals. The XRD analyses and thin section studies have revealed that the siliciclastic component mainly comprises silt-sized quartz and illite, while feldspars and chlorite occur in subordinate amounts. Besides, kukersite oil shale contains authigenic pyrite.

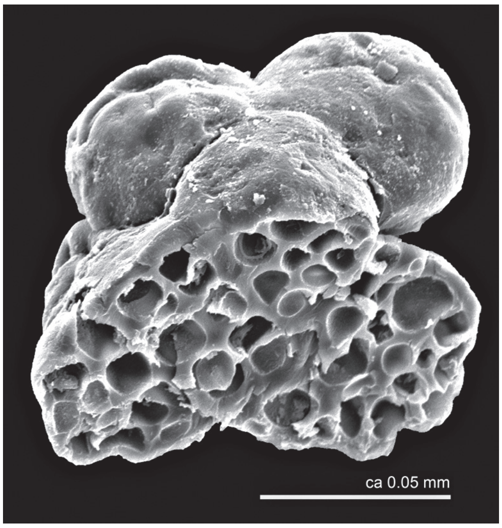

Fig. 9.5. *Gloeocapsomorpha* prisca SEM image (photo: Jaak Nõlvak).

The origin of kukersite

Major kukersite-type OM accumulations have been recorded in the late Uhaku to Kukruse age rocks (Kõrgekallas and Viivikonna formations). However, a few thin kukersite beds or kukersite OM-enriched marlstone beds are known to occur at several other stratigraphic levels in the Ordovician succession (Kõrts 1992): in the Kunda Stage (lower Darriwilian) as well as in the Keila and Nabala stages (uppermost Sandbian to Katian). Based on the dominant OM type, the kukersite is classified as a *Gloeocapsomorpha*-related telalginite (Cook & Sherwood 1991; telalginite refers to the presence of lensoidal, flattened spheroidal or fan-shaped algal remains in OM).

The algal structure of the kukersite was recognised by a Russian botanist M. Zalessky in 1917. He described oval bodies in kukersite kerogen and interpreted them as the remains of an extinct microorganism. Due to morphological similarity with the extant cyanobacterium *Gloeocapsa quaternata* Kützing, he named the colonial cellular bodies in kukersite as *Gloeocapsomorpha prisca*. Viewed under the light microscope, the microfossils are bright yellow. The individual colonies are spherical to oval in outline and range in size from 10 to 40 µm (Fig. 9.5). The external surface is smooth and unbroken, with no pitting (Burns 1982). A thorough revision of *Gloeocapsomorpha prisca* by Foster et al. (1989) showed that based on morphological and biochemical characteristics, *G. prisca* has a close similarity with the extant, mat-forming and stromatolite-forming marine cyanobacterium *Entophysalis major*.

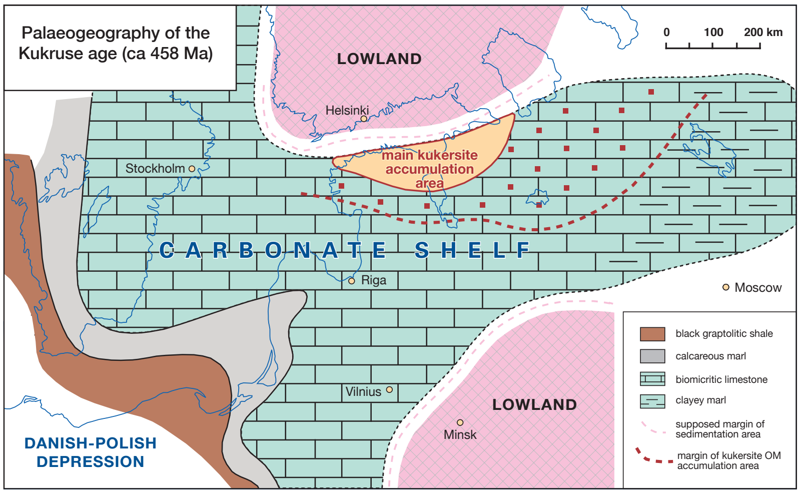

Fig. 9.6. Palaeogeography of the Baltoscandian basin during the Kukruse time, earliest Late Ordovician, when the majority of kukersite oil shale accumulated. Scheme from Bauert & Nõlvak (2014).

Depositional environment of kukersite

The depositional environment of the kukersite is still vaguely known. The few points so far established are as follows:

1. A major kukersite deposition occurred during a regression of the Kukruse sea southwards. The regression is suggested by detailed bed-by-bed lithostratigraphic studies, which have revealed a hiatus in sedimentation for beds of the Peetri Member of the Viivikonna Formation in northern Estonia and the appearance of younger kukersite beds (beds III – IX) on north-south transect in a distance of 80 km. At the same time, most kukersite beds are traceable for over 250 km in the west-east direction (Bauert & Kattai 1997).

2. The kukersite OM deposited along the northern margin of the shallow carbonate shelf, bordering the Finnish lowland in the north (Fig. 9.6).

3. Many hardgrounds, either with thin pyritic impregnation veneer or without impregnation, have been recorded in the Uhaku – Kukruse succession. Most represent synsedimentarily lithified carbonate seafloors (Wilson & Palmer 1992), but a few resemble modern coastal microkarst forms. The surfaces attributed to microkarst have developed narrow, subvertical cavities with highly irregular walls that may extend down to 25 cm from the hardground level (Bauert 1989). One such surface is observed on top of kukersite bed III and is traceable over several hundred square kilometres.

4. Based on the premise that *G. prisca* was an intertidal mat-forming cyanobacterium (similar, but not identical to extant *E. major*), Foster et al. (1990; Fig. 9.6) proposed a model that *G. prisca* grew on broad intertidal mats that may have been subaerially exposed. Tidal movements and offshore winds were suggested as agents for transporting algal mat fragments to deeper-water accumulation areas. Another plausible alternative for kukersite deposition could be a sink-down of relatively inert cyanobacterial OM directly from algal blooms.

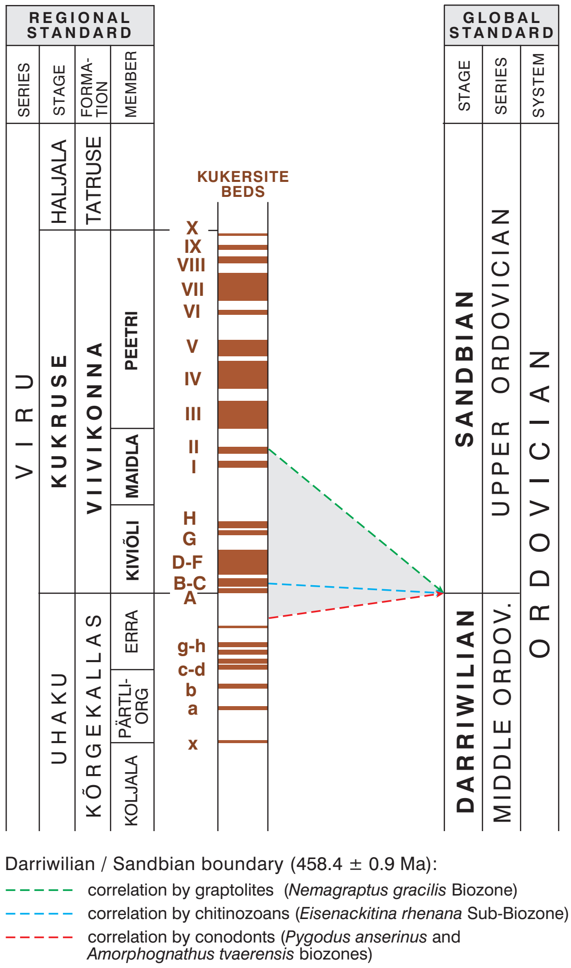

Fig. 9.7. Stratigraphic chart of the Kukruse Stage, showing levels of main indexed kukersite seams and possible correlation between global and regional time scales (redrawn from Hints et al. 2007).

Faunas of the Kukruse Stage

Abundant marine fossils, with more than 250 species listed (Bekker 1921; Rõõmusoks 1970), have been collected from both argillaceous limestones and kukersite oil shale beds during the past two centuries (Fig. 9.8 to 9.10). The most common fossils encountered are trilobites, brachiopods and bryozoans, whereas, in some kukersite beds, even delicate feathery structures of bryozoans may be well preserved (Fig. 9.9). It should be pointed out that contrary to most other organic-rich rocks, no anoxia is recorded during the accumulation of kukersite, as indicated by flourishing bottom life, the abundance of trace fossils and the relative scarcity of authigenic pyrite.

Kukruse Regional Stage and the base of the Upper Ordovician

The Fågelsång section in Scania, southern Sweden, has been chosen as the GSSP for the global Upper Ordovician Series as it represents the level of the first appearance of *Nemagraptus gracilis* Hall (Bergström et al. 2000). An overview of the present knowledge for correlating the base of the global Sandbian Stage with Baltoscandian stages by means of graptoloids, chitinozoans and conodonts was given by Hints et al. (2007).

Graptoloids are rare and only occasionally found in shallow shelf carbonate successions, the first reliable finds of *N. gracilis* come from the middle part of the Kukruse Stage in some central Estonian sections (Nõlvak & Goldman 2007). No *N. gracilis* has been recorded from the

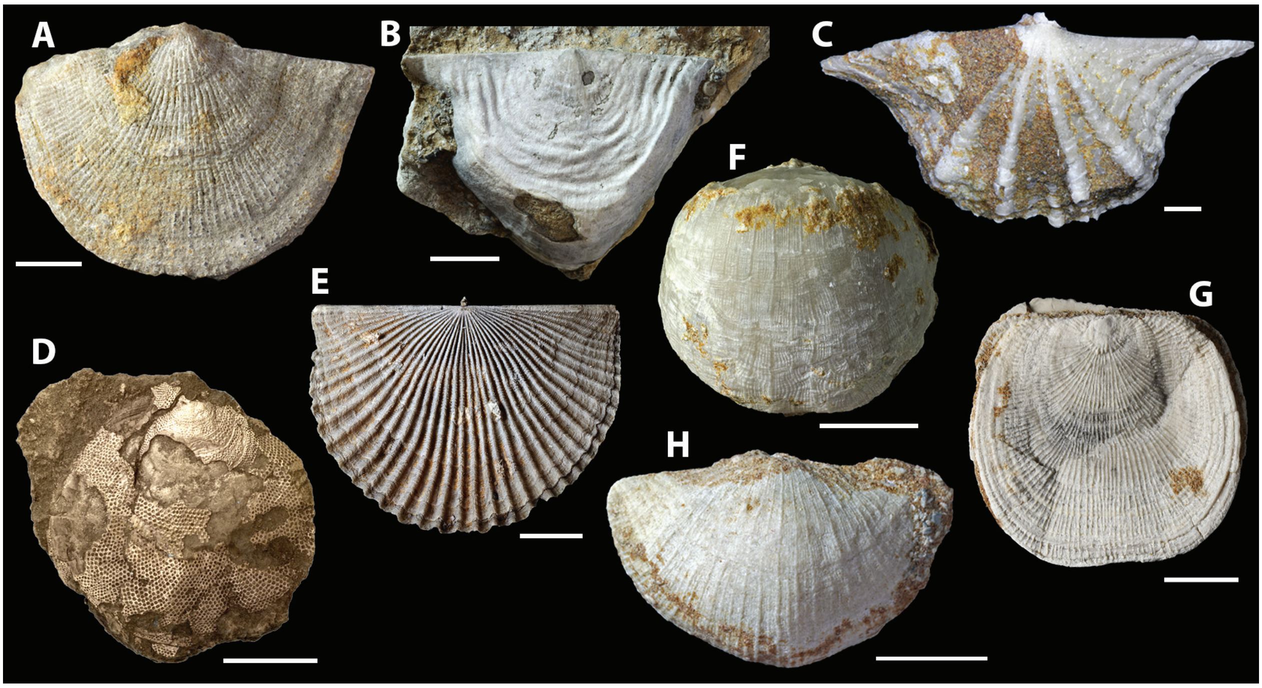

Fig. 9.8. Selected brachiopods from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: B, C, D – 1 cm; A, E–H – 5 mm. **A** – *Estlandia marginata*, Humala, GIT 543-1305. **B** – *Kiaeromena* (*Kiaeromena*) *estonensis,* Küttejõu, GIT 677-4. **C** – *Kullervo lacunata*, Kiviõli, GIT 543-433. **D** – *Foveola ivari*, Küttejõu, TUG 1003-307. **E** – *Cyrtonotella kuckersiana kuckersiana*, Kukruse, GIT 400-124. **F** – *Bekkerina dorsata*, Kohtla, GIT 251-179. **G** – *Orthisocrania planissima*, Küttejõu, GIT 772-125. **H** – *Sowerbyella* (*Sowerbyella*) *liliifera,* Kohtla-Järve, GIT 675-590.

outcrop area of the Kukruse Regional Stage in northern Estonia (Fig. 9.7).

A study on conodonts from the Kiviõli Member of the Kukruse Stage in the Kohtla section (ca 15 km east of the Põhja-Kiviõli open-pit mine) was conducted by V. Viira and co-authors in 2006. They recorded the FAD of *Amorphognathus tvaerensis* within the limestone interbed A/B, just above the base of the Kukruse Stage. It should be noted that in the Fågelsång section in Scania, *A. tvaerensis* was recorded above the *N. gracilis* find (Bergström et al. 2000), which means that in Estonian sections, the base of the Upper Ordovician lies either at the boundary of the Uhaku/Kukruse stages or somewhat lower.

Some chitinozoan species, particularly *Eisenackitina rhenana* and *Conochitina savalaensis* (Nõlvak & Bauert 2015), have proven to be reliable indicators for correlating the base of the Kukruse Stage throughout Estonia. Both chitinozoans appear close to the kukersite bed A in the Viru underground mine and Savala drill core sections. Estonian researchers have found these chitinozoans also in Latvia, Lithuania and NE Poland; T. Vandenbroucke (2004) identified *E. rhenana* in the Fågelsång section.

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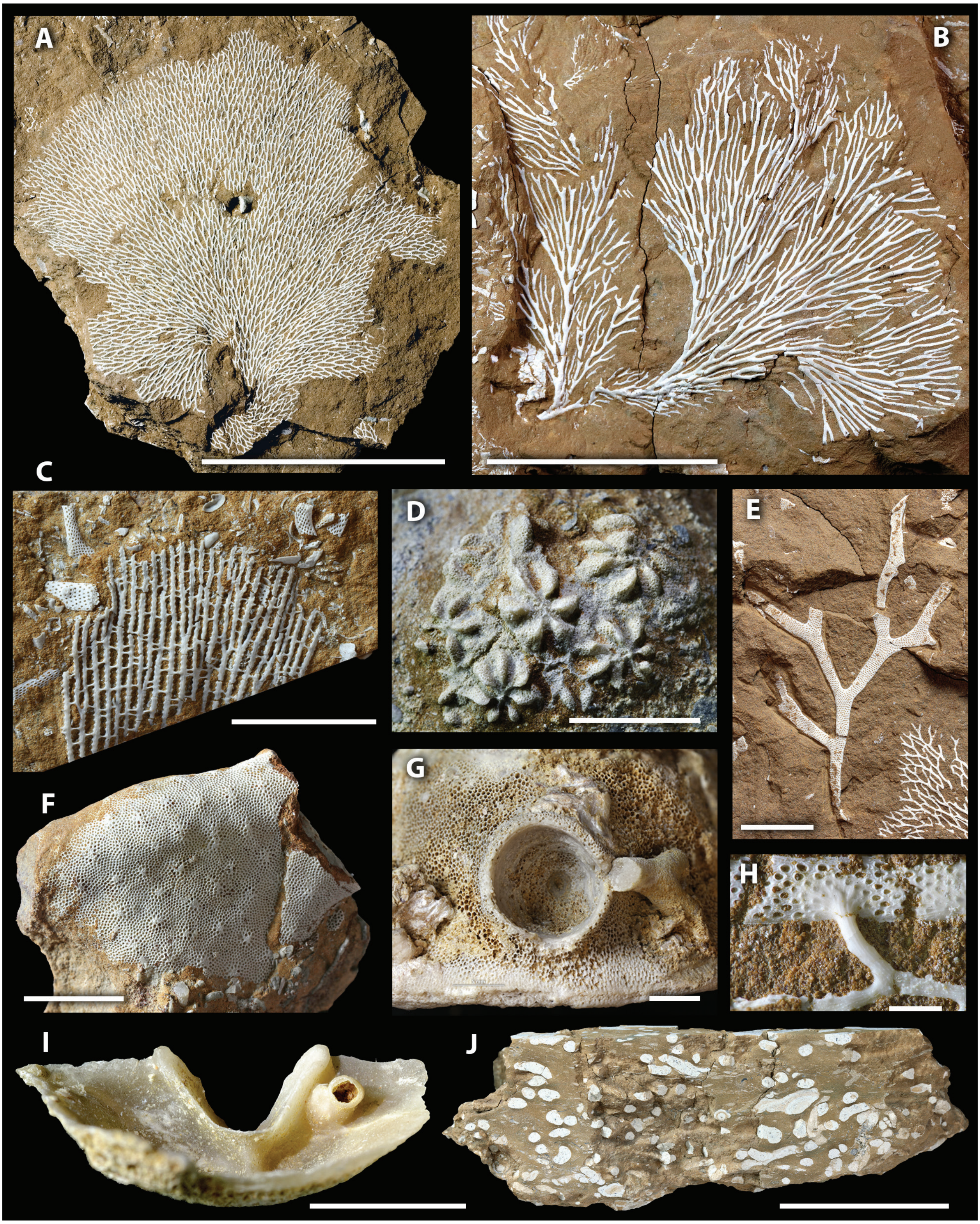

Fig. 9.9. Selected fossils from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: A, B, J – 5 cm; C–F – 1 cm, G, I – 5 mm; H – 1 mm. **A**–**F**, **H** – bryozoans; **A** – *Chasmatopora furcata*, North Estonia, GIT 398-995; **B** – *Pseudohornera bifida*, North Estonia, GIT 369-315; **C** – *Esthonioporina quadrata*, Küttejõu, GIT 537-2501; **D** – *Revalopora revalensis*, Põhja-Kiviõli, GIT 343-168; **E** – *Pachydictya kuckersensis*, Kohtla, GIT 537-1602; **F** – *Hemiphragma panderi*, Kohtla-Järve, GIT 537-3664; **H** – *Graptodictya bonnemai,* Kohtla, GIT 537-1606-2. **G**, **I**, **J** – trace fossils; **G** – *Kuckerichnus kirsimae* in *Diplotrypa*, Kohtla-Järve, TUG 72-826-2; **I** – *Burrinjuckia clitambonitofilia* in the ventral valve of *Clitambonites squamatus*, North Estonia, GIT 343-236-1; **J** – *Tisoa siphonalis*, North Estonia, GIT 362-612.

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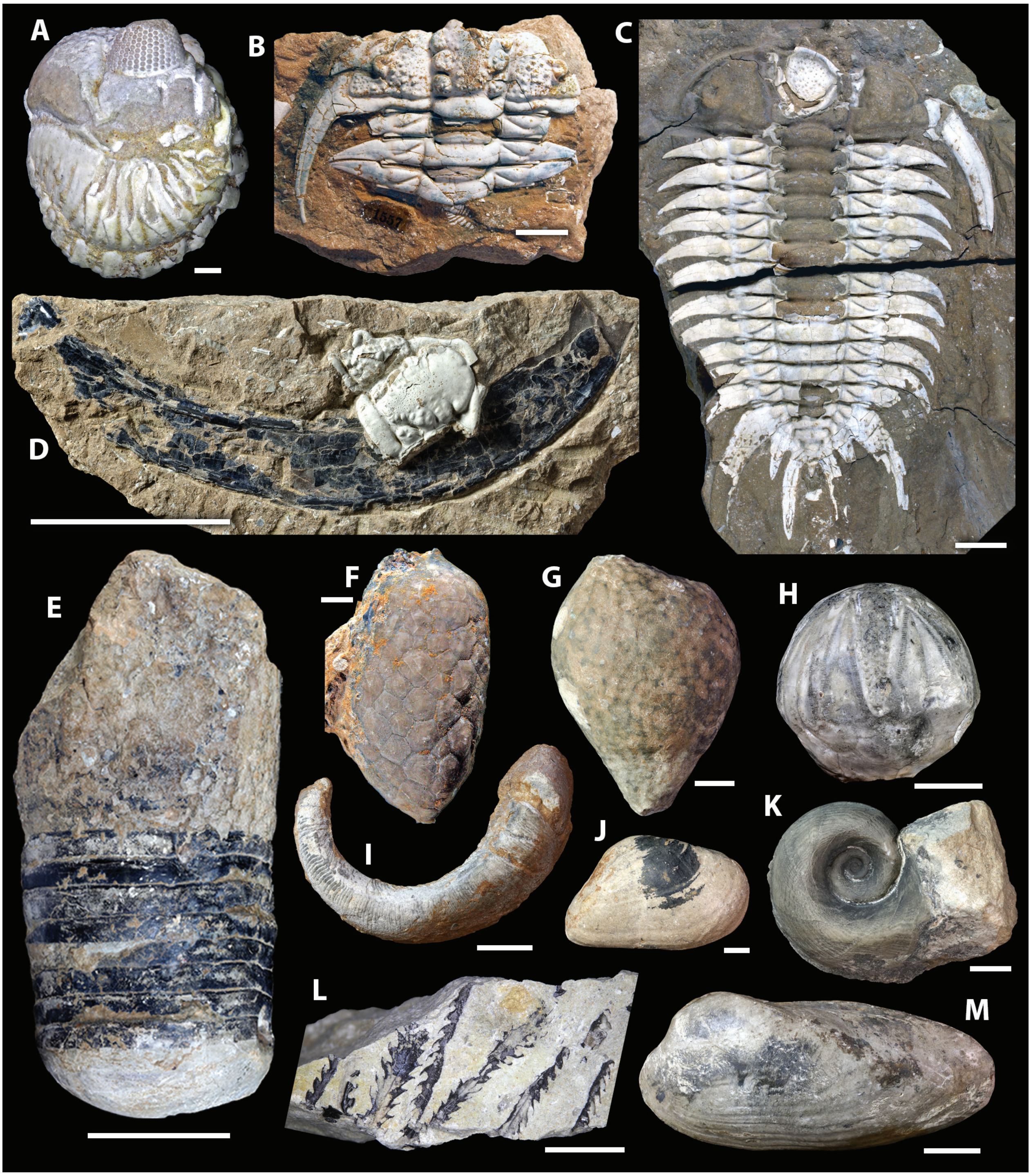

Fig. 9.10. Selected fossils from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: D, E – 5 cm; B–C, G - I, M – 1 cm; F, J, I – 5 mm; A – 1 mm. **A**–**C** – trilobites; **A** – *Estoniops exilis*, Kohtla, GIT 459-165; **B**, **C** – *Paraceraurus aculeatus*, **B** – Kukruse, TUG 1085-79, **C** – Kohtla-Järve, TUG 1672-52. **D** – cnidarian *Sphenothallus kukersianus* (together with a trilobite fragment), Kohtla, TUG 1087-32-1. **E** – cephalopod *Ormoceras*, North Estonia, GIT 695-51. **F** – eocrinoid *Heckerocrinus laevis*, Ubja, TUG 1589-137. **G**, **H** – blastozoans; G – *Echinosphaerites pirum*, Kiviõli, GIT 631-81; **H** – *Cystoblastus kokeni*, Kohtla-Järve, TUG 1727-548. **I**, **K** – gastropods; **I** – *Ecculiomphalus*, Küttejõu, GIT 343-89; **K** – *Bucania czekanowskii,* Küttejõu, TUG 666-37. **J**, **M** – bivalves; **J** – *Dystactella aedilis*, North Estonia, GIT 398-200; **M** – *Goniophora*, North Estonia, GIT 398-207. **L** – graptolite *Oepikograptus bekkeri*, Kohtla, GIT 343-613-1.

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