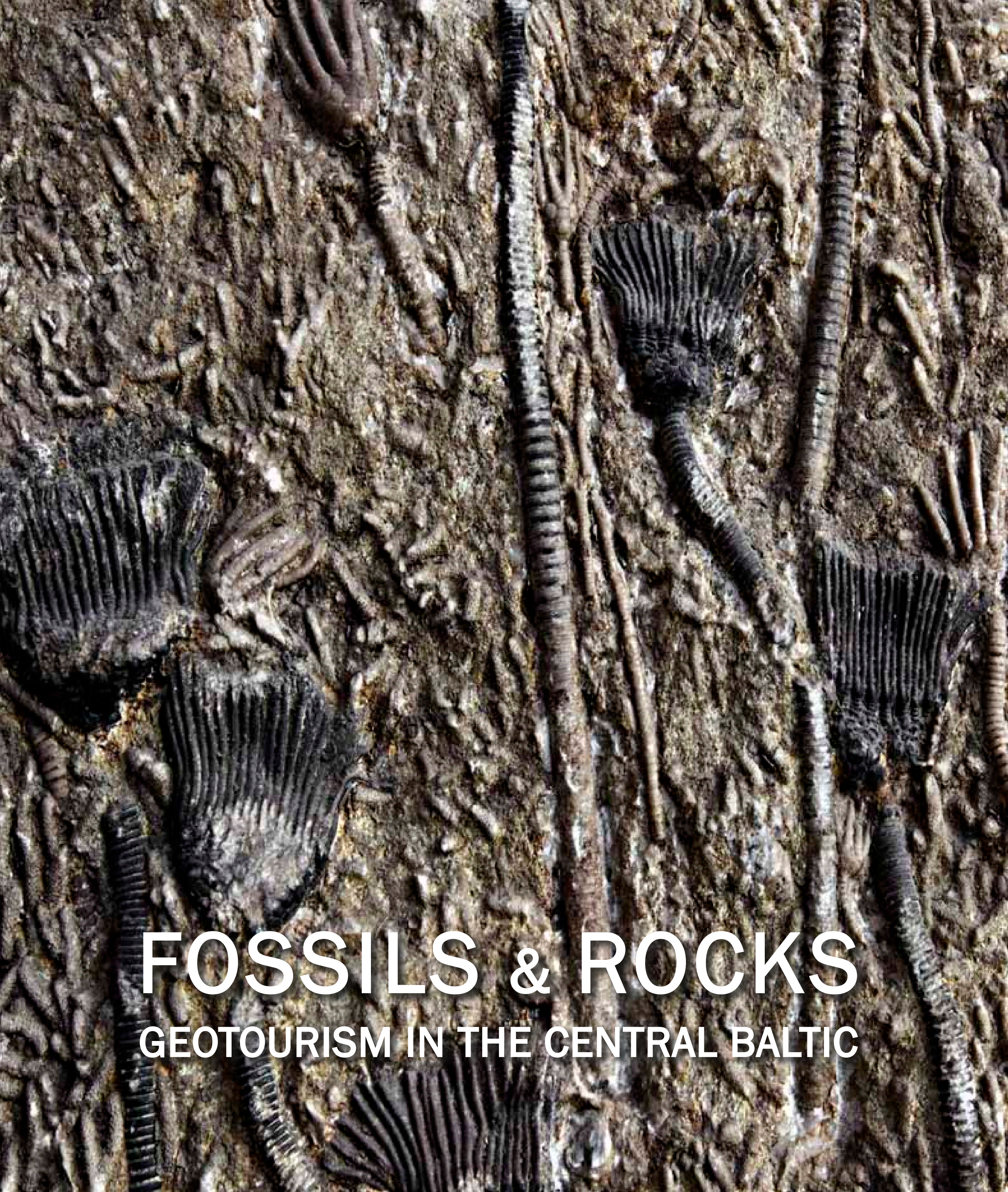

FOSSILS & ROCKS

GEOTOURISM IN THE CENTRAL BALTIC

DEPARTMENT OF EARTH SCIENCES, UPPSALA UNIVERSITY
NGO GEOGUIDE BALTOSCANDIA

FOSSILS & ROCKS

GEOTOURISM IN THE CENTRAL BALTIC

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Compiled by: Graham E. Budd
Tõnu Meidla
Sebastian Willman

Layout: Heikki Bauert

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E-mail: baltoscandia@yahoo.com

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INTRODUCTION

While much of the bedrock of the central Baltic region is crystalline and ancient, small but important patches of younger sedimentary rocks are found in various districts within it. Although some of these patches are rather limited in extent, especially in Sweden, they contain fascinating sediments and fossils of world importance that, among other things, chart the rise of various groups of animals and the changing of the environment over several hundred million years ago. The sequences in Estonia are, conversely more widespread and extensive. In addition, these rocks and fossils are often found in areas of outstanding natural beauty that have much to offer the tourist in terms of nature and culture. These rocks were some of the first old sedimentary rocks anywhere in the world to be systematically investigated, and continue to be of interest to researchers into the early evolution of organisms and environments during the early history of the Palaeozoic, some 540 – 375 million years ago.

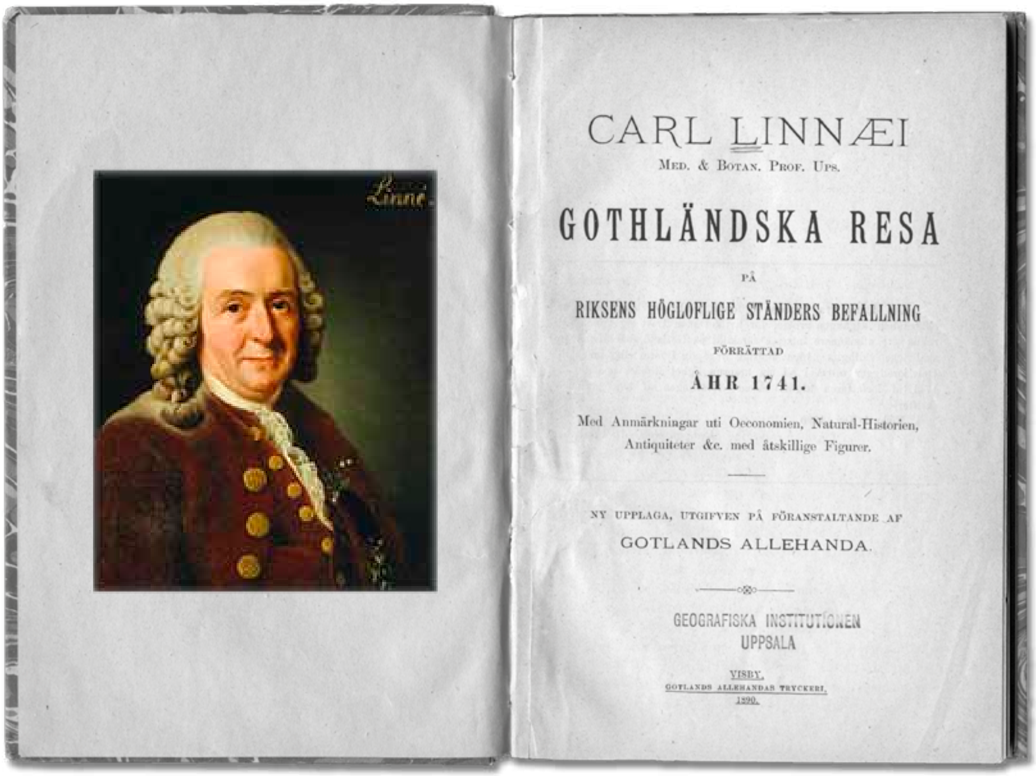
This book outlines the history of the sedimentary rocks and fossils of the region, especially those of the central Baltic islands, as well as offering a brief introduction to the sorts of fossils that can be found there, together with some hints about how to find fossils in the region. Remember that many of the beautiful areas described are in nature reserves, and that it is usually much better to look at than to collect fossils, so that localities can be preserved for future generations. At the end of the book is a list of museums where many fine specimens from the region can be found, as well as specialist help for identifying material.

Emmanuel Swedenborg

THE RISE OF PALAEONTOLOGY IN SWEDEN AND ESTONIA

The Baltic region was one of the most important anywhere in the world for the development of palaeontology, especially that of the lower Palaeozoic rocks. Some of the first Cambrian rocks in the world to be scientifically studied, those from the upper Cambrian of the Andrarum mine in Scania (then Denmark) were discovered in 1635 by the Danish nobleman **Jockum Beck**. Anyone who has looked at these rocks even casually could hardly fail to be impressed by the huge masses of fossils (mostly trilobites) found in them. By the beginning of the 18th century at the latest, these fossils, from both Andrarum and similar ones from Västergötland, had come to the attention of early Swedish protoscientists such as **Emmanuel Swedenborg, Lars Roberg** and **Magnus von Bromell**, the latter two both medical professors at Uppsala University, Sweden. They correctly concluded that the fossils represented the remains of past life, which they thought were insects – a not totally unreasonable suggestion.

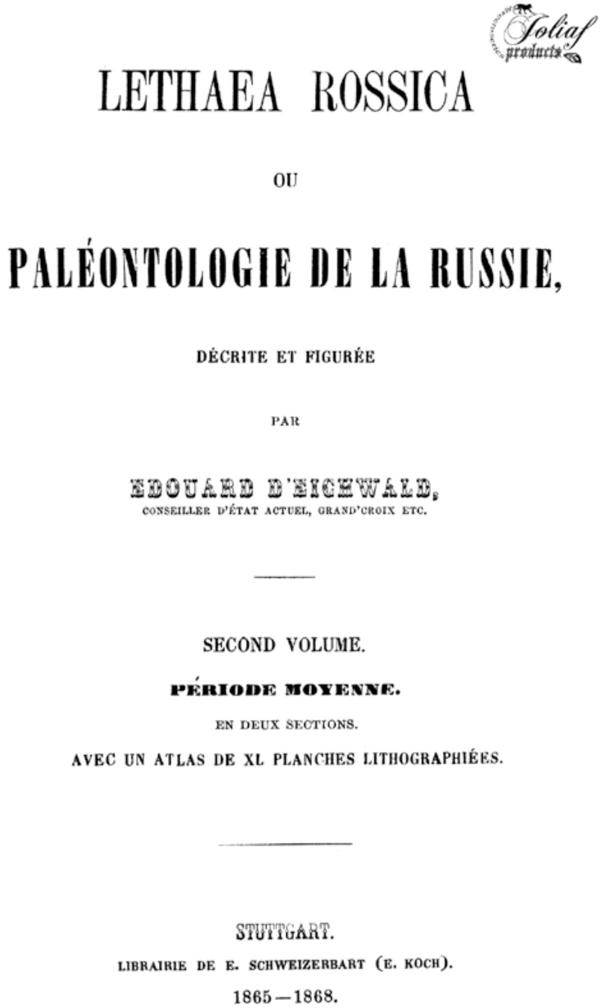
In the middle years of the 18th century, Scandinavian geology and palaeontology were advanced further by the investigations of **Carl Linnaeus**, who learnt much about geology during his celebrated "journeys" in Sweden, especially those to Dalarna (1734), Öland and Gotland (1741) and Västergötland (1746). In Dalarna he pointed out the difference between rocks we would now refer to as "drift" and "solid", i.e. the overlying and very recent glacially-derived



deposits of the Quaternary period, and the older bedrocks that in Dalarna date back to the Devonian and before. During his trips to Öland and Gotland, where he stayed a month, he described fossil corals and discussed how they might be preserved, and after his trip to Västergötland, he published a geological cross-section through the famous “table mountain” of Kinnekulle that was one of the first published anywhere in the world. Because the sequence of rocks of Kinnekulle and the nearby hill Billingen are so similar, Linnaeus correctly reasoned that they represented remnants of rocks that had once covered a much broader area (indeed, he thought, the whole world), and that by carefully studying these small areas, one could therefore learn about earth history more generally. As these rocks, and the fossils they contained, were found far from the sea today, Linnaeus concluded that the sea had slowly receded, and that more and more land had been exposed. These interesting ideas of Linnaeus were taken up by some of his students, notably **Torbern Bergman**, who was an important influence on 18th century views of earth history.

Nils Angelin

These early attempts at describing the Palaeozoic rocks and fossils of Sweden, and in particular the rocks and fossils of Gotland, were continued by several 19th century Swedish scientists as such as **Wilhelm Hisinger**, **Göran Wahlenberg**, **Gustav Lindström**, **Gustav Linnarsson**, and perhaps above all for the central Baltic region by **Nils Angelin**. Indeed, Gotland became such an important locality for the study of Silurian rocks that this geological system nearly became called the Gothlandian, a decision in favour of Silurian being finally taken as late as 1960. At the time these mid-nineteenth century works, the details of stratigraphy in Scandinavia were being established, and these played an important role in the eventual establishment of the now-familiar tri-partite division of the Lower Palaeozoic into Cambrian, Ordovician



LETHAEA ROSSICA

OU

PALÉONTOLOGIE DE LA RUSSIE,

DÉCRITE ET FIGURÉE

PAR

EDOUARD D'EICHWALD,

CONSEILLER D'ÉTAT ACTUEL, GRAND'CROIX ETC.

SECOND VOLUME.

PÉRIODE MOYENNE.

EN DEUX SECTIONS.

AVEC UN ATLAS DE XL PLANCHES LITHOGRAPHIÉES.

STUTTGART.

LIBRAIRIE DE E. SCHWEIZERBART (E. KOCH).

1865—1868.

and Silurian. The reasons for this influence are clear: rocks of this age in Sweden are in general richly fossiliferous and mostly flat-lying, so that their relative order, and the sequence of the fossils within them, can be easily seen.

Today, Swedish rocks and fossils continue to be of international importance, and this is reflected in the fact that two internationally recognised geological boundaries – Fågelsången in Scania, and Diabasbrottet on Hunneberg, Västergötland – are formally defined here. Nevertheless, the rocks and fossils of the central Baltic region of Sweden – above all of Gotland – also offer much for the geo-tourist to see and learn from.

Eduard Eichwald

In Estonia, the first published reference to the fossils was most likely made by **J. B. Fischer** in 1778. A more systematic study of fossils in this area was started by **Eduard Eichwald** (1795 – 1876), private docent at the University of Tartu, who also introduced the course of oryctozoology (palaeontology) in 1821. His contribution to palaeontological studies during 1825 – 1871 was remarkable. His major monographic work *Lethaea Rossica* (1855 – 1860), with extensive descriptions of invertebrate, vertebrate and plant fossils from Estonia, also contains descriptions of many new taxa.

The fossil fishes in the Devonian sandstones near Tartu, southern Estonia, were first mentioned by **J. Kutorga** (1835) who interpreted them as remains of turtles and crocodiles. The correct interpretation of this material was offered only a few years later by **A. Quenstedt** (1838) and E. Eichwald (1844).

A major contribution to the palaeontology of the Ordovician and Silurian strata, with a high number of fossils taxa described, was made by **Friedrich Schmidt** (1832 – 1908) during 1855 – 1908. In the monograph *Untersuchungen über die Silurische Formation von*

Friedrich Schmidt

Armin Öpik

Ehstland, Nord-Livland und Oesel (1858) he provided a detailed description of the Ordovician and Silurian rocks and proposed a subdivision of these based on a combination of palaeontological and rock evidence. The first record of Cambrian fossils in Estonia is known from the second half of 19th century (Linnarsson, 1873) although reports of fossils in the same rock units in the neighbouring areas of Russia were published considerably earlier.

The 20th century was a period of extensive monographic studies of virtually all groups of early to mid-Palaeozoic fossils in Estonia. Studies on Ordovician brachiopods, trilobites and echinoderms, Ordovician and Devonian ostracods, and also Cambrian fossils were performed by Armin Öpik (1898–1983), professor at the University of Tartu during 1930–1944. Major monographic investigations on stromatoporoids (Nestor), corals (Sokolov, Klaamann), trilobites (Ralf Männil, Reet Männil), bivalves and gastropods (Isakar), brachiopods (Rubel, Hints, Rõõmusoks), echinoderms (Ralf Männil, Hints) and fish (Obruchev, Mark-Kurik, Märss) were produced during the subsequent decades.

Since 1960s, particular attention has been paid to micropalaeontology in Estonia. This part of the fossil world is difficult or even impossible to study in the field, as it requires magnifications from a few tens of times up to the range of electron microscopy. Studies on ostracods, aquatic micro-arthropods (Sarv, Meidla, Tinn), early chordate microremains represented by teeth-like conodonts (Viira, Männik), the problematic group of chitinozoans (Männil, Nõlvak, Nestor), the problematic (but likely algal) acritarchs (Uutela) and microscopic remains of fish of various size (Märss) are of a very great importance to palaeobiology, palaeoecology and practical geology, as they can effectively be used for dating and correlating geological sections.

GEOLOGICAL HISTORY OF THE BALTIC REGION

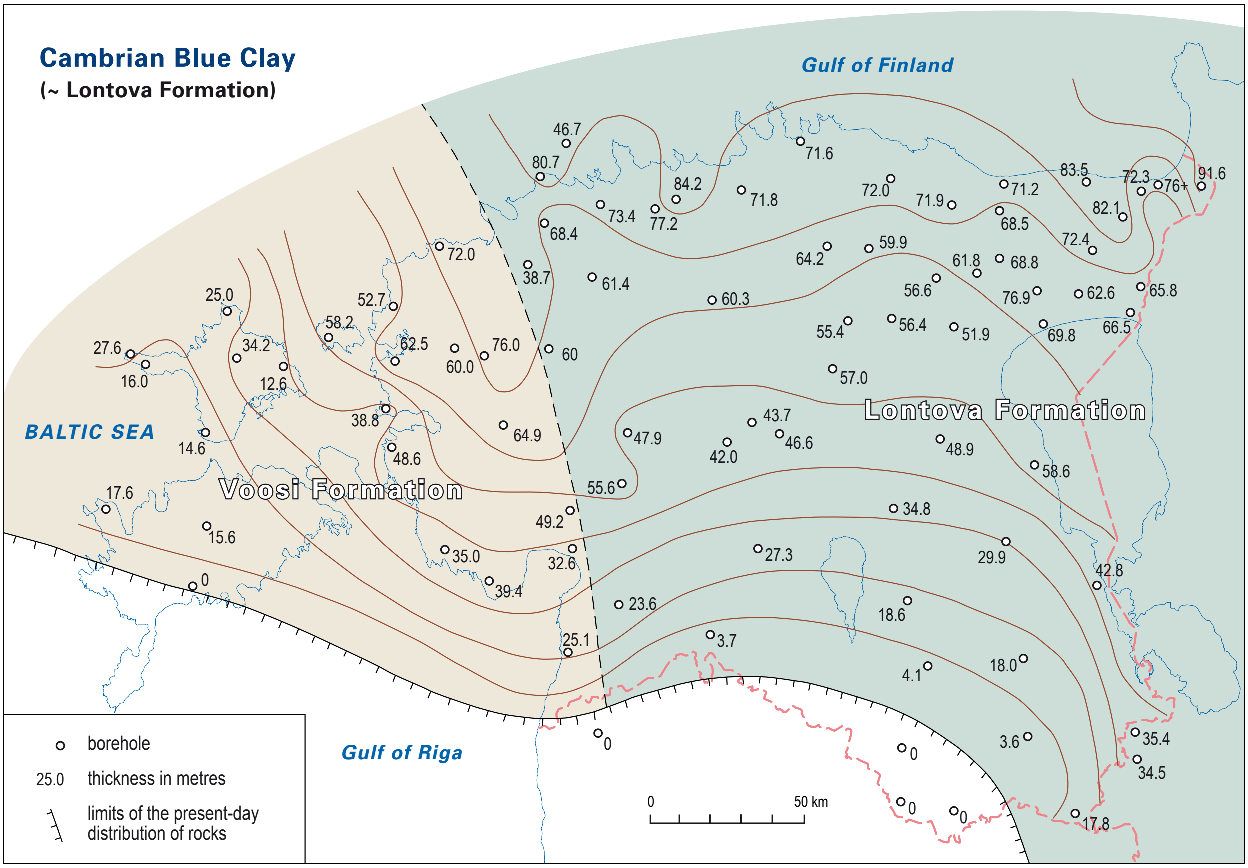
The geological history of an area can be interpreted from the rocks that are present in the area and nearby. The history of the Baltic region can be traced back about two billion years, to an era when plate tectonic movements had created a very different geographic pattern, compared to that of today. A continental mass called Fennoscandia collided with several other land masses to form the so-called Baltica palaeocontinent about 1.8 billion years ago. This event was very important in the geological history of the region, as it remained a unified whole throughout the later stages of geological history. The parts of Baltica were positioned in the vicinity of masses of rock that nowadays make up North America, the area around Brazil, and West Africa, all together likely forming a continental massif, rimmed by an orogenic, i.e., mountain-building belt. Active tectonic movements terminated around 1.5 billion years ago. As a result of magmatic and sedimentational processes, and metamorphism of the rocks at high temperature and pressure conditions, the basement of the Baltoscandian area was formed. This stage of its geological history left behind a mosaic of crystalline rocks, comprising metamorphosed units (gneisses and related rocks) and a variety of magmatic rocks, in many places represented by granites. The subsequent period of about 800 million years was characterized by deep erosion of these formations and only episodic sedimentation in restricted areas in the Baltoscandian region. Although several metamorphosed rock units were originally formed as sediments, it is hopeless to look for possible fossils in these rocks. The crystalline basement is extensively exposed in Sweden and Finland, whereas it is covered by younger sedimentary rocks everywhere in the Baltic countries.

The oldest fossiliferous sediments in the central Baltic area, comprising southern Sweden, Estonia and the numerous islands between them, are known from Estonia. These sediments were formed in a large and cool body of water to the east of the Baltic countries of today. Sandy and argillaceous sediments with coarser sedimentary material in west Estonia resulted from deposition in the coastal zone of this body of water. These strata contain the first minor signs of life in this area – rare dark films interpreted as probable algae and problematic microfossils of likely algal origin, called acritarchs. This fossil evidence allows us to refer these strata to the Ediacaran System. The Ediacaran is not exposed, being overlain by younger strata everywhere in Estonia, although it is known from borehole material.

A new episode of sedimentation started in the succeeding early Cambrian (called the Terreneuvian epoch today). Shallow marine conditions were established in the area but developments east and west of the present Baltic Sea were rather different in detail. In Sweden the corresponding strata comprise hard quartz sandstones, cross bedded and of shallow marine origin, which locally may be preserved only as fissure fillings in very old crystalline bedrock. The deeper part of the sedimentation basin was in the same place as the site of the previous sedimentation, i.e. east of the Baltic countries. Argillaceous sediments formed in the transition zone are known as the Blue Clay, a unit of silty clay, named after its peculiar colour. This unit may rarely yield fossil arthropods of various groups, early mollusc remains and various other fossils, mostly of problematic affinity. This unit occasionally crops out in the eastern part of the North Estonian Klint, but more extensive outcrops can be found in a few clay pits.

In Sweden, the sandstones of the lowermost Cambrian grade upwards into the bituminous shales comprising the rest of the Cambrian System. This major shale unit, the Alum Shale Formation, was likely formed in a shallow (50 – 100 m deep) sea. It contains large flat sulphurous limestone lenses or concretions of about 0.1 – 2.0 m in diameter, known as “Orsten” or “stinkstone”. This rock is famous for occasionally yielding the fossilized remains of various Cambrian bottom-dwelling arthropods with exceptional, three-dimensional preservation of soft parts. Outcrops of these strata are well-known in Västergötland, Scania and Öland.

The earliest Cambrian Blue Clay in Estonia grades into a multitude of lens-like sandstone and siltstone units, irregularly distributed all over Estonia and extending also to Latvia and Russia. Only a few of them crop out in the North Estonian Klint sections and most of them are nearly or completely unfossiliferous. The only exception is the topmost Cambrian to lowermost Ordovician Kallavere Formation (historically known also as the Obolus Sandstone) which may locally contain occasional conglomeratic beds formed as concentrations of phosphatic brachiopod shells in sandstone.

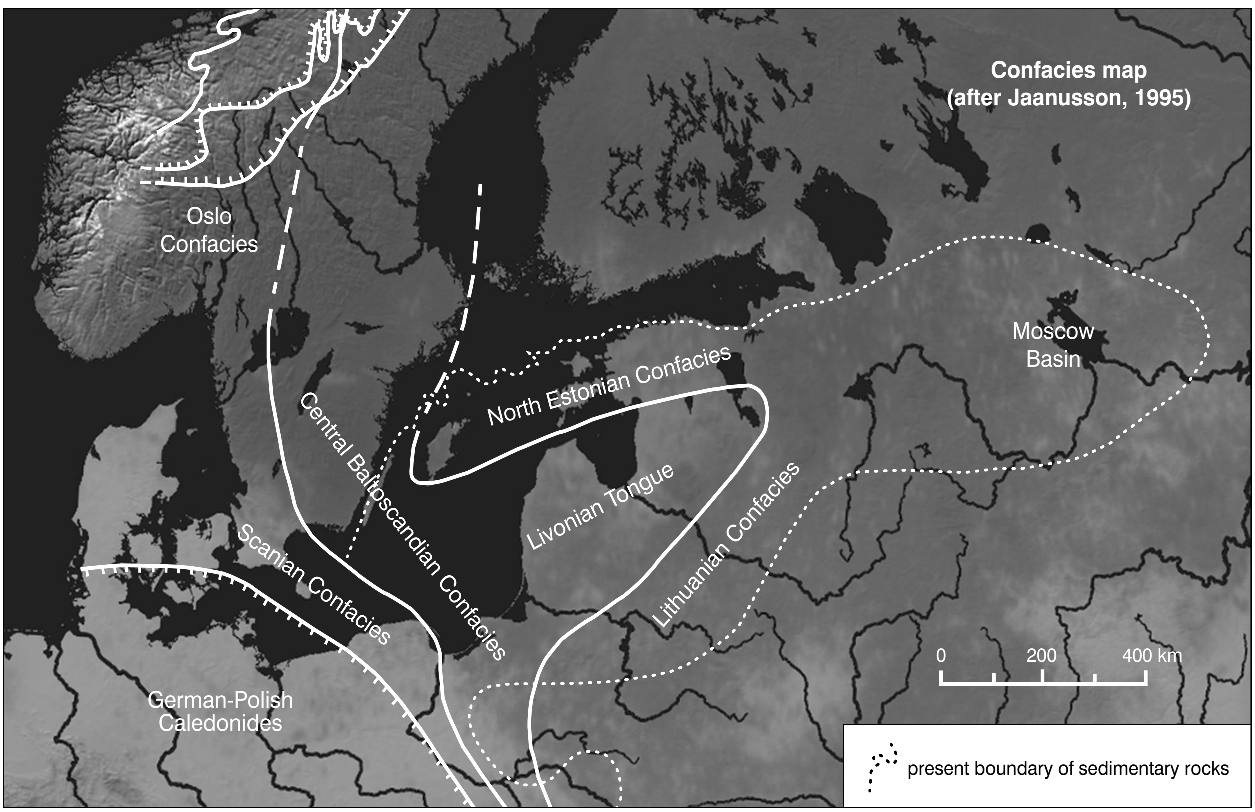


Distribution and thickness of the Cambrian Blue Clay in Estonia

The sedimentation pattern of the very beginning of the Ordovician Period was similar to that in the later Cambrian. Thin sandstone and shale units, with occasional thin carbonate interbeds recorded in Öland, were, towards the end of the Early Ordovician, replaced by limestones. This was actually a major turnover in the sedimentation style as carbonate sedimentation then dominated throughout the Middle to Late Ordovician and Silurian. Carbonate rocks are biogenic by their nature but deposited primarily as fine-grained carbonate mud where only larger par-

The Cambrian Blue Clay often has a variegated color as can seen in the Kunda clay quarry. Scale – 20 cm ticles can be attributed to a particular organism with certainty. They may also contain more or less complete fossil shells of marine organisms. Fossiliferous carbonate rocks are rather common in the central Baltic area.

The similarity of fossils in the early Palaeozoic carbonate rocks east and west of the Baltic was already noted by Sir Roderick Impey Murchison, a famous British geologist and author of the original concept and the name of the Silurian System, in his paper from 1844. This similarity is today widely accepted and serves as the basis of interpreting the development of the rocks during the Ordovician Period in the area. The area of Ordovician carbonate deposition comprised southern Scandinavia, most of the Baltic depression and a huge territory east of the Baltic, reaching from Estonia south to northeastern Poland and Podolia and extending as far east as the surroundings of Moscow in Russia. All the Ordovician carbonates were formed in the Ordovician shelf sea, which was the shallowest in north Estonia and the deepest in western Sweden and in Scania. The distribution of Ordovician rocks in Sweden is discontinuous, because of extensive erosion. Outliers are preserved as small spots in the map, exposing mostly brownish red to dark grey limestones, which are thermally altered in Scania and in some other sections. Carbonates in Estonia show no evidence of thermal alteration but are characterized by a variable content of dolomite. The dolomitization of the rocks (recrystallization, with partial replacement of calcium by magnesium) happened long after they were formed, most likely in the Permian.



The carbonates on both sides of the Baltic also contain some evidence for volcanic activity: ancient volcanic ash beds, which are more numerous and thick in Scandinavia. The source area of the volcanic material was likely east and southeast of Scandinavia where volcanicity was related to plate tectonic activity, the approaching collision of Baltica with the Laurentian palaeocontinent, i.e. North America and Greenland of today. This collision started to influence sedimentation in the Baltoscandian Palaeozoic sea later in the Silurian and in the Devonian and gave rise to the Scandinavian Caledonide mountain chain.

During the Silurian, the Baltoscandian sedimentation basin retreated slowly to the southwest. Silurian shallow-water limestones and dolomites are widely distributed in western Estonia, particularly along the coast of the island of Saaremaa. Large cliffs with bedded limestones and reefs are also widely distributed in the island of Gotland. In both areas the rocks are very rich in fossils. In the mainland of Sweden, Silurian strata (Llandoverian limestones) have only a limited distribution in the southern part of Scania.

The Devonian Period started with active mountain-building along the Scandinavian "backbone", but most of the rocks formed in course of this process were largely eroded both in Scandinavia and in Estonia. The Devonian is nowadays present only in southern, central and northeastern Estonia, but east and south of Estonia this is one of the most widely distributed parts of the Palaeozoic succession. The Lower and Middle Devonian in Estonia comprise predominantly sandstones, the material eroded from the Scandinavian Caledonides. Fossils are rare in these strata but exoskeletal plates, scales and teeth of large fish can occasionally be found, and some rare plant remains are also known. The Upper Devonian has only a very limited distribution in southeastern Estonia, being mostly represented by dolomites.

The formation of the large palaeocontinent called Pangaea converted the Baltoscandian area into a terrestrial area towards the end of the Palaeozoic. A few continental sediments, clays and coarse clastics, are known from southernmost Scania. Marine conditions only returned in the Jurassic, but deposition was restricted to southern Lithuania and southernmost Scania and to the areas south of the Baltic. When the Atlantic Ocean started to form in the Mesozoic, it caused rising of some areas around the Baltic and intensified the erosional processes, resulting during the Palaeogene in the formation of a network of river valleys all over the area. Slow movement northwards brought Baltoscandia into the area where it is situated today. In the recent past, in the Quaternary, a global cooling resulted in formation of glaciers in northern Scandinavia that merged and flowed to the south as a huge continental glacier, covering very large areas in northern Europe with an ice sheet with a thickness of up to 2 km. Moving glaciers have eroded several tens of metres of rocks all over the area and redeposited this material in a form of glacial deposits, tills, sands and gravels, which are widely distributed all over northern Europe. The glaciers gained their maximum extent about 18 000 years ago and were mostly gone about 8000 years later.

Geological maps of today show that the crystalline basement of the Baltic countries is covered by a thick layer of sedimentary rocks, within which latitudinal belts of the sediments become younger the further south you go. Ordovician strata also crop out in several western Estonian islands and in the island of Öland. Silurian strata are common in the mainland of Estonia, but also on Saaremaa and Gotland. The mainland of Sweden is characterized by discontinuous distribution of fragments of the Palaeozoic succession on the very old crystalline rocks. Well-known outliers occur in the vicinity of Östersund (Jämtland), around the lake of Siljan (Dalarna), in Västergötland, Östergötland and Scania.

PALAEOZOIC ENVIRONMENTS FROM THE EDIACARAN TO EARLY DEVONIAN

The formation of the crystalline bedrock of the Balto-scandian area mainly took place more than 1.5 billion years ago. The sedimentary bedrock of the central Baltic area was formed on the eroded and largely levelled surface of these very old rocks.

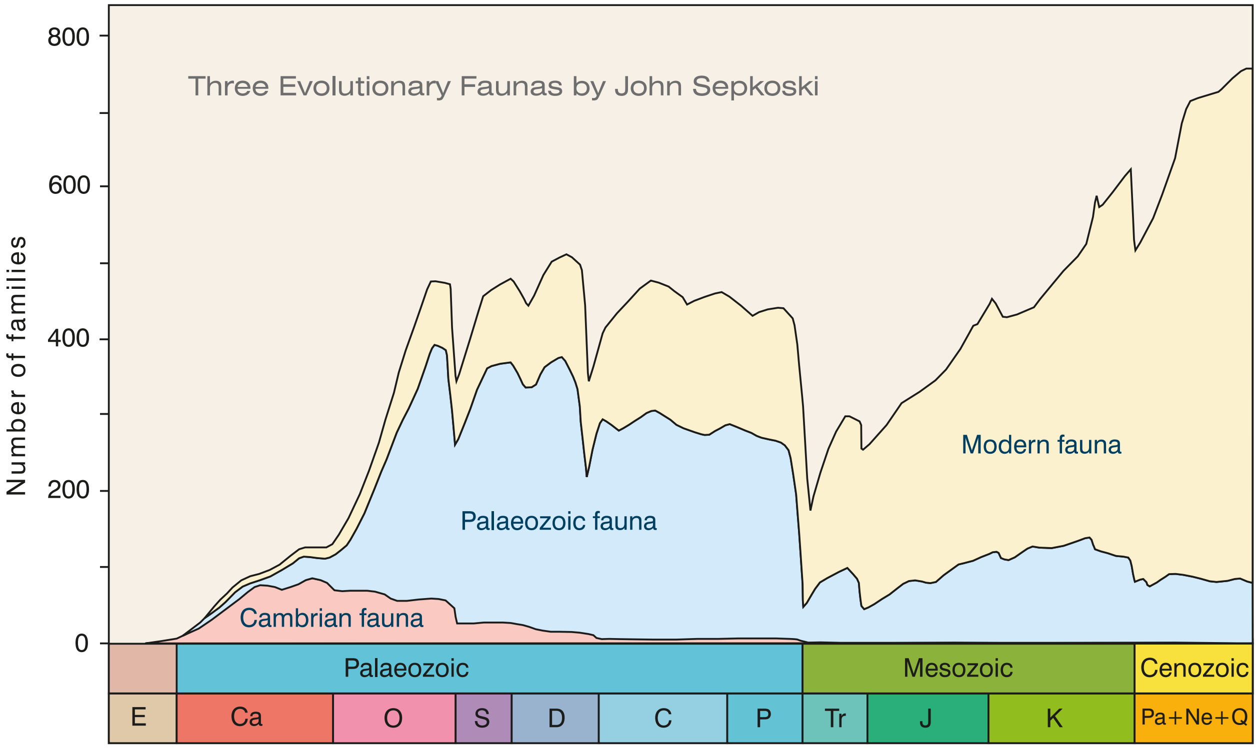
The late Proterozoic eon was characterized by a major glaciation that left behind some glacial sediments in western Russia and northernmost Scandinavia. The palaeogeography of this period is poorly known, but we know that the glaciers retreated about 635 million years ago. This dating marks the beginning of a period of slow warming of the Earth´s climate.

The environments and biota of the latest Proterozoic, known as the Ediacaran Period, were very different to those we can see today. Even some of the most important parameters were very different: the atmosphere contained much less oxygen (likely less than ten per cent) and the carbon dioxide level was many times higher than today. A major difference of this period, compared with today's environment, was also the lack of organisms in the terrestrial environments. The life of the Precambrian, with the probable exception of some microbes, was exclusively confined to the sea.

Although the origin of several major groups of marine animals (e.g. foraminiferans, sponges, cnidarians), might date back to the Precambrian, most of the data available are very tentative, as the fossil evidence is poor and controversial. This is largely because of the lack of solid skeletons and shells in rocks that old. The oldest organisms with hard shells appeared in the latest Ediacaran and the Ediacaran environments were instead mostly characterized by soft-bodied organisms and various algae. The relationship of the Ediacara biota to modern animals is complex and it is even possible that the organisms might be viewed as a “failed experiment” that left no or very few descendants. Sediments containing Ediacaran fossils are not present in central Sweden, whilst in Estonia they are deeply buried under the Cambrian strata and are very poor in fossils.

The beginning of the Cambrian Period about 543 million years ago marks a series of very important events in the evolution of life and environments. Against a backdrop of slowly rising oxygen concentration in the atmosphere, many invertebrate animal phyla developed a skeleton of some sort. This epoch, often called “the Cambrian Explosion“, marks a very rapid diversification of marine life. Many animal phyla seem already to be present in the Cambrian, and even the first chordates (the group containing vertebrates) are known. Fossils also become much more abundant in the Cambrian, compared to Ediacaran strata. It is not clear yet why the process of diversification and distribution of the biota was so fast. Reconstruction of Cambrian palaeogeography is quite well resolved today, and the appearance of the major groups took place rapidly in all shallow parts of the ocean whilst deeper parts of the ocean were probably not suitable for marine life at that time. The abundance of skeletal fossils from the Cambrian onward is generally very high.

Phanerozoic fossils are documented in a huge number of palaeontological publications. A very



remarkable attempt to document the changes in animal diversity on Earth was made by John Sepkoski (1948–1999), an American palaeontologist. In 1981, he published his concept of three great Evolutionary Faunas in the marine animal fossil record. This pattern is well known and widely discussed today, although the driving forces that shaped this "stepwise" evolutionary pattern still remain unclear.

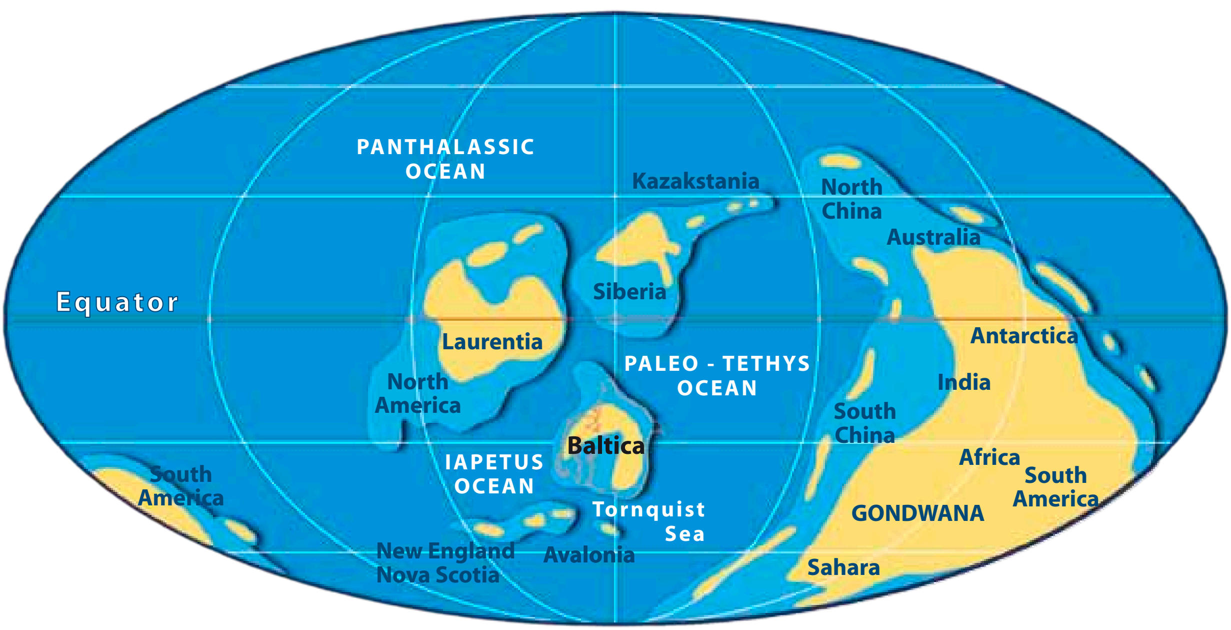
The oldest of the three faunas, the Cambrian Evolutionary Fauna was dominated by suspension feeders – trilobites, worms and inarticulated brachiopods. However, these skeletal fossil groups record only part of the entire diversity of the Cambrian. This data set is complemented by the evidence from a very limited number of extraordinarily rich localities of soft-bodied faunas with extraordinary preservation, the so-called lagerstätten. These famous localities and horizons (e.g. the Burgess Shale in the Canadian Rocky Mountains, Chengjiang in the Yunnan Province of China, Sirius Passet in northern Greenland) contain abundant fossils and give some idea of the richness of the Cambrian biota, which was actually dominated by soft-bodied organisms. These localities provide us with unique information about the evolutionary changes in the Cambrian. All principal marine areas – the sea bottom, the upper part of the soft sediments and the water column itself were likely already occupied by a multitude of taxa. Although very many representatives of this fauna were deposit-feeders (surface-digging animals), specialized predators that were already present in the Cambrian made the Cambrian food chains longer than ever before. The diversity increase in the earlier Cambrian was very fast and brought along the appearance of an extraordinary morphological diversity, and a multitude of body plans. Although the diversification rates decreased throughout the Cambrian, the animal diversity reached its maximum in the early Furongian (i.e. upper Cambrian) only. This diversity peak was followed by a decline. It is also important to mention that several groups of the Cambrian fauna display an irregular distribution pattern that can be taken as the first evidence of distinct provincialism in the Earth history.

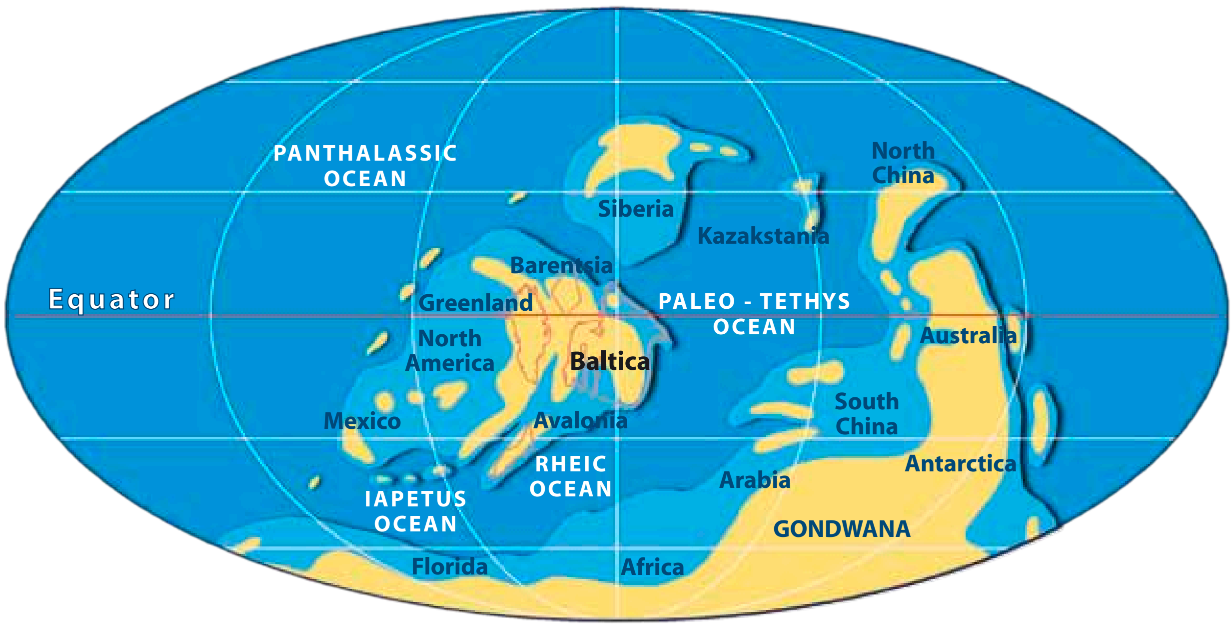
The Ordovician Period marks a new increase in animal diversity, the appearance of the Palaeozoic Evolutionary Fauna in the sense of Sepkoski. It was one of the largest adaptive radiations in the Earth's history. The members of this new evolutionary fauna diversified rapidly from the beginning of Middle Ordovician. The number of families of known marine invertebrates more than doubled compared to the Cambrian. The widespread shallow, warm continental seas were a perfect environment for many groups of organisms. The members of this evolutionary fauna quickly developed narrower ecologic requirements. Suspension feeders started to diversify. Articulated brachiopods, cephalopods, ostracods, crinoids and corals were most characteristic of this marine fauna, and coral reefs were widely distributed over the low latitude marine basins. The first easily recognisable vertebrates, the earliest fish-like agnathans, are also known from the Ordovician.

The Ordovician Period marks the appearance of the typical Palaeozoic shelf sea communities, which were strongly dominated by brachiopods, ostracods and bryozoans. Today, we are used to see clam and snail shells on beaches of virtually all latitudes but they replaced brachiopods in this position "only" about 260 million years ago.

Palaeogeographic reconstructions of the Middle Ordovician show a major palaeocontinent called Gondwana lying across the southern latitudes, and a number of smaller palaeoplates, mainly confined to low and middle latitudes. Detailed reconstructions

Position of continents at the beginning of the late Ordovician, ca 460 Ma (after C.R. Scotese in www.scotese.com)





Position of continents in the mid-Silurian, ca 425 Ma (after C.R. Scotese in www.scotese.com)

suggest that several larger and smaller terrains were subject to northward drift. Among them was also the Baltica palaeocontinent, comprising today's Balto-scandia and western Russia, moving rapidly from the southern 50th latitude in early Middle Ordovician time to the tropical southern latitudes by the end of the Ordovician.

The land areas were still largely uninhabited, except, perhaps, for a very narrow coastal belt near the water level where the conditions were not so much different of those in the tidal zone and where some algal life could likely survive. The distribution of the organisms in the Ordovician seas was rather uneven. The deep ocean was largely uninhabited, although occasional episodes of water mass mixing, so-called ocean turn-overs, were to take place towards the end of Ordovician. Distribution patterns of different fossil groups often display a provincial (i.e. continental) recurrent pattern. Recent investigations show that planktonic taxa tend to show a palaeolatitudinal, climatically controlled pattern in their distribution, and that these latitudinal belts slowly shifted towards the poles towards the end Ordovician as the climate deteriorated. It is not clear how long this cooling event lasted for but it was the start of a new and very different chapter in early Palaeozoic history – a glaciation.

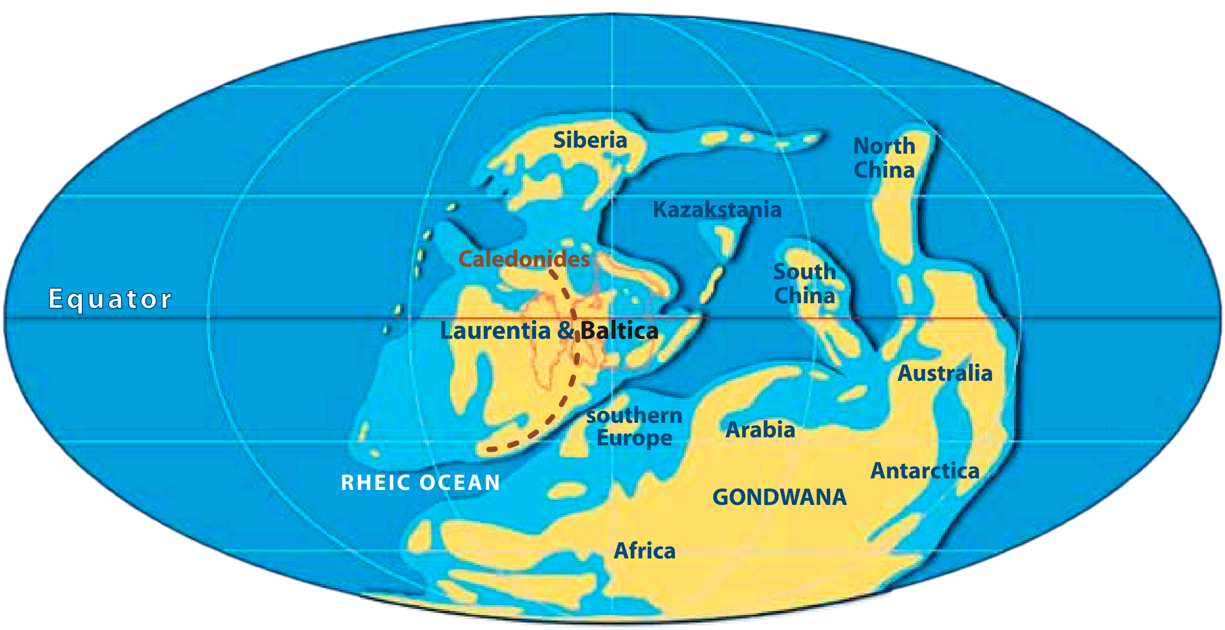
A link between the evidence of glaciation, a sea level fall and remarkable faunal changes around the end of the Ordovician was first suggested as long ago as 1973, but documentation of biotic and sea level changes and distribution of the glacial and glacio-marine deposits has been greatly extended over the succeeding decades. Today we have data from stable isotopic geochemistry that provide additional evidence for the glaciation. Specific glacial deposits probably covered the polar area below 60°S, with some glacial deposits reaching the 40th–50th latitude in South Africa and western South America. In terms of modern geography, it would mean that the distribution area of glacio-marine deposits almost reached the southern points of Africa and Australia, and glaciers covered New Zealand, Tasmania and Patagonia – a wider extent of polar ice than we see in modern Antarctica.

The triggers of the rapid end-Ordovician glaciation are still poorly understood and this major glacial event did not last long. Its duration is estimated to be between 0.5 and 1 million years, thus being rather similar to that of the recent northern hemisphere glaciation in the Quaternary. There are also other similarities. The sea level drop in the latest Ordovician was estimated to be 50–100 m (up to 120 m in the Pleistocene), and the decrease of sea surface temperatures may have been up to 10°C (up to 7°C in the Pleistocene).

The biotic consequences of this complex oceanographic event – simultaneous mixing of water masses, sea level drop and sharp temperature decrease in many areas – were harsh. A taxonomic loss of 85% of all species and 61% of genera is estimated, caused by a two-fold extinction event. The first stage of the extinction was caused by a rapid sea level drop and narrowing of the shelves, along with temperature changes in many areas. Some groups (like conodonts) survived the first extinction but were strongly affected by the second stage of extinction, caused by rapid sea level rise in the mid Hirnantian.

The beginning of the Silurian was a time of recovery of diversity. The early Silurian faunas were much less diverse and much less provincial than before the crisis, and the increase in diversity was of only moderate speed. Coral reefs returned quickly after the end-Ordovician crisis. The dominant groups of invertebrates remained largely the same, although new genera and species of brachiopods, bryozoans, molluscs and trilobites appeared in great abundance. A decrease in atmospheric carbon dioxide levels, and increase in atmospheric oxygen, is recorded from the Ordovician onward and this process continued

Position of continents in the mid-Devonian, ca 390 Ma (after C.R. Scotese in www.scotese.com)



throughout the Silurian, as well as into the Early and Middle Devonian.

The Silurian was also a major diversification episode for marine vertebrates, leading to the appearance of the oldest jawed fish – the acanthodians. For the first time in Earth's history, significant developments also reached the terrestrial environments. The first significant vascular plants invaded land areas in the second half of the Silurian Period. There is also evidence of the first terrestrial arthropods – a limited number of arachnoids and myriapods.

The Silurian was not a period of drastic climate changes or extensive volcanism, but tectonic activity is known from several areas. The event of major importance to Laurentia (North America) and Baltica was the closure of the Iapetus Ocean which led to a collision of these two palaeocontinents and the rise of mountains along the collision front. A direct evidence of this mountain rise is the so-called Old Red Sandstone, the products of extensive mountain erosion, which already started to accumulate in the latest Silurian in some areas of the British Isles and extended over vast areas in the eastern Baltic region and elsewhere along the Caledonian mountain belt in the Devonian. A relict of this process is the Scandinavian mountain chain.

Although Devonian rocks have a very limited distribution in the central Baltic area (i.e. in central-southern Sweden and Estonia), they were very common in the past, as erosion of the Caledonian mountains produced huge amounts of sand that possibly covered most of this area with a kilometre-thick layer. These sandstones were eroded later, during the Devonian, Carboniferous and Permian.

Devonian climates did not differ much from the Silurian ones, and the dominant invertebrate groups were largely the same in the seas. However, forests spread rapidly in suitable land areas. The earliest forests, inhabited mostly by insects and other arthropods, were hardly higher than one metre, but the height of the trees increased very quickly, already reaching several tens of metres in the Late Devonian. The increasing food availability on land was a precondition for the appearance of the first amphibians in the Middle Devonian. Some evidence of this important event is also present in the Devonian of the eastern Baltic region, but these localities occur far off the modern coastline, in southeastern Estonia and in Latvia.

MAJOR FOSSIL GROUPS

The central Baltic region yields a very rich diversity of Cambrian to Devonian fossils, and an introduction to the principal groups that can be easily found is given here. Whilst this section covers most of the fossils that are likely to be found, many minor groups (sponges, receptaculitids etc) are not described as they are likely to be overlooked by anyone apart from a specialist. The taxonomy (i.e. naming) of many of these groups such as the cephalopods remains unclear, and it is not expected that non-specialists will be able to identify any fossils they find precisely. Nevertheless, it is hoped that the following guide will allow most of the fossils that can be found in the area to be placed within its broad group. For more specialist information, we recommend that one of the museums listed in the appendix is contacted.

STROMATOPOROIDS

Stromatoporoids are a problematic group of large, calcareous fossils that are extremely common in calcareous rocks of the Palaeozoic, and easy to find on Gotland and in the Silurian rocks of Estonia. The

largest specimens can be around a metre or more in diameter, but much smaller specimens are more typical. They are often dome-shaped, and can be seen to have a layered construction. However, other morphologies are possible, such as encrusting or branched forms. Superficially, some specimens can look like corals with which they are most often confused. When the outer surface of a stromatoporoid is examined closely, it can be seen to be covered with faint, irregular polygons. Another striking feature of the surface, and often seen in specimens that can look very puzzling, are sets of swellings from the surface that are called mamelons. Finally, this surface

Above: stromatoporoid, horizontal size – 15,5 cm. Courtesy of Naturhistoriska Riksmuseet, Stockholm (NRM)

Right: stromatoporoid *Clathrodictyon* sp., vertical size – 7,5 cm. Courtesy of Institute of Geology at Tallinn University of Technology (IGTUT)

Stromatoporoid *Clathrodictyon boreale*, horizontal size – 23 cm. Courtesy of IGTUT

also often shows faint irregularly-branching structures called astrorhizae.

Stromatoporoids were very important components of the reefs and reef-like structures found in the Silurian such as on Gotland and the Estonian islands, and they can be seen to have different shapes according to the energy of the environment they live in. For example, at the high-energy environment seen at Holmhällar on Gotland, the stromatoporoids are highly flattened; but at Kuppen, they are much more domed.

Stromatoporoids are found in both Palaeozoic and Mesozoic rocks, but it seems that they represent several groups that are not closely related to each other. For many years, their affinities were very unclear. They were traditionally assigned to the cnidarians (corals and their relatives), but were also compared to certain types of stromatolite – sheet-like or domed structures built by cyanobacteria. However, Palaeozoic stromatoporoids are now generally regarded as being related to sponges. This reassignment came about principally after the description of a group of living sponges, the sclerosponges or coralline sponges, that form massive carbonate skeletons just like the stromatoporoids. They also share some other including structures strikingly similar to the astrorhizae.

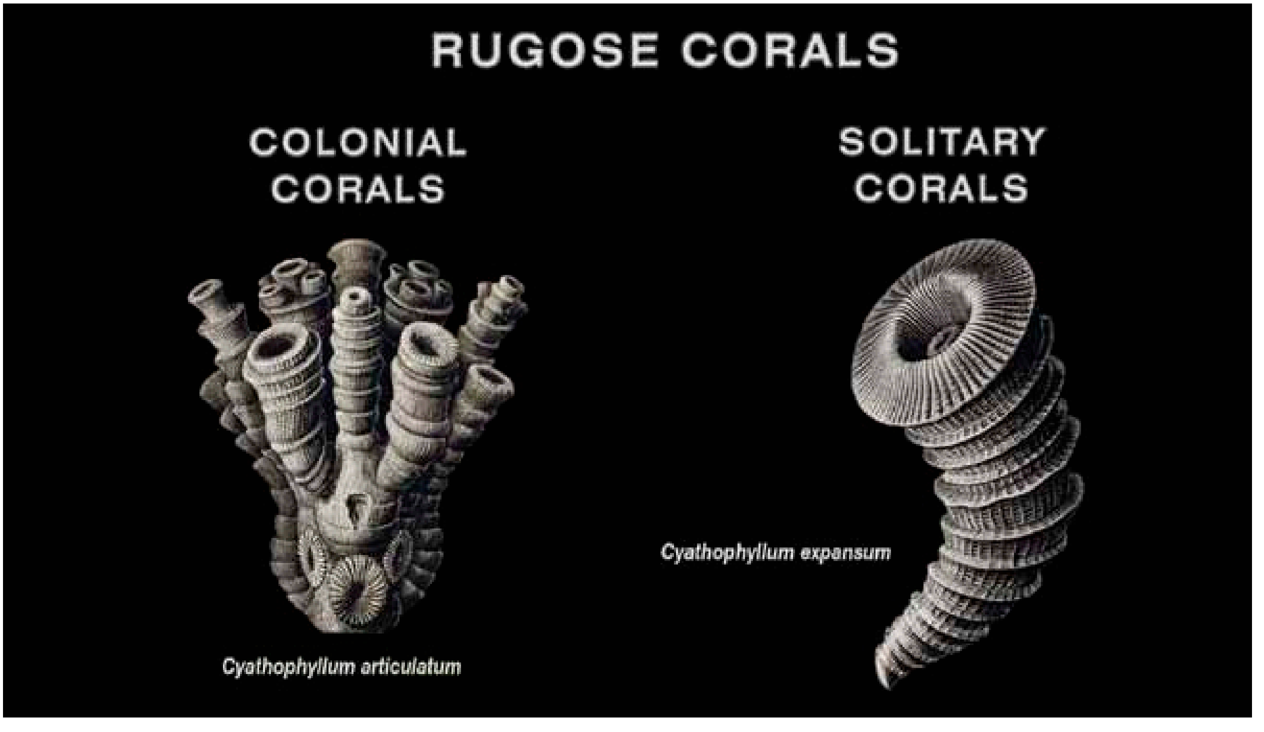
When stromatoporoids were living in muddy carbonate environments, the importance of finding a firm surface to attach to was very great, to avoid being toppled over by storms, or simply sinking into the mud. As a result, they often started growing on the shell of another organism such as a gastropod or coral. If you turn over a stromatoporoid to look at its undersurface, you can sometimes still see the impression of the original shell that the stromatoporoid moulded as it grew.

The classification of stromatoporoids is difficult, and it is unlikely that you will be able to identify any stromatoporoids you find to species or even genus level. However, typical genera found in the central Baltic include *Clathrodictyon*, *Stromatopora* and *Syringostromella*. Typical localities where they may be seen in life position are Kuppen (where they are a distinctive pink colour), Holmhällar and Ljugarn on Gotland, and Liiva, Undva, Katri and Kaugatuma on Saaremaa. Please note that when found in life position, stromatoporoids often form part of scientifically and scenically important outcrops, and no attempt should be made to collect them.

CORALS

The corals are a large group of rather simple animals related to the jellyfish and anemones: together, they form the phylum Cnidaria. They evolved during the Cambrian but did not become common until the Ordovician and Silurian. Although the corals of the Palaeozoic are related to the familiar corals of today that make up reefs, they are classified in different groups, the Rugosa and Tabulata.

Examples of colonial and solitary rugose corals



Corals can be solitary or colonial. In each case, a tiny tentacle-bearing animal sits in a cup made out of calcium carbonate called the calyx. As the animal grows, it grows successive cups on top of the old ones, so that the skeleton elongates. The colonial corals consist of groups of these sets of structures – called "corallites" – that are fused together, and a very massive structure can result. Like all the other cnidarians, the small coral animal or "polyp" uses its tentacles that are covered in stinging cells to catch small prey.

RUGOSE CORALS

Rugose corals can either be solitary, in which case they usually grow in a distinctive curved horn shape (they are sometimes called horn corals), or colonial. The horn corals have an obvious ridged outer surface, which is related to their episodic mode of growth. The colonial forms can form large masses some tens of centimetres or even metres across. The corallites in colonial rugose corals can either be somewhat separated from each other, or be in close contact, in which case they can form striking geometrical patterns.

The internal structure of rugose corals is quite complex, and scientists have given a number of technical names to individual components. The most obvious of these are the septa, vertically and radially arranged sheets that form the distinctive appearance of a rugose coral. The individual polyps sat on a transverse basal plate called a tabula. In some forms, these structures are partly or fully replaced by smaller, angled blister-like structures called dissepiments, which presumably evolved to allow the polyp to grow more gradually, rather than the episodic growth implied by insertion of the tabulae. Although they appear at first glance to have radial symmetry, a closer look at an individual corallite shows it to have more of a bi-radial construction. This comes about by the distinctive way in

Rugose coral *Goniophyllum pyramidale*, height – 2.5 cm. Courtesy of NRM

Above: rugose coral *Schlotheimophyllum* sp., horizontal size – 11 cm. Left: rugose coral *Palaeocyclus porpita*, diameter ca 2 cm. Courtesy of NRM

which rugose corals grew. Young corallites possessed six primary septa, but as the coral grew, septa were only inserted in four of the gaps between them, so that a bilateral symmetry develops. Because of this method of growth, rugose corals are sometimes referred to as tetracorals.

Rugose corals seem not to have had any particular means to attach to hard surfaces, and to have mostly rested in soft sediments, where the horn-shaped colonies would sink in slightly. As a result, they were not able to form large reefs as the modern corals do. Rugose corals appear in the middle

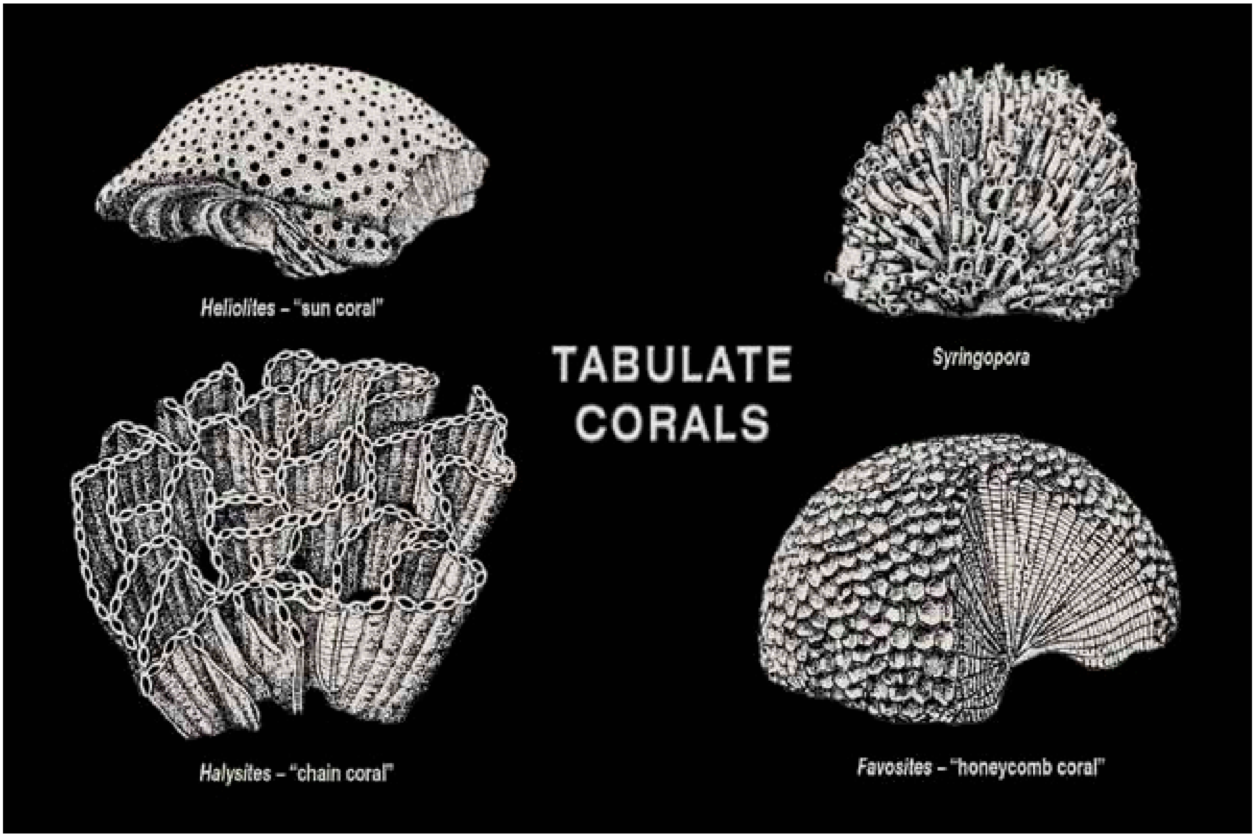
Above: rugose coral *Grewingkia europaeum*, horizontal size – 8.5 cm. Left: rugose coral *Cystiphyllum siluriense*, height – 6.8 cm. Courtesy of IGTUT

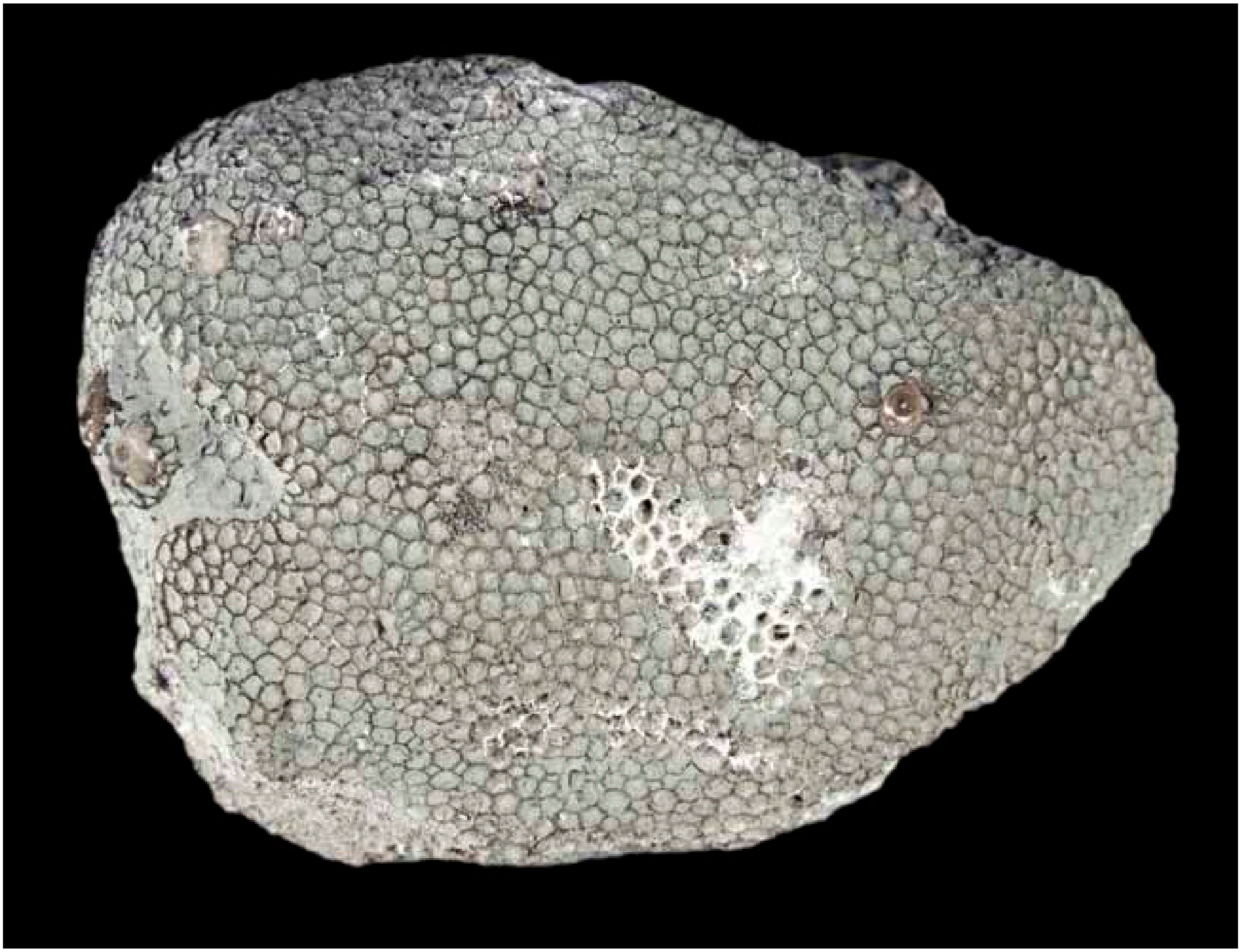
Ordovician as small solitary forms. It is not until the early Silurian that colonial forms evolved, but they became quite common at this time, and can often be found within the reefal limestones of Gotland and Saaremaa. The classification of extinct corals is difficult in general because of their variable morphology, but typical forms found in the central Baltic region include the solitary forms *Cystiphyllum*, the small button-shaped *Palaeocyclus* and the spectacular form *Goniophyllum* with its distinctive square-shaped corallites, and the beautiful *Schlotheimophyllum*, which is often found in groups. Colonial forms include *Siphonodendron*.

TABULATE CORALS

The tabulate corals are a distinctive group of organism that for a long time were considered by some not to be related to the other corals at all: indeed they were thought to be algae! However, the discovery of specimens with preserved tentacles in Canada convinced most people that they were after all true corals. Like the rugose corals, they are only found in Palaeozoic rocks.

All tabulate corals are colonial, and these can range in size from a few centimetres to huge structures several metres across. The Ordovician and Silurian rocks of the central Baltic region yield a large number of them, especially in the Silurian reefs. Some of the more massive forms look superficially rather like both stromatoporoids and colonial rugose corals. In particular, the undersurface of some tabulates can show sheet-like patterns of growth similar to that of the stromatoporoids. However, they can be distinguished from both of these groups by the presence of very prominent, finely-spaced tabula; from the rugose corals by a lack of septa, and from the stromatoporoids by the presence of the corallites. In addition, the diameter of the individual corallites is usually small compared to that of the rugose corals. Several types of tabulate coral are particularly common in the Silurian of the region: *Favosites*, or the "honeycomb coral", and the two chain corals *Catenipora* and *Halysites*. In the first of these, the small corallites are packed together to form a honeycomb-like mass – note the lack of septa distinguishing it from a rugose colony.





Above: tabulate coral *Favosites* sp. from Gotland, horizontal size – 6.5 cm. Right: close-up of the same specimen. Courtesy of NRM

When viewed from the side, *Favosites* shows the masses of small transverse tabulae. The chain corals have a different construction whereby the corallites are attached together in chains rather than packed together. If you find a chain coral, you can see which one it is by whether or not the corallites are all the same size or not: if they are, it is *Catenipora*, and if they alternate in size, it is *Halysites*. However, you will probably need to use a hand lens to see the dif-

Above: tabulate coral *Halysites laticatenatus* from Gotland, horizontal size – 15 cm. Left: close-up of the same specimen. Courtesy of NRM

ference clearly. One further type of tabulate quite often found is *Heliolites* with its distinctive, small corallites slightly separated from each other – note again the lack of septa.

Corals can be found widely distributed in the Silurian rocks of the central Baltic; they are also found, less commonly, in the Ordovician. For example, the chain corals are often found in the marls of the Visby formations, where they form reef-like masses. Good

examples of these can be seen at Ireviken and Korpklint on Gotland. Corals are also common on Saaremaa and other Silurian localities of Estonia, as well as on Vormsi, where they occur in the Upper Ordovician limestones there.

Above: tabulate coral *Syringopora* sp. from Gotland, horizontal size – 12 cm. Top of right page: *Heliolites* sp. from Gotland. Bottom: close-up photos of the specimens as shown on top. Courtesy of NRM


Stockholm.
Gotl. Ardre,

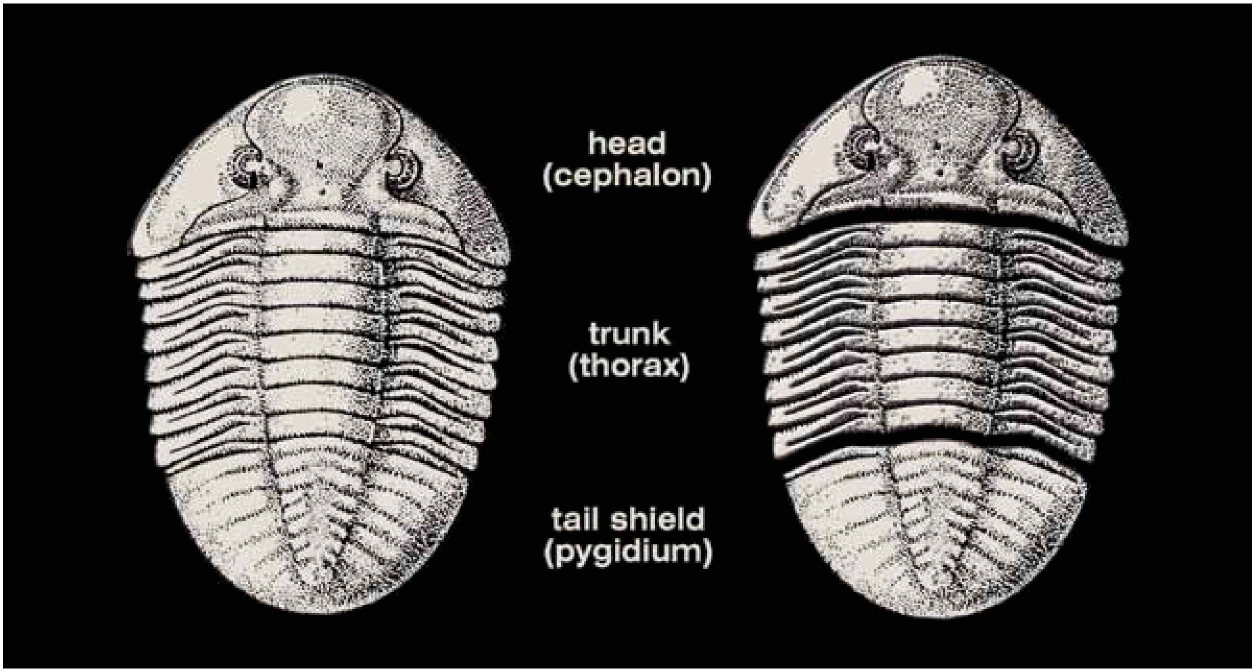
ARTHROPODS

The arthropods are a major group of animals that make up almost 80% of living animals species. Most of these are insects, but other arthropods such as spiders, scorpions, millipedes and centipedes, and the crustaceans (lobsters, crabs etc) are also very common. Arthropods are distinctive in several ways. Their bodies are divided into segments, and they have a tough exoskeleton on the outside that has to be periodically moulted to allow the animal to grow. The group gets its name from the presence of jointed legs: other well-known features include the often large compound eyes and the common presence of mandibles and antennae.

Fossil arthropods are also very common, and are found from the early Cambrian onwards. However, the insects, centipedes and millipedes did not evolve until somewhat later than this, with the first fossil insects not being known until the Devonian. As well as representatives of the modern groups, several distinctive extinct groups are also well known, of which the most famous are the trilobites. Most of the fossils from the central Baltic region are from groups that placed mineral salts into their exoskeleton to harden it, and these include the trilobites and ostracods, a form of small crustacean.

TRILOBITES

Trilobites are the most well known fossil arthropods, and most people will recognize their distinctive form. Because trilobites mineralised their dorsal exoskeleton, it was easily fossilized. Their body is divided into three sections, a head (cephalon); trunk (thorax) and tail (pygidium) of which only the second is clearly segmented. In addition, most trilobites are divided along their length into three as well, and it is this trilobation that gives the group their name. Most trilobites possessed a

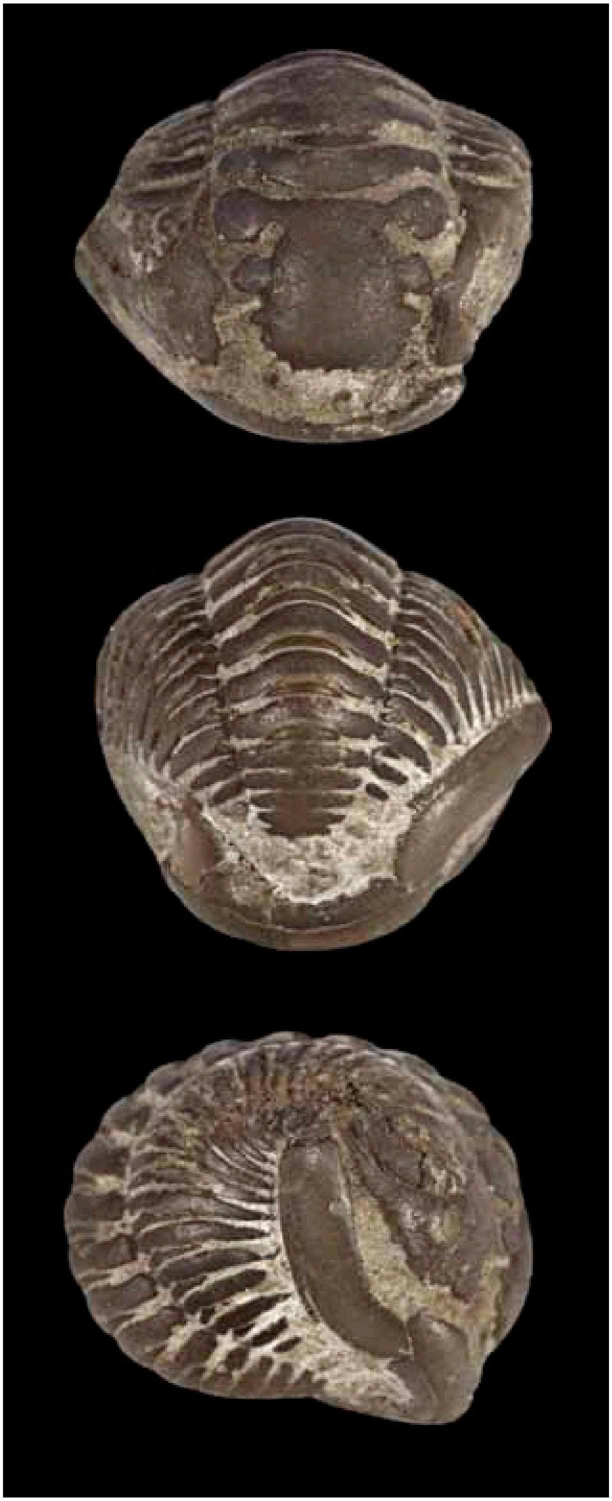


large pair of compound eyes on the dorsal surface of the cephalon. The cephalon also possesses distinctive lines of weakness called facial sutures that represent places where the exoskeleton first breaks when the trilobite is moulting. Their precise form is important in the classification of trilobites.

Soft parts of trilobites are known from some famous deposits in the USA and China, and from these we know that trilobites also possessed a pair of antennae. Most trilobites are a few centimetres long, but the largest known examples got up to nearly a metre in length. One of the largest trilobites from the Baltic region is probably *Megistaspis*, some species of which can grow up to 40 cm in length.

Most fossil trilobites found are the remains of moulted exoskeletons, and as a result tend to be fragmentary – either the head, or more commonly the pygidium is found on its own. However, one distinctive ability of trilobites was to be able to roll up into a tight ball when danger threatened, and they can sometimes be found complete in this way, such as in the Mulde Brick-clay of Gotland, or in the Ordovician Haljala Stage of Estonia (commonly the species *Chasmops wenjukowi*). Trilobites were exclusively marine animals, and seem to have had a diverse set of ecologies, from predation to feeding off detritus on the sediment surface. In addition, although most lived on the sea floor, some could swim and others spent their whole time in the water, such as the Cambrian and Ordovician agnostids or Ordovician telephinids.

Trilobites first appear in the fossil record about 520 million years ago, and then rapidly diversified. Early trilobites (*Schmidtiellus*) have sometimes been found in the early Cambrian sandstones in the Bal-



Rolled-up trilobite *Calymene* sp., size ca 1.5 cm. Courtesy of NRM tic region, such as those found at Kunda and Saviranna in Estonia, but they are extremely rare. By the late Cambrian, trilobites are common and found in huge numbers in the Alum Shale Formation that is widespread throughout Scandinavia, although these rocks are not found in the central Baltic region. Trilobites diversified again during the Ordovician and genera like *Megistaspis*, *Asaphus* and *Nileus* can be found in the limestones of the region. At the end of the Ordovician, they underwent a severe extinction like many other groups, but diversified once more in the Silurian. Whilst they are not normally easy to find in the Ordovician and Silurian rocks of the region, some patient searching will usually be rewarded by a few specimens. Famous trilobites from the Silurian include *Calymene* and *Encrinurus*. While Ordovician trilobites are commonly rather smooth and featureless, those of the Silurian are quite often spiny and covered in tubercles, so make quite distinctive fossils even when fragmentary.

Above: trilobite *Calymene tuberculata*, length – 4.5 cm. Courtesy of NRM. Below: trilobite *Estoniites laurssoni*, length – 18 cm. Courtesy of GMUT

OSTRACODS AND SIMILAR ARTHROPODS

Trilobites are the most prominent and distinctive arthropod fossils of the Baltic region, but other arthropod fossils can sometimes be found. The most common of these are the ostracods, or seed shrimps. These are in fact much more common than trilobites, but because of their small size and lack of distinctive features they are easily overlooked. Ostracods possess a pair of bean-shaped oval shells or valves that, like the exoskeleton of the trilobites, were impregnated with calcite, so that they leave good fossils. Superficially, many of them look much like bivalve molluscs, with which the larger specimens are often confused. Most ostracods, fossil and recent, are quite small, with even the largest ones not exceeding a couple of centimetres in length, and most commonly they are only a few millimetres in length. A hand lens is thus useful if you are interested in looking for them! Their shells are often smooth and featureless, but some groups have very ornamented surfaces, commonly with sulci and lobes, and in larger specimens occasionally with small tubercles showing the position of the eyes.

Ostracods are not the only arthropods with bivalved shells, and in the absence of soft parts, which are only rarely preserved, the exact affinities of many Palaeozoic bivalved arthropod groups remain unclear. Palaeozoic ostracods and ostracod-like groups are marine and can be found in most of the carbonate rocks in the region. They were particularly adaptable to high salinity conditions. For example, the large, ostracod-like leperditicopid *Hermannina* can be commonly found in some of the very shallow water rocks such as the Tofta Formation of Gotland (exposed at Galgberget near Visby, for example).

The ostracod-like arthropod *Hermannina hisingeri*, length – 1.5 cm. Courtesy of NRM

EURYPTERIDS

Another type of arthropod occasionally found in the Silurian rocks of the central Baltic region is the eurypterids or "sea scorpions". These were relatives of the modern day spiders and scorpions, and indeed have a broadly scorpion-like appearance. However, they were marine or (later) freshwater, not terrestrial. The largest forms were huge, with the longest individuals estimated to have been up to three metres in length. Most were however much smaller than this, with a length of about 20 cm or less. They had an elongate body with a spiny tail called a telson, and a set of formidable appendages at the front of the animal makes it clear that most of them were predators. Specimens of eurypterids can sometimes be found in the carbonate rocks of Gotland and Saaremaa, but are never common. Rare specimens show brown remnants of the original cuticle. A typical eurypterid of the region is, appropriately enough, called *Baltoeurypterus*.

SCORPIONS

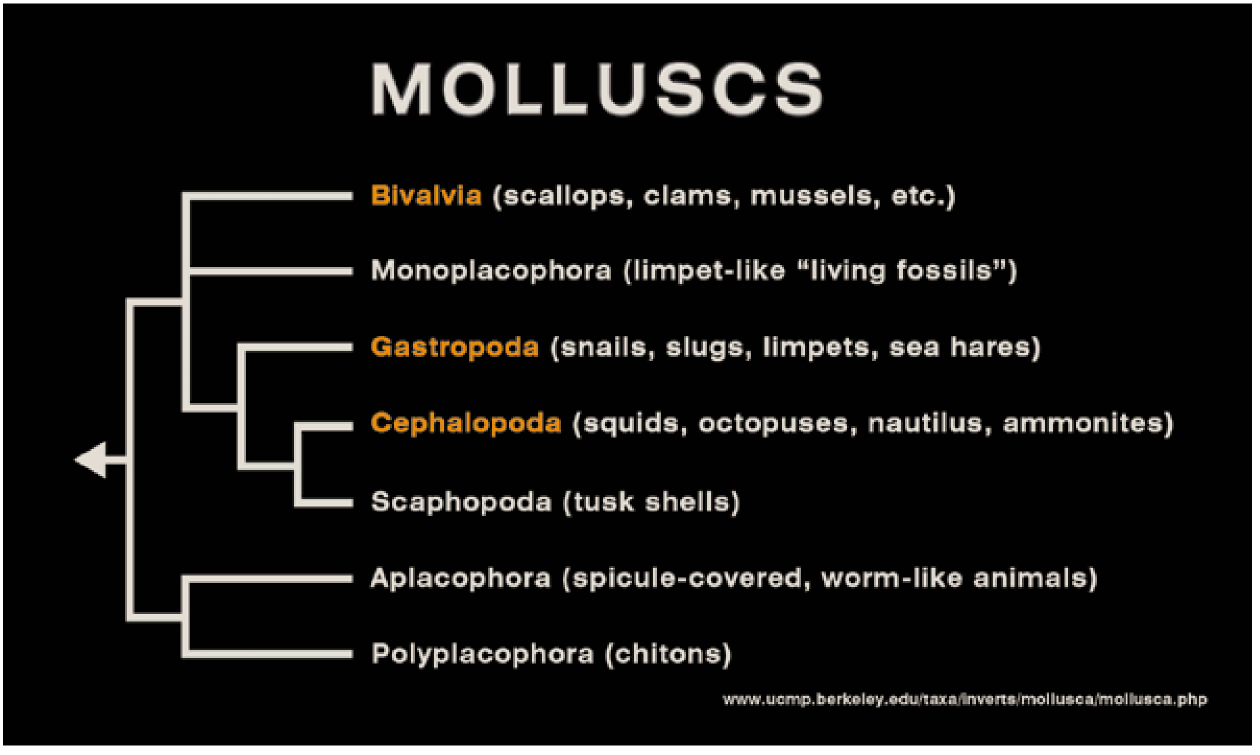
In 1884, Thorell and Lindström published a description of a virtually complete specimen of the world's oldest fossil scorpion, *Palaeophonus nuncius*, from the Högklint Formation in Visby, a sensational find that was reported around the world. However, such finds are extremely rare and to date only two specimens of this remarkable animal have been found. Unfortunately the locality in Visby where it was found is no longer accessible. It is likely that despite its modern appearance, *Palaeophonus* was a marine animal with gills. Nevertheless, it is possible that even in such a well-studied area as the central Baltic, new and rare specimens can always be found.

Left top: eurypterid *Baltoeurypterus* sp. from Saaremaa, length – 7 cm. Courtesy of GMUT

Left bottom: scorpion *Palaeophonus nuncius* from Gotland, length – 6.2 cm. Courtesy of NRM

MOLLUSCS

Molluscs form a large group of marine and terrestrial, normally shell-bearing animals that include the familiar snails, slugs, bivalves (mussels, scallops, oysters etc) and cephalopods (cuttlefish, squid, octopus and *Nautilus*), together with a variety of lesser-known forms such as the polyplacophorans, monoplacophorans, aplacophorans and scaphopods, together with some extinct forms. They first appeared early in the Cambrian and diversified strongly in the Ordovician into most of the modern forms. They exhibit a very diverse set of morphologies, and today, in the form of the extraordinary giant and colossal squids, are the largest invertebrates, reaching some 14 metres in length. They are quite common in the rocks of the Baltic region, although many of the ecological niches occupied today by the bivalves were then occupied by the brachiopods.



GASTROPODS

The gastropods are characterized today by the usual presence of a coiled shell, most well-known from the terrestrial snails and marine whelks. Their shells are made of aragonite, a form of calcium carbonate that does not preserve particularly well, so they are probably somewhat underrepresented in the fossil record. Nevertheless, they are quite common in the Ordovician and Silurian rocks of the region. Most gastropods do not divide their shell into chambers, and in this they can be distinguished from small coiled cephalopods in the fossil record.

One of the most commonly found genera is *Euomphalopterus*, a quite large low-spiral form with a distinctively ridged shell, from the Silurian that reached quite large sizes of several centimetres in diameter. Shells of these gastropods quite often show signs of repair after damage that has been taken as a sign of failed predation attempts on them.

Below: gastropod *Euomphalopterus* sp. from Gotland, length – 4 cm. Courtesy of NRM

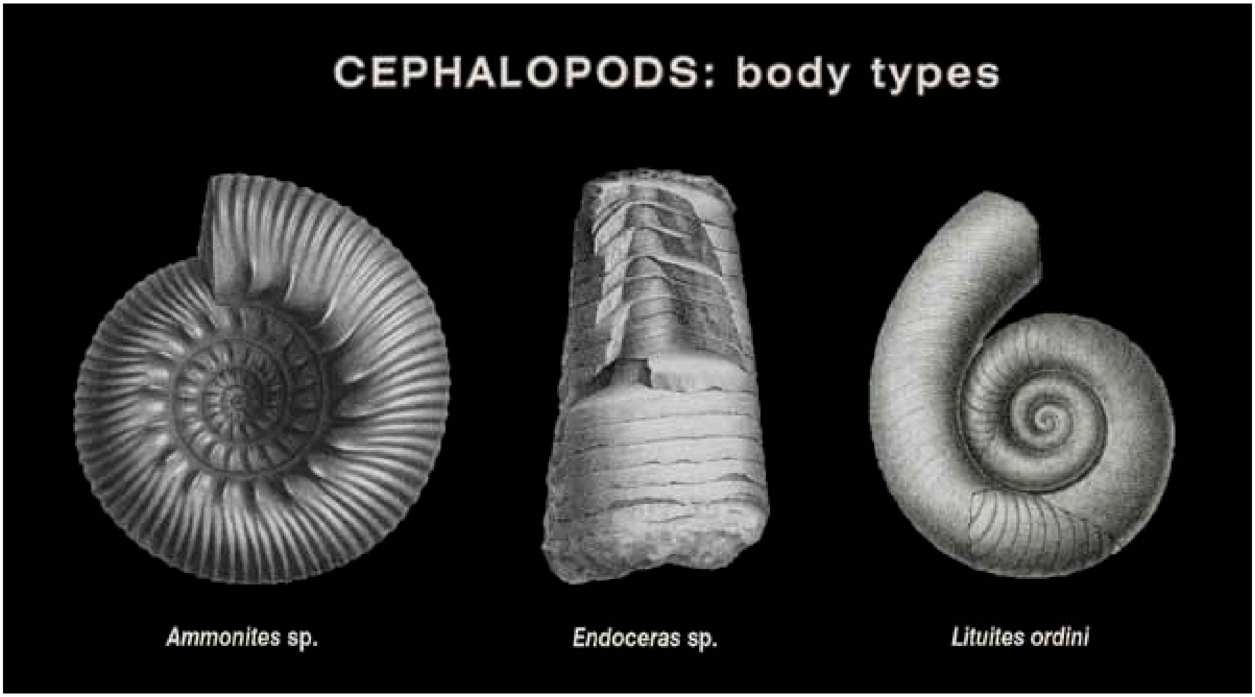
Right top: *Murchisonia* sp., length – 7 cm. Right bottom: *Holopea* sp., length – 6 cm. Courtesy of GMUT

CEPHALOPODS

The most commonly found molluscs in rocks of Ordovician age in the Baltic region are the cephalopods. Unlike the more familiar coiled shells of the later ammonites, these cephalopods normally had a straight, narrowly-tapering conical shell called an orthocone, or a curving shell called a cyrtocone. Some of these cephalopods reached an enormous size, with the largest Ordovician individuals being estimated to have reached some nine metres in length. Whilst these monsters are rare, large specimens of up to a metre or more are not too uncommon. The shells of cephalopods are divided into chambers by meniscus-shaped or complex internal walls called septa, and these are often seen in fossil specimens. The bodies of these cephalopods are generally thought to have resembled that of their living relative, *Nautilus*, with large eyes and tentacles protruding from the opening of the shell.

Recent cephalopod *Nautilus pompilius*

Two of the most well-known fossil forms are the endocerids and orthocerids. The difference between them can most clearly be seen in their internal structure, most easily in broken specimens or those seen in cross section. Cephalopods in general swim



and maintain their position in the water column by changing their density. They do this by pumping gas in and out of the chambers in their shell. The organ with which this is done is called the siphuncle. Part of the siphuncles is fleshy and porous to allow gas exchange, but where it passes through the septa it is calcareous, these regions being called the septal necks. In endocerids, the siphuncle is large and placed ventrally within the shell, whereas in the orthocerids, it is sub-central, as in the modern *Nautilus*. In addition, specimens of endocerids possess deposits of carbonate within the siphuncle called endocones. Orthocones also possessed deposits of calcite within the chambers. These deposits probably had the function of acting as a counter-weight to the buoyant shell, so that the body could be kept horizontal when the animal was swimming.

Octameroceras unguifer from Gotland, length – 5 cm. Courtesy of NRM

The shells of orthocones are in general not particularly well preserved, and as a result precise identification to the genus or species level of a particular specimen is often difficult. Where the outer surface is seen, it can sometimes be seen to be ridged or otherwise ornamented.

Orthocones in general are thought to have been active swimmers, but a few of the more peculiar forms were probably benthic. They were probably the "top predators" of their day until the jawed fish evolved sometime at the end of the Silurian. Characteristic genera include *Endoceras*, *Orthoceras*, *Estonioceras* (a curved form) and the extremely peculiar egg-shaped form *Octameroceras*. As the end of the shell of this form is almost sealed up, it is not at all clear how it would have fed or even moved.

BIVALVES

The bivalves are a familiar group of benthic animals that live in sea- and freshwater. As the name suggests, they possess a pair of calcareous shells or valves that enclose the body laterally. The two shells meet along the dorsal surface of the animal with a straight hinge line, and the shells can open and close with a combination of muscles and an elastic structure called the ligament. The body is soft and fleshy and lacks a head region, although some forms such as the scallops possess sets of eyes around the edge of the body. These shells grow by accretion of carbonate around the edges, and thus typically show sets of narrowly-spaced growth lines that parallel the shell margin. Whilst they are not particularly common in rocks of the central Baltic region, they can be found in large numbers in

Pteronitella retroflexa from Gotland, length – 5 cm.
Courtesy of NRM

certain deposits. For example, the large form *Pteronitella retroflexa* is found in great numbers in the Burgsvik Formation at Kettelvik. Bivalves are much more common in rocks of Silurian than Ordovician age.

ROSTROCONCHS AND MONOPLACOPHORANS

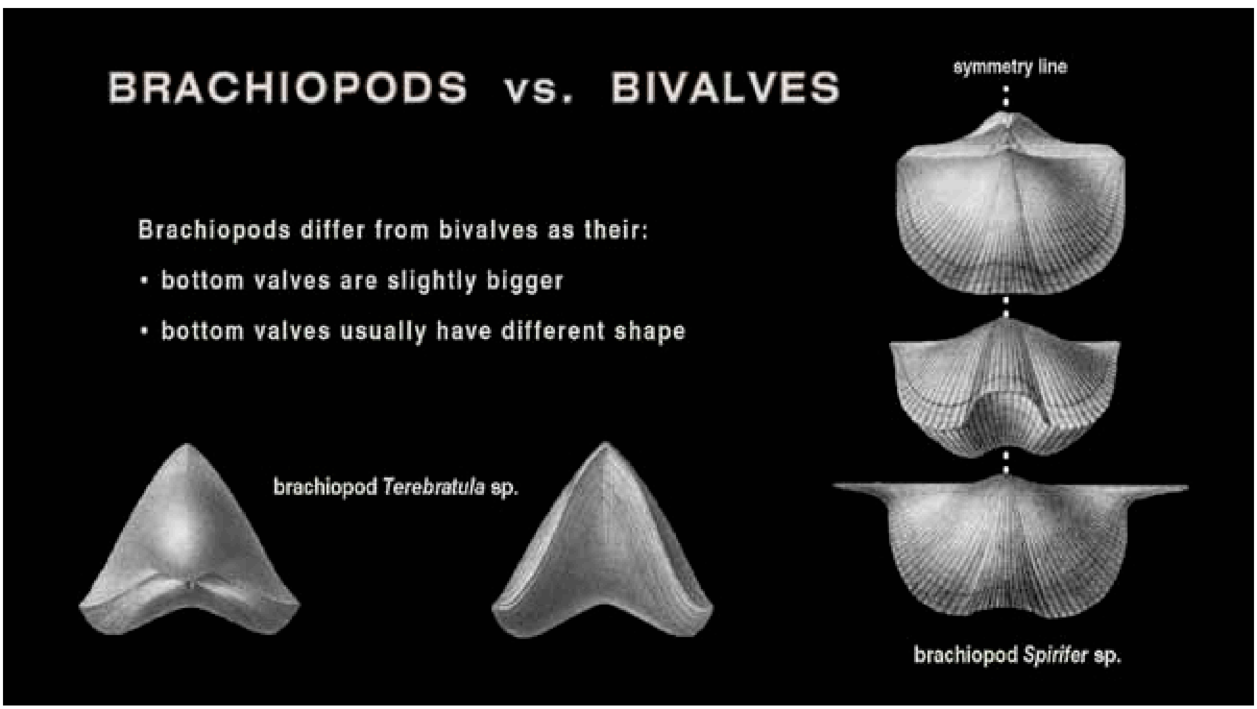
As well as representatives of the familiar groups described above, the bivalves, cephalopods and gastropods, the Silurian rocks of the central Baltic region also yield rare specimens of extinct or rare modern groups. One of these is the rostroconchs, a small group of bivalve-like forms that evolved in the Cambrian and went extinct in the Carboniferous. Although the adult shell is in the form of two valves, the juveniles had only a single shell, and it does not seem that the rostroconch shells functioned in the same ways as bivalves. The forms that are found in the Silurian of the central Baltic are typically small (approximately 1 cm long) and have a ridged, elongated bivalved form with a permanent gape. The edge of the shell is crenulated, and this forms a distinctive pattern that is the easiest way to recognize them in the field.

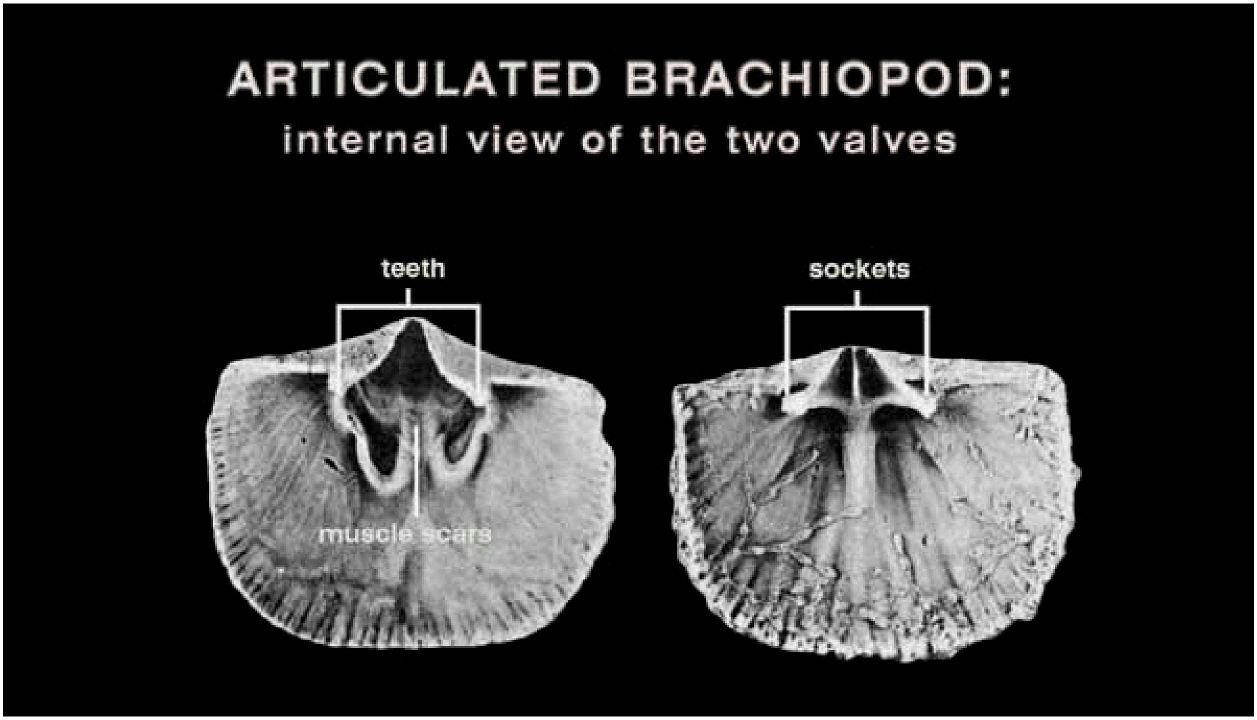
Another rare form of mollusc occasionally found in Silurian rocks is the monoplacophorans. This group today is rare, and was known only from the fossil record until their discovery in the deep sea in 1852. Monoplacophorans possess a single, cap-shaped shell and the internal surface is marked by a series of paired muscle scars that have suggested to some that molluscs were originally segmented. The most common form in the Silurian of Gotland is *Tryblidium*, which reaches quite a large size (ca 4 cm long) and has a ridged, rather oyster-like shell; the inside is marked by a series of paired muscle scars like the living monoplacophorans. Nevertheless, neither rostroconchs nor monoplacophorans are common fossils – count yourself skilful or at least lucky if you find one.

Tryblidium reticulatum from Gotland, length – 3.5 cm.
Courtesy of NRM

BRACHIOPODS

The brachiopods are today a relatively small group of shell-bearing marine invertebrates that show a superficial similarity to the bivalve molluscs. However, they form a very distinct phylum of their own, and are not close relatives. Like the bivalves, they possess two shells, but whereas those of the bivalves enclose the body laterally, those of the brachiopods are dorsal and ventral. Whilst the shells of bivalves are typically identical to each other, those of the brachiopods are of different shapes and sizes, and the plane of symmetry of the animal passes through the midline of both shells rather than between them as in bivalves. Inside the shell, the brachiopod body possesses relatively little tissue, but does have a prominent, tentaculate feeding organ called the lophophore. Many groups possess a structure called the brachidium that supports the lophophore. Most brachiopods possess an opening at the back of the ventral valve (which in life position is positioned dorsally) called the pedicle foramen, and through it a fleshy stalk called the pedicle emerges. The oldest tips of the shells are called the umbones, as in bivalves. The pedicle is usually used to anchor the brachiopod to a patch of hard substrate. However, some of them, notably the living *Lingula* are active burrowers and do not permanently attach themselves to anything. Brachiopods are traditionally divided into two groupings; the inarticulated, consisting of forms with a poorly mineralized phosphatic shell, of which the most prominent form today is *Lingula*; and the articulated forms, consisting of calcitic-shelled forms with a hinged joint between the two shells. However, this simple scheme does not do justice to the complexity of the fossil forms and has now been abandoned by specialists in the field, although it retains a certain practical usefulness. Fossil brachiopods emerged very early in the Cam-





brian and quickly radiated to become one of the most common Palaeozoic fossils along with the trilobites, and many thousands of species are known. They are extremely common, in many different forms, in most of the rocks of the central Baltic region. Indeed, many forms have yet to be described.

The diversity of the Palaeozoic brachiopods is divided up into a number of major groupings, only some of which are described here.

TEREBRATULIDS

The terebratulids are the most diverse group of brachiopods today. They possess a smooth, oval shell that gives them a vague resemblance to a Roman oil lamp, hence their alternative name of lamp shells. They were until recently thought to have evolved at the beginning of the Devonian, but are now known from rocks of Wenlock age from the Silurian.

ATRYPIDS

Atrypids are probably the most common form of brachiopod found on Gotland, in some places making up some 80% of the local brachiopod fauna. They are sub-oval in shape and possess distinctive radiating ribs radiating out from the umbone, together with clear growth lines that parallel the shell margin.

Brachiopod *Atrypa marginalis* from Gotland, length – 1.5 cm. Courtesy of NRM

STROPHOMENIDS

Strophomenids are flattened brachiopods with concave dorsal valves that lacked pedicle foramens as adults. As a result, they presumably "floated" on the sediment surface. Several distinctive forms are known from the region, with the most striking probably being the leptaenids.

RHYNCHONELLIDS

The rhynchonellids, like the terebratulids, still have living representatives today. They typically have rather bulbous shells with strongly developed ridges on them.

PENTAMERIDS

The pentamerids are another distinctive form of brachiopod, with a strongly ridged external shell and curving umbones. The most easily recognized form on Gotland is *Conchidium*, which is a large brachiopod several centimetres across. It is common in for example the Klinteberg Formation.

ORTHIDS

The orthids are some of the most basal calcareous brachiopods, having evolved early in the Cambrian. They form a large and rather poorly defined group with flattened shells and usually quite strongly developed radial ribs. They were very common and widely distributed during the Ordovician. One of the most distinctive and famous orthids from the Silurian of the region and elsewhere is *Dicoelosia biloba*, a form originally described by Linnaeus, the shells of which are divided into a bilobed shape.

TRIMERELLIDS

Some of the most interesting brachiopods from the central Baltic region are the trimerellids. These are large, sub-spherical brachiopods several centimetres across that grew in large stands, forming reef-like

Brachiopod *Strophomena rhomboidalis* from Gotland, length – 3 cm. Courtesy of NRM

Brachiopod *Rhynchotreta gracilis* from Saaremaa, length – 1.2 cm. Courtesy of IGTUT

Brachiopod *Conchidium binoculare* from Gotland, length – 3 cm. Courtesy of NRM structures. They are found in a few places within the Slite Group. They are particularly distinctive because unlike all the other calcareous brachiopods, they appear to have formed their shells from aragonite, as opposed to calcite.

BRYOZOANS

The bryozoans, ectoprocts or moss animals, are a group of colonial organisms that – like the brachiopods – posess a lophophore. Whether or not the two groups are closely related is not clear. They seem to have evolved at the end of the Cambrian, and were very common during the Ordovician and Silurian. Like most other groups with a good fossil record, they often make a skeleton out of calcium carbonate that allows them to be easily preserved. Although the colonies themselves can be quite large (several centimetres across) the individual animals or zooids are tiny – much less than a millimetre. As a result, the colonies appear to have a finely perforate appearance. They can sometimes be confused with small colonial corals unless inspected closely with a hand lens, when the tiny openings for the zooids can be seen to be lined up in rows.

Bryozoans form a variety of colony shapes – sticks that are often branched; button shaped, encrusting, or even feather shaped. They are common components of both Ordovician and Silurian limestones, and are often found growing on other organisms such as corals and stromatoporoids, presumably after the host died. Their skeletons are usually pure white in specimens, and this can form a striking contrast when in darker coloured rocks such as the upper Ordovician kukersite, or oil shale, of Estonia. Like most filter feeders, they prefer the clear water of carbonate environments as opposed to the murky waters of muds

Well-preserved bryozoans *Pseudohomera bifida* in kukersite oil shale. Length of slab – 23 cm. Courtesy of IGTUT

Bryozoan *Ptilodictya lanceolata* from Gotland, length – 7 cm. Courtesy of NRM

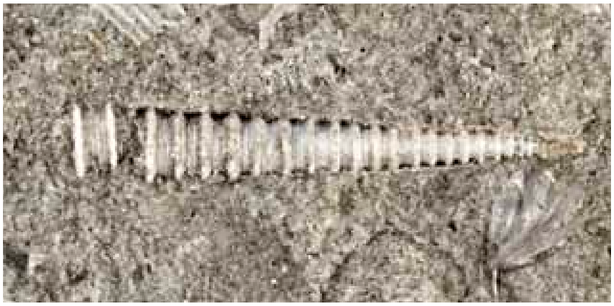
and clays. Fragments of their colonies are often found within beds full of crinoids (encrinites), and it is likely that they occupied very similar environments in life.

A particularly striking form of bryozoan is the large, feather-shaped colony called *Ptilodictya lanceolata* that can be found at, for example, the Slite Group beds at Valleviken. However, there are many other forms of bryozoans to be found as well, even though identifying them in detail can be difficult for the non-specialist.

PROBLEMATIC WORM-LIKE FOSSILS

There are several groups of fossils found in the central Baltic region that have uncertain zoological affinities. The most prominent of these are probably the tentaculitids, small conical tubes with pronounced transverse ridges that make them superficially resemble small wood screws. They are often found in carbonate rocks of Silurian age such as on Gotland and Saaremaa. Although their affinities are not known, they have often been thought to be related to the segmented worms or annelids. Most annelids have soft bodies and thus have a very poor fossil record. However, several groups build calcareous tubes that they live in, and the tentaculitids have often been compared to them. This assignment remains uncertain however, and they have also been more recently compared to some of the lophophorates like brachiopods and bryozoans. A much more certain record of annelids in the region is from their microscopic jaws called scolecodonts. However, these are in general too tiny to be noticed except by a specialist. One other type of fossil now known to belong to the annelids is the machaeridians, normally found as small, plate like structures with distinctive ridges on, that are

Tentaculites annulatus from Gotland, length – 1.5 cm. Courtesy of NRM

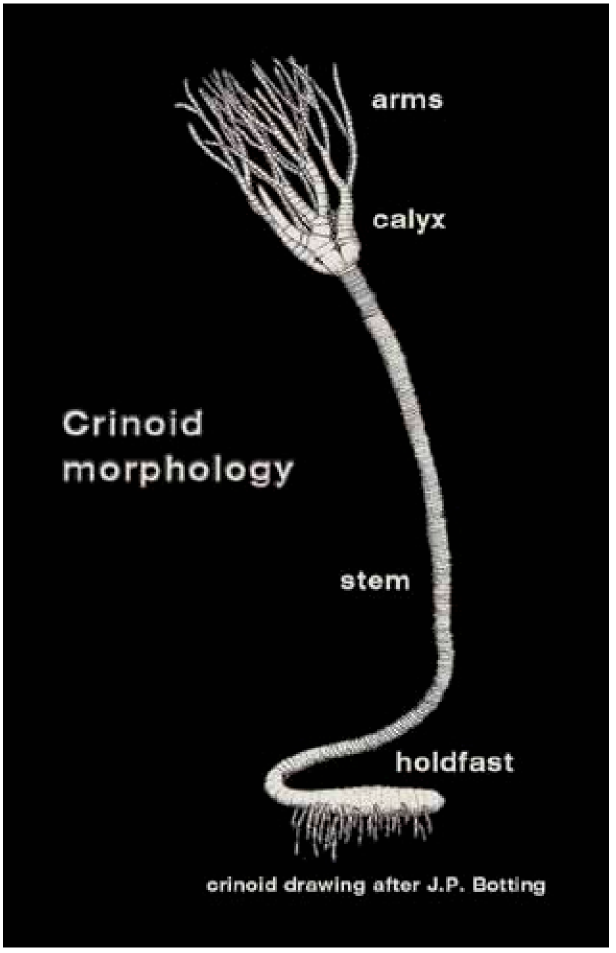


very rarely, found articulated together into worm-like forms. The recent discovery of a machaeridian with soft parts from Morocco has confirmed the suspicions of many workers that they are indeed related to the annelids. Machaeridians can be found in many carbonate rocks of the region, especially in the Silurian, but are rare and very hard to spot unless you are well equipped and specifically looking for them.

ECHINODERMS

The echinoderms are a very distinctive group of exclusively animals very distantly related to vertebrates but with completely different morphology. They possess a skeleton that is divided into a series of plates made of a porous mass of calcite called the stereome, which is technically an internal (endo-) skeleton. All modern, and most fossil, echinoderms possess a unique five-fold symmetry in their morphology. Internally, as well as the calcitic skeleton they possess a complex system of internal canals called the water vascular system that is connected to small external structures called tube feet. The surface of echinoderms is also often covered in spines and small pincer-like structures called pedicellariae that seem to be involved in keeping the animal's surface free of debris. The most familiar living echinoderms are the echinoids or sea urchins (divided into regular and irregular forms) and the starfish and brittle stars, the latter possessing a series of arms (often five) that they use to crawl around with. Other living forms include the slug-like holothurians, which have reduced the skeleton to a set of isolated ossicles embedded in the soft tissue, and the stalked and free-living crinoids.

Echinoderms have a rich fossil record because their calcitic skeleton is easily preserved. The skeleton is divided into a series of plates that often disarticulate



on death and they are therefore usually found in fragmentary form. The Palaeozoic record is dominated by stalked forms of crinoids, which often occur in enormous numbers, but a number of other, relatively poorly-understood forms are also quite common.

CRINOIDS

The crinoids or sea lilies are a group of distinctive echinoderms that consist of a small calyx that bears the mouth and anus, surrounded by a set of feathery arms. They evolved near the beginning of the Ordovician period. Most modern forms are free-swimming or stalk-less, but the Palaeozoic forms are typically stalked and spent most of their life attached to one spot, although it is known that the few modern stalked crinoids can in fact slowly walk around. The stalks are composed of a long stack of individual round or star-shaped stereome ossicles that often disarticulate, either into individual ossicles or into short segments of the stalk. The bottom of the stalk usually broadens out into a solid holdfast with small root-like structures by which the crinoid firmly attached itself to the substrate. When found complete, some fossil crinoids can be seen to have had extremely long stalks of several metres in length.

Crinoids were very common components of reef-like assemblages in the Palaeozoic, and their fossils are sometimes found in extremely high numbers. Indeed, some rocks, such as in the Ordovician of Dalarna, central Sweden, are composed almost entirely of crinoid ossicles, and are called encrinites. It is thus likely that many Palaeozoic reefs had very dense

Crinoid calyx from Gotland, height – 2 cm. Courtesy of NRM

Crinoidal limestone from Gotland with crinoid fragments 1 – 2 cm across. Courtesy of NRM

stands of crinoids growing on around and on them. When fossil crinoids are found complete, this was usually the result of extremely rapid burial during storms that suddenly swamped the animal before there was time for the skeleton to disarticulate. An extremely famous slab with many such complete crinoid specimens was found somewhere near När on the east coast of Gotland during the 19th century, and is now in the Swedish Museum of Natural History in Stockholm – and also on the cover of this book. Unfortunately, it was not collected in situ and its precise stratigraphic level is not known, although it is from the Eke Formation at least.

The taxonomy of Palaeozoic crinoids is not well established because of the fragmentary nature of most of the remains. On Gotland, common genera include *Calliocrinus*, *Dimerocrinites* and *Eucalyptocrinites*. Crinoids are common in many of the reefal limestones of the central Baltic region, for example at Kuppen and at Ljugarn, where large fragments of stalk some 2 cm in diameter can be found; in both cases they are associated with stromatoporoids. More commonly, such as at Korpklint, masses of fragmentary crinoid remains make up rocks composed of the debris swept off the reefs. Crinoids are often pure white as fossils, but some of the specimens in the region, such as at Kuppen, have a striking pink or red colour.

BLASTOZOANS

A variety of now extinct, crinoid-like fossils, broadly referred to as blastozoans are also known from the Ordovician and Silurian of the region. They typically had short stalks, and small, often oval calyxes with short arms. In practice, they are difficult to distinguish from crinoids without specialist knowledge. The most well-known of the region are the so called "crystal apples" of the Ordovician, specimens of the cystoid *Echinosphaerites*, so called because the large internal cavities of their calyxes are often filled with coarsely crystalline sparry calcite.

HOMALOZOANS

One other form of echinoderm occasionally found in the region is the homalozoans, an extremely bizarre, often asymmetrical type of echinoderm that has been much discussed in terms of their evolutionary significance. They are now normally regarded as being very basal forms of echinoderms that represent a stage of evolution before the characteristic five-fold symmetry evolved.

VERTEBRATES

Vertebrates are now thought to have arisen during the Cambrian period, but they only diversified during the succeeding Ordovician. Nevertheless, vertebrate fossils from this period are rare and usually important. An exception is made by the tiny conodonts that are now considered to represent the teeth of a basal vertebrate. While these are very common, and important for dating rocks during the Palaeozoic, they are too small and inconspicuous to be noticed apart from by the specialist in the field; normally, rocks have to be dissolved before the conodonts can be properly studied. During the Silurian, various types of jawless fish developed, and by the end of the period the first jawed fish appeared, with land vertebrates appearing in the succeeding Devonian period.

Vertebrate fossils from the west of the region are scattered and typically fragmentary. Some 26 species are known from the Silurian of Gotland, all representing various types of jawless fish. These are unfortunately

Reconstruction of placoderm fish *Psammolepis alata*, fish length – 83 cm. Reconstruction made by E. Mark-Kurik

typically in the form of scales, not complete specimens. At least five major groups seem to be represented: acanthodians, actinopterygians, anaspids, katoporidids and theolodonts. Similar fossils have been found on Saaremaa. However, the Devonian rocks of Estonia are much richer in fish yielding, in addition to the groups known from the Silurian, large placoderm fish (e.g. *Pycnosteus*, *Psammolepis*) and fragments of lungfish, relatives of the earliest tetrapods.

CONSERVATION, SAFETY AND COLLECTION

Collection of fossils is fun and interesting. However, fossils and their localities can also be protected as a part of natural conservation. Before starting or planning a collecting trip to a new area or new outcrop, some preliminary investigations should be performed.

Countries may have very different regulations regarding fossil collecting, and some countries have restrictions in place on exporting fossil material. In some cases the restrictions can be selective, applying only to certain groups of fossils or some important fossil species.

In Estonia, rules of collection and exporting fossils are based on the Law on Nature Conservation. Fossil collecting may be restricted both in protected areas, but also for protected objects. Additionally, a number of fossil taxa are subject to special protection.

The rules and restrictions on collecting within protected areas and objects may be specific and should always be checked in good time. Protected species may belong to two protection categories. In case of the rarest taxa (I protection category), it is not allowed to remove the fossil from its natural position. The list of such taxa is not very long, consisting today of a few taxa of brachiopods (*Dicoelosia anticipata*, *Costistricklandia lirata*), sponges (stromatoporoids *Clathrodictyon regulare*, *Plectostroma schmidtii*), corals (*Mesofavosites dualis*), echinoderms (sea urchins *Bothriocidaris pahleni*, *Bothriocidaris eichwaldi*, *Bothriocidaris parvus*, *Bothriocidaris globulus*) and vertebrates (*Phlebolepis elegans*). Export of these fossils is allowed for research purposes only and is subject to permission signed by the Minister of Environment of Estonia. All known localities of these fossils are protected by law. Species of sponges, corals, bryozoans, brachiopods, molluscs, arthropods, echinoderms and vertebrates (those which are not listed above) may also belong to the II protection category, if they occur in threatened localities only, or are rare as complete specimens. Important localities of these fossils are protected. Export of complete specimens is allowed for research purposes only and is subject to permission of the Environmental Board.

In Sweden, the rules for collection of fossils are unfortunately rather unclear, but at least it is forbidden to remove bedrock from nature reserves. No collection at all should be undertaken at protected localities such as Holmhällar, Kuppen etc. In addition you may not remove larger pieces of rock that have economic value. It is also not allowed to collect for commercial reasons. Therefore it is highly recommended that you leave a fossil in its natural position if it does not seem to be easily available. Material of good quality can often be much more easily found in loose debris on the shores – this you can collect.

Many of the fossil localities occur on private lands. Permission of the landowner is mandatory in such cases. This is also valid for big commercial quarries where unauthorized visits may not be safe.

Collecting usually requires only minimal equipment: a real geological hammer (an ordinary construction hammer may produce dangerous metal splinters) and safety goggles, a hand lens of up to 10 times magnification, a ruler for documenting the position of a fossil, and sample bags or paper. Sometimes a drove chisel may be necessary, although in most cases a chisel will only destroy fossils in inexperienced hands. Many small specimens of a perfect quality can often be obtained from fine debris collected from the section, just by means of washing of this material through a fine (0,2...0,5 mm) sieve.

The value of a fossil collection is very much dependent on the documentation of the material. Documentation can never be too precise. Every location should be marked on a map. GPS coordinates may be very useful also. A description and simple drawing or photograph of the locality should be made and the collecting point(-s) carefully marked. It is also very important to pack every valuable specimen separately (to avoid scratches on the surface) and to provide an individual label providing information for the collected object, the name of a section, the exact horizon and other details of the location, together with the name of the collector and collecting date.

Steep sections and escarpments are potentially very dangerous, particularly in early spring during the thaw. Use of a helmet is highly recommended when working close to such sections (in quarries it is mandatory) and all actions should be undertaken with necessary care, avoiding falling blocks and unstable parts of a section.

LOCALITIES

HALLSHUK (N 57° 55.499, E 018° 44.717)

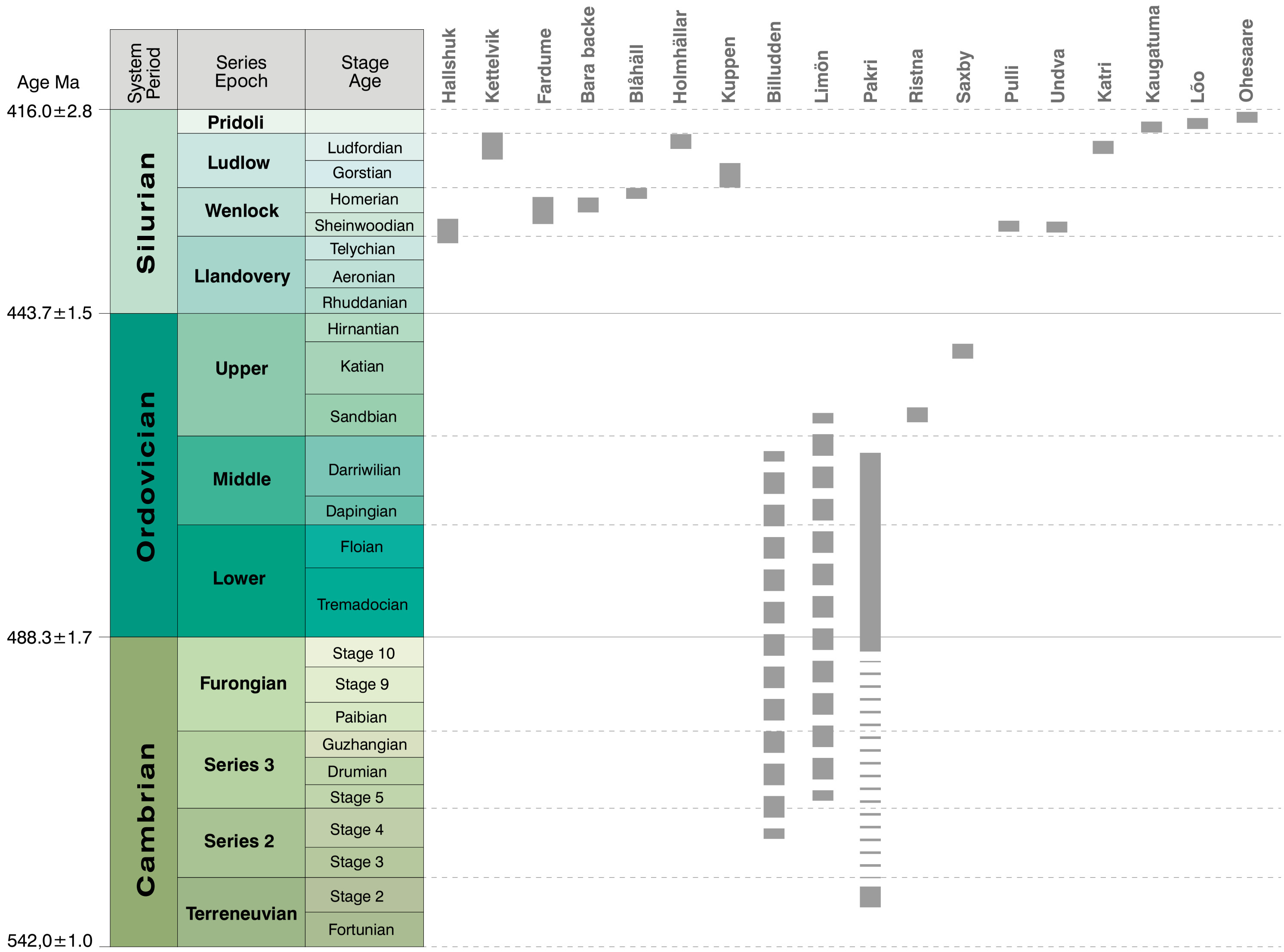
This beautiful and secluded peninsula on the north-west coast of Gotland is the site of a small fishing village, Hallshuk fiskeläge, consisting of a small collection of wooden fishing huts, a chapel, and a small lighthouse that sits on top of the cliffs. There is no natural harbour, but the present fishing harbour with its stone pier was built in 1927. At one time, Hallshuk was one of the richest fishing places on Gotland: during the 17th to 19th centuries, very plentiful Baltic herring (strömming) could be caught here. Fishermen also caught cod, flounder and later salmon.

The remaining wooden fishing huts where fishermen used to sleep during the fishing season nestle near the cliffs to the north of the village. The cliffs themselves are about 25 m high, and a very fine view can be had from the top where the lighthouse is, for example along the coast north to Fårö. On a fine day and with the help of binoculars it is even possible to see the "rauk" field of sea stacks at Långhammarshammar, far to the north. Looking directly below, one can see the shallow shell of limestone just underwater, with a distinctive concentric structure known as a "Philip structure", a circular depression marking where a reef has caused the underlying beds to sag.

From the fishing village, walk north along the grassy path and down to the beach. The cliffs at Hallshuk are made up of the Upper Visby Formation and the base of the Högklint Formation, which are some of the oldest rocks on Gotland, dating to the Upper Llandovery

Hallshuk cliff in northern Gotland

Distribution in time of the sedimentary rocks described from the central Baltic region



Stratigraphy is given after the International Stratigraphic Chart (September 2010) and Lower Wenlock of the Silurian. Both are richly fossiliferous. The Upper Visby Formation here consists of thinly bedded, grey-green marls, i.e. limestones with a significant component of non-carbonate mud in. Here, the furthest north that the Upper Visby Formation can be seen, there are no reefs developed in this formation, but just to the south, at Ireviken, small patch reefs a few metres across and about 1 metre high can be seen within it, with the principal component of the fauna being the chain coral *Halysites*. The typical rich fauna of the Upper Visby Formation can be collected here at Hallshuk however, including the characteristic "button coral" *Palaeocyclus*, a small solitary rugose coral, that marks its base, as well as other corals, gastropods, etc. Large gastropods such as *Euomphalopterus* are particularly common. Typical tabulate corals include the chain coral *Halysites*. Golden nodules of pyrite are also sometimes found in the Visby beds, indicating low oxygen levels.

Above the Upper Visby Formation is the Högklint Formation that consists of a series of reef-like bodies of a type similar to those also seen in the youngest rocks on Gotland, at Hoburgen. They are best seen along the path down to the beach. These rather massive structures are rather poorly fossiliferous themselves, but the rocks surrounding them are very rich in the debris that washed off the top of the reefs during storms. These include various stromatoporoid species together with crinoid and bryozoan fragments. Large white blocks of Högklint limestone litter the beach, and are often covered by huge lamellar stromatoporoids.

When one looks at the transition between the Upper Visby Formation and the Högklint Formation, one is seeing a distinct change in sea level and environment, from the probably quite deep water of the former to quite shallow water of the latter. Whilst it is always difficult to put an exact value on sea depths in the rock record, it has been suggested that the Visby formations were formed in at least 100 m of water, whereas the Högklint Formation must represent depths of only a few metres. The small patch reefs developed in the Upper Visby Formation must thus have formed at quite a great depth compared to most reefs.

In addition, just like modern reefs, ancient reefs only formed where the water was clear and there was little input of non-carbonate sediment. As the Upper Visby Formation contains quite a lot of mud, it seems that as the water depth decreased, the supply of sediment from the land also diminished. One can also see this in the change of colour from the darker Upper Visby Formation to the almost pure white Högklint Formation.

The boundary between the Upper Visby Formation and the overlying Högklint Formation is well exposed elsewhere along the north-west coast of Gotland as well, from Ygne just to the south of Visby, up to Hallshuk itself. Other notable exposures include those at Rövar Liljas Håla near Högklint; Korpklint just north of Visby, and Ireviken, all of which are also well worth visiting.

Careful dating of the rocks here has shown that the base of the Högklint Formation in different places is not always of the same age – for example, it is younger at Hallshuk than at Korpklint. This probably means that the Högklint Formation represents a mobile reef belt that slowly moved through time, being developed in some places earlier than others.

Getting to Hallshuk: Driving from Visby, take road 149 northeast out of Visby and follow it for about 36 km until you reach Hangvar, then turn right following the signs to Hallshuk, driving for another 4.5 km until you reach your destination.

KETTELVIK (N 56° 56.870, E 018° 09.460)

Kettelvik lies in the far south of Gotland, close to the southernmost point at Hoburg. It lies on a beautiful stretch of low-lying coastline. Along the coast are the remnants of old quarries where the upper Silurian Burgsvik sandstone was quarried for many centuries. The sandstone is a greyish, fine-grained, dense, but still quite soft rock that is ideal for use as a grinding or sharpening stone, and it was used for this purpose as long ago as the Viking age. It can also be quite easily shaped, and can be turned into decorative or practical objects such as candlesticks, weights, etc. Today, a small open-air museum at Kettelvik allows summer visitors to try their hand at sharpening knives and on certain days even to try to make their own objects such as birdbaths or plant containers out of the stone. The sandstone is one of the few non-carbonate rocks on Gotland, and represents a quite different environment from most of the other rock types found there. They, together with the beds that overly them even further south at Hoburgen, are the youngest rocks on Gotland. It may represent a delta or beach deposit. If you make your way across the old quarries to the beach, you can see the sequence of rocks represented here. The beach and the base of the low cliffs is composed of the Burgsvik sandstone, and overlying it are the Hamra-Sundre beds, which represent a return to the more normal carbonate depositional environments of Gotland. The top of the Burgsvik Formation is marked by a thick, massive unit of sandstone. If

Burgsvik sandstone cliff at Kettelvik, southern Gotland

you search on the beach, you will probably find some blocks of the sandstone with many examples of the rather large bivalve *Pteronitella retroflexa* on. Much of the normal fauna of Gotland is missing in this sandy environment, but other bivalves such as *Nuculoidea* can be found, as well as fragmentary crinoids and some trilobites such as *Calymene* and a low diversity of brachiopods. The fauna taken together suggest that this was a shallow-water environment. Some of the blocks of sandstone also show large spectacular trace fossils (the remains of burrows made by annelids and other animals) and yet others show distinctive wrinkled surfaces called "elephant skin structure", indicating that the sediment surface was once covered by algal mats. As well as the various sandstone blocks, massive stromatoporoids also litter the beach.

The low cliffs, about 7 m high, show the sequence, with the lower part consisting of the Burgsvik Formation, and the upper the Hamra-Sundre beds.

The overlying Hamra-Sundre beds show many interesting features. You may find blocks of these carbonate rocks on the beach as well. They have many fossils in such as stromatoporoids, tabulate corals, bryozoans, brachiopods etc. If you look closely at them, you will see that many are in fact coated with a thin white carbonate layer. These structures are called oncolites, and probably represent the activity of various types of cyanobacteria. Such structures are formed in extremely shallow water environments such as the lagoons that exist behind reefs. Periodic storms roll the fragments of fossils around and allow them to slowly build up an even coating of the carbonate. Many different types of fossil can be seen as coated grains here, including crinoid stems, bivalves, brachiopods and bryozoans.

Similar environments can be found today in the tropics, and this is a reminder that during the Silurian Period, Gotland was in fact situated very close to the equator.

Getting to Kettelvik: From Visby, take road 142 south to Burgsvik. Pass through Burgsvik and then drive on through Vamlingbo. A couple of kilometres south of the church, turn right onto the scenic coast road to Hoburgen ("vacker väg till Hoburgen"). Park on the right hand side of the road directly after passing through a cattle grid, about 700 m before the stone cutting museum. To get to the cliff outcrop, cross the old quarries and carefully make a descent to the beach; the section is just to the north.

FARDUME STENBROTT (N 57° 48.107, E 018° 55.485)

Fardume mire is the third largest lake on Gotland, and is a favourite haunt of many bird species. On its banks lies the ruins of a 13th century castle variously called Fardume slott, Mynttornet or Sören Norrbys källare.

Along the banks of the mire also lie several abandoned quarries. Quarrying was naturally very common on Gotland for many centuries, as people used the limestone to burn to make quicklime, or for building purposes. The quarries at Fardume were cut into the Slite Group.

Two major quarries can be visited easily, one larger water-filled one at the beginning of the road to Fardume träsk, and one about 250 m past the castle. This quarry, with walls that are about 5 m high, contains orange-grey Slite Group limestones that are slightly younger than the ones in the water-filled quarry. In places they show cross-bedding some 30–40 cm thick, indicating strong water currents. The beds here are richly fossiliferous, and a full range of fossils can be found here including many types of brachiopods, small stromatoporoids, rugose and tabulate corals

Fardume stenbrott quarry in northeastern Gotland

(especially *Favosites*) and trilobites. Note that many of the fossils here are very fragmentary, even though they are extremely common. Indeed, some beds are composed almost entirely of small fragments of fossils such as crinoid ossicles. Such shell accumulations are similar to those that form in high energy environment today, an indication that many of the rocks here were probably deposited during storms and other high energy events.

Getting to Fardume stenbrott: By road from Visby, drive along road 148 towards Fårösund. Upon reaching Rute parish church, take the turning towards Valleviken. At the "Folkets hus" at Rute, turn off on the road that leads to Fardume träsk and follow the signs. The first water-filled quarry is immediately on the right; then after a short distance comes the ruins of the castle, and about 250 m after this the smaller quarry.

BARA BACKE (N 57° 35.049, E 018° 36.453)

Rocks that occur in about the middle of the stratigraphic sequence on Gotland are referred to the Halla Formation. These rocks are very diverse, and different types can be seen in different parts of the island. The lower part of the formation consists of a particular type of rock called an oolite that forms in shallow water. These rocks can be seen in the low cliffs (about a metre or so high) of an old quarry at the base of Bara backe (Bara hill). They are thinly-bedded, brilliant white limestones that in places are cross-bedded. When examined carefully, the limestone can be seen to be composed of small (less than 1 mm across) pure white spheres called ooids, referring to their egg-like appearance. These have a layered structure, and form as waves rolled the growing ooids around in shallow warm waters. Above the quarry on the hill itself are other quarries cut into more typical rocks of the Halla Formation, with richly fossiliferous reefal limestones.

According to Hans Nielsen Strelow, writing in 1633, Bara backe was once the site of a sacred evergreen ash tree and pagan sacrificial site. However, the tree was supposedly moved in 1452 to Visborg Castle, by the powerful nobleman Ivar Axelsson (later to

Bara backe in central Gotland. The oolite crops out by the carpark at the base of the hill

become virtual co-regent of Sweden), where it soon however withered and died. The associations of the hill with holiness led to a great oak cross being set up there later, where villagers would bring gifts of money or wood with the hope of restoring lost animals or reversing other ills.

Two hundred metres away, on the other side of the road, lies the deserted Bara ödekyrka (Bara church). Probably dating from the 13th century, it was already in decay by the 16th century. Today, its atmospheric remains are the perfect setting for calm reflection in a beautiful environment.

Getting to Bara backe: Drive east from Visby on road 147 towards Slite. About half way, turn right at Burs towards Källunge kyrka. About 2 km past the church, turn left towards Bara, and at Bara turn right towards Hörsne; Bara backe is about 400 m down the road on the right, and the abandoned church is on the opposite side of the road.

BLÅHÄLL (N 57° 18.893, E 018° 09.675)

Rocks assigned to the upper part of the Halla Formation are quite different to the Bara oolite. They are best seen along the southwest coast of Gotland from Blåhäll to Djupvik, just to the north of the outstanding Ekstakusten nature reserve. The beach can be accessed by parking on the road on the top of the low cliffs at Sandhamn and climbing down one of the sets of wooden steps. You will immediately be struck by the view out to the two islands Lilla and Stora Karlsö, which are well-known bird sanctuaries, and accessible during guided tours in the summer months. The beach is littered with small, rounded, ice-transported granite boulders.

The low cliffs here are composed of what used to be called the Mulde Beds, and now referred to as the Mulde Brick-clay Member of the Halla Formation. They consist of green-grey marls interbedded with thin layers of limestone that are thicker at the top of the 2.5 m high section. The soft marls erode easily, and the more resistant fossils often weather out completely. The best place to find fossils here is thus to look carefully through the gravel on the beach, which, when you "get your eye in" will yield quite a large number of small but well-preserved fossils. Brachiopods such as *Resserrella*, *Leptaena* and *Atrypa* are common, together with small stromatoporoids and various rugose and tabulate corals. Small enrolled trilobites of the genus *Calymene* are also not uncommon, and some very attractive specimens can be found. However, the most famous site for these rolled up arthropods, the nearby Mulde Brick-clay pits, is unfortunately no longer accessible.

Some of the bedding planes of the marls show distinctive branching patterns on their surfaces – these are trace fossils made by worms of various sorts that burrowed into the marls when they were still soft just after they were deposited. Graptolites of the genus *Gothograptus* can also sometimes be found in these beds. They appear as small, parallel-sided dark streaks on the bedding planes, which with a hand lens can be seen to have a fine reticulate pattern. Overall, the rocks at Blåhäll (and nearby Djupvik just to the south) reflect an environment rather similar to that shown by the Visby formations, but are considerably younger, showing how the environment shifted backwards and forwards through time.

Blåhäll shore cliff in western Gotland

Getting to Blåhäll: From Visby, drive south to Fröjel, then after about 2 km turn right to Sandhamn. Follow the road to the coast, then turn left and follow the road for another 800 m until it climbs the hill and passes into woods with small holiday houses. Park on the side of the road here and access the beach as described above.

HOLMHÄLLAR (N 56° 55.817, E 018° 17.363)

The Holmhällar rauk (or sea-stack) field is one of the most famous outcrops in the central Baltic region. The rauks themselves, left behind by ancient coastal erosion, are massive structures that form a variety of intriguing shapes, and are covered in striking white and yellow lichens. They are formed from the Sundre Formation, the youngest beds on Gotland. If you examine the surfaces of the rocks, you will see that they are composed of greyish limestones that in places contain dense accumulations of salmon-pink, lamellar stromatoporoids that form reef-like bodies. These low-lying stromatoporoids must have grown in very high energy conditions, with a low profile so that they were not damaged during storms. These reefs are thus considered to be among the shallowest and highest energy of all the reef types on Gotland. The stromatoporoids are not the only fossils found in these beds: it is also possible to find large, brilliant-white crinoids that can often be seen in cross section, and large corals of various types. By walking around the outcrops, you will see that the units with stromatoporoids are spaced by intervals with rubbly grey limestone and crinoids, reflecting how the conditions slowly changed through time.

Researchers have shown by carefully mapping out the extent of the stromatoporoids that they grew in large horse-shoe shaped or circular structures that can be compared to similar modern day features found in places like the Maldives called faros.

Please note that this famous outcrop is a protected nature reserve and that any type of hammering or collecting is strictly forbidden.

Getting to Holmhällar: Holmhällar lies close to the southern tip of Gotland about 90 km southeast of Visby, on the east coast. From Visby, drive to Burgsvik and turn left, then right again and follow the road right down to park at the Holmhällar pensionat. The outcrop is a short walk along the coast from here.

Rauks at Holmhällar, southern Gotland

KUPPEN (N 57° 25.292, E 018° 55.727)

Another famous stromatoporoid reef locality on Gotland is at Kuppen, close to the idyllic fishing village of Herrvik. The reefs form banks in the upper Silurian Hemse Formation, slightly older than those at Holmhällar. As you walk towards the locality from the parking place, you will see how parts of the cliff has slumped away, revealing excellent cross sections through the stromatoporoid reefs, which are also well exposed at the point and in the huge boulders that have toppled into the sea here. Just like at Holmhällar, the stromatoporoids are a distinctive pink colour, which makes them stand out clearly from the grey-green limestones and marls they are embedded in. Even more clearly than at Holmhällar, the banks of stromatoporoids are clearly separated by intervals of limestones with detritus composed mostly of crinoids with some tabulate corals. Note the different shape of the stromatoporoids here. Whilst those at Holmhällar are very flattened and lamellar in shape, the Kuppen examples are much more domed, suggesting that they grow in lower energy, slightly deeper water. If you look carefully at the stromatoporoids, you will see that many of them have been toppled over, presumably by storms at the time they were living.

Careful examination of the rocks here has shown that they were repeatedly elevated above sea level, where they were eroded, before being submerged once more, the entire outcrop giving a remarkable insight into how the environment was evolving at the time. Please note once again that this is a protected and important locality, and that no collecting or damage of any kind should be done.

Getting to Kuppen: At the picturesque fishing village of Herrviken on the east coast of Gotland, take the gravel road that leads up behind the village and keep right, following the sign to Sysne until you reach the coast, and park by the tourist information sign.

Close-up of a stromatoporoid in a cliff wall

The lower part of Kuppen cliff (eastern Gotland) consists of a massive stromatoporoid bed

BILLUDDEN (N 60° 38.613, E 017° 28.727)

Although sedimentary outcrops are rare on the Swedish mainland of the central Baltic region, they can be found just off the coast of Gävle on the island of Limön, and as scattered blocks on the north coast of Uppland in the nature reserve called Billudden. Billudden is a long spit of land that lies sub-parallel to the north Uppland coast, and is a well-known nature (and naturist) reserve. It represents the most northerly land extent of the esker (i.e. glacial ridge) that Uppsala is built on. Its long, curving and banked beach is littered with small blocks of red granite and coarse red sand. However, it is also possible to find various small blocks of sedimentary material. These include green, red or grey, often weathered, blocks of Ordovician limestone, within which fossils such as orthocones and trace fossils can be seen. As well as these blocks, various Cambrian lithologies can also be found; small fragments of black Alum Shale, and various types of sandstone. The most common of these are grey-brown, and are an immature (i.e. rather heterogeneous) silty-sandstone. Some of these blocks contain small Lower Cambrian fossils such as inarticulate brachiopods and small tubes. Please note that this is a nature reserve, so look but do not break or collect rocks!

Getting to Billudden: From Uppsala, drive north along the E4 towards Gävle. Just after Mehedeby, turn right on road 291. At Älvkarleby, turn left on road 76 towards Skutskär, and then right towards Rullsand and Billudden. At Billudden, park in the small car park and walk a few hundred metres through the forest along the path, cutting through along any path to the left to access the beach. The best blocks are found by walking further along towards the end of the spit.

Boulders of sedimentary rocks at Billudden, right boulder is a Cambrian sandstone, left boulder is an Ordovician limestone with trilobite fragments

LIMÖN (N 60° 43.054, E 017° 21.777)

Limön, meaning "limestone island", is a small island about 2 km and 1.5 km across just off the coast at Gävle. It was long used as a base for seasonal fishing from at least the eighteenth century, in the next century, fisherman permanently settled there, although the island is now no longer permanently inhabited. However, there are some 150 summer houses scattered around the island. The combination of its sheltered position and calcareous soil gives Limön a rich flora, with many plants rarely seen in Gästrikland, the province it belongs to. These include viper's bugloss, wood cow wheat, bloody crane's bill and hoary whitlow grass. A particularly prominent feature of the plants of Limön are the sea-buckthorn bushes that grow plentifully around the coast. In the autumn they are covered with bright orange berries, a rich source of vitamin C. In addition there is a varied population of birds along the coast, and terns, gulls and various duck species such as tufted duck, eider, velvet scoter and red-breasted merganser can all be seen. Today, Limön is a popular summer destination, and boasts two lighthouses, a café and a memorial to the many soldiers who drowned (and are buried) there in 1808 when the Fru Margaretha foundered off the island on its way to fight in the Swedish-Russian war in Finland.

Although much of the island consists of crystalline rocks, it also contains some large blocks of Cambrian-Ordovician sedimentary rocks. These rocks are substantial enough to look as if they are actually in place, but in fact they appear to have been pushed into their present position by glacial movement, as boreholes show that they rest on much younger glacial deposits. These rocks were quarried for limestone from at least the 16th century up until the end of the 19th. They are best seen at the northeast of the island, where about 10 m or so of a section through lower Ordovician red limestones are exposed along the beach. These rocks

Ordovician limestone on the northeastern coast of Limön

Disarticulated trilobites in Ordovician limestone (top) and ripple marks in Cambrian sandstone (bottom) on Limön

are quite fossiliferous, and it is easy to see trilobites such as *Megistaspis* and *Asaphus*, cephalopods and brachiopods within them. Blocks of coarse Cambrian sandstones also litter the beach. Watch out for adders here!

Getting to Limön: A 40 minute ferry ride from Södra Skeppsbron in Gävle takes you to Limön during the summer months. To reach the outcrop, walk from the harbour past the lighthouses to the northeastern end of the island, where there is a sheltered picnic spot. Note the raised beaches of red limestone fragments you cross to reach the shore, caused by the land rising in this area after the last ice age.

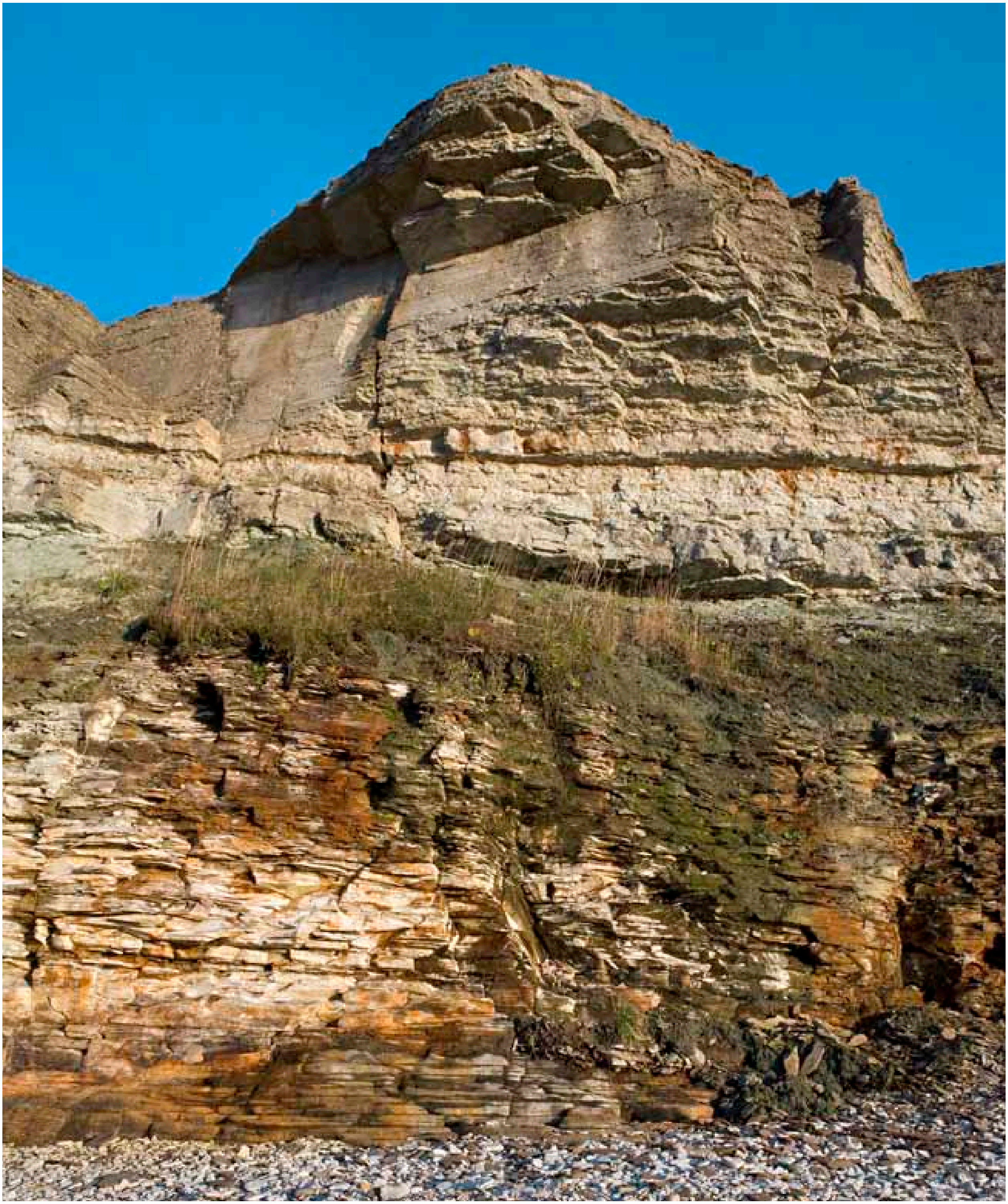
PAKRI PENINSULA (N 59° 22.648, E 024° 02.189)

The coast of the Pakri peninsula consists of a nearly continuous, more than 12 km long and up to 24 m high escarpment of Cambrian and Ordovician rocks that is part of the well-known, nearly 1200 km long Baltic-Ladoga Klint.

The lower part of the section exposes light grey Cambrian sandstones (Tiskre Formation) in its northernmost part, overlain by approximately 3.5 m of brownish-grey Cambrian to Ordovician sandstones (Kallavere Fm), 4.5 m of dark brown Ordovician argillites (Türisalu Fm or the so-called Dictyonema shale), a thin (about 0.5 m) poorly exposed grey-coloured clay unit (Varangu Fm) and about 4 m of bright dark green glauconitic sandstones and siltstones (Leetse Fm) overlain by carbonate rocks high in the upper part of escarpment. Glauconitic sandstones and carbonate rocks are far too high to access in the northern sections. Sandstone and argillite beds are very poor in macrofossils, although the phosphatic (linguliformean) brachiopod *Ungula ingrica* may be present in the lenses of the basal conglomerate of the Kallavere Fm. This section is dangerous throughout the year: occasional collapses may bring single blocks or even several tens to hundreds of cubic metres of rock down to the coast where it is then slowly eroded by the sea. There is always some fresh material available.

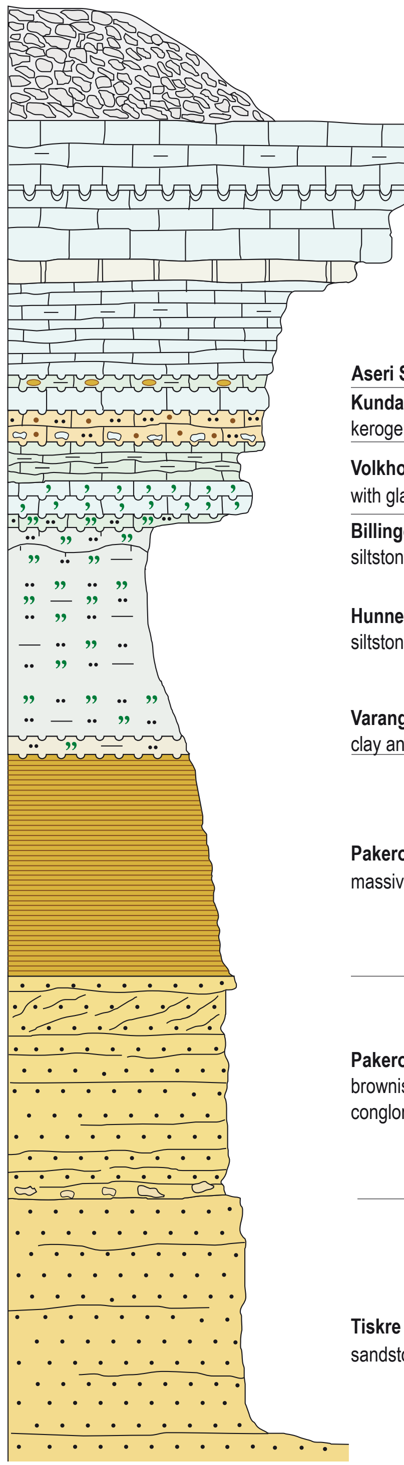
The upper units are much more easily accessible immediately north of Paldiski where the escarpment is much lower and exposes only the Lower to Middle Ordovician rocks. After travelling north of Paldiski along the main road, walk left a few hundred metres

Next page: this part of the Pakri cliff section exposes the sequence from the weathered Dictyonema shale (at foreground) to hard Middle Ordovician limestones, forming a protruding ledge on top



Pakri cliff (composite section)

SYSTEM	SERIES	STAGE	FORMATION	Thickness in meters
ORDOVICIAN	MIDDLE ORDOVICIAN	UHAKU	Väo	4.4+
		LASNA-MÄE		
		ASERI	Aseri	0.2
		KUNDA	Pakri	1.0
		VOLKHOV	Toila	1.3
	LOWER ORDOVICIAN	BILLINGEN	Leetse	4.0
		HUNNEBERG		
		VARANGU	Varangu	0.5
		PAKERORT	Türisalu	4.5
CAMBRIAN	U. CAMBRIAN		Kallavere	3.7
	LOWER CAMBRIAN		Tiskre	4.0+



Uhaku Stage: medium-bedded limestone with numerous discontinuity surfaces

Lasnamäe Stage: brownish-grey dolomitic medium- to thin-bedded limestone

Aseri Stage: clayey limestone with Fe-ooids

Kunda Stage: sandy limestone with kukersite kerogene and limy sandstone

Volkhov Stage: light grey limestone with glauconite and marly intercalations

Billingen Stage: greenish-grey glauconitic siltstone and sandstone

Hunneberg Stage: greenish-grey glauconitic siltstone and sandstone with intercalations of clay

Varangu Stage: greenish to yellowish-grey clay and silty sandstone with glauconite

Pakerort Stage, Türisalu Formation: massive dark brown kerogenous argillite

Pakerort Stage, Kallavere Formation: brownish-grey sandstone with spectacular conglomerate at the lower boundary

Tiskre Formation: light grey silty sandstone with intercalations of clay of the town border. As you approach the coast, head north for a few hundred metres to reach the best exposure.

The bedrock section begins with the green glauconitic sand- and siltstones of the Leetse Fm. This unit is overlain by the Toila Formation, a glauconitiferous limestone about 2 m thick. Glauconite can be observed as dark green grains of sub-millimetre size or as a fine dispersed accessory that makes the carbonate rocks greenish-grey. The rock is rich in bioclastic material. The commonest macrofossils here are the pygidia of the large trilobite *Megistaspis*, which can be observed in cross section of the beds, but are also abundant on bedding planes of the loose blocks that are very common in this locality. The glauconitiferous limestone is overlain by a very hard sandy limestone unit (Pakri Fm) of about 1 m thickness that contains nautiloid cephalopods, mostly observable in cross section. This unit may also contain thin subvertical limy sandstone injections, formed as the result of an earthquake or a possible impact event. The sandy limestone unit is overlain by a brownish-grey dolomitic limestone (Väo Fm), with a very thin (about 0.2 m) interbed of oolitic limestone (Kandle Fm) at its base.

Similar sections can also be found in the easternmost part of the Pakri cliff near the former Leetse Manor, and on the northern coast of the islands of Suur-Pakri and Väike-Pakri. There is no regular traffic between the Pakri islands and the mainland.

Paldiski has long been considered as an important port, first used by the Swedish fleet in the 17th century and later by the Russian fleet, as the water depth is considerable and the sea mostly ice-free in winter. In 19th century it developed as a commercial port. Various military fortifications were constructed in the area during the last centuries. The Pakri peninsula together with Paldiski town was completely militarized and made inaccessible for civilians during 1962–1994. Remains of the military infrastructure of different ages can be recognized in many places at or near the escarpment.

Getting to Pakri peninsula: Drive north through the town of Paldiski. To reach the limestone units, turn left just a few hundred metres from the town border. For the lower part of the section, you may just walk north from the previous location.

RISTNA CAPE (N 59° 16.420, E 023° 43.908)

The lower part of the Upper Ordovician is exposed in several parts of the small peninsula known as the Ristna cape. Its western part exposes bedrock surfaces, whereas the eastern side, the western coast of the Ristna Bay, is shaped as a low cliff, with a maximum height of 2 metres. The total thickness of the strata exposed in the continuous escarpment is about 3.5 metres, with the youngest part of the section exposed in the southernmost part of the exposure.

The section exposes light grey to bluish-grey or yellowish-grey, pure to slightly argillaceous micritic limestones that represent the younger part of the Kahula Formation and look rather monotonous from a distance. This is the less argillaceous part of the Kahula Formation. In the northern part of the escarpment, a volcanic interlayer, the so-called K-bentonite, can be observed in an erosional niche in the lower part of the section. It can be easily distinguished by its yellowish colour, and is about 5 centimetres. The limestone beds right above and below the bentonite bear a clear signature of silicification, and this may have affected the fossils in these strata. It is one of the volcanic interbeds that belongs to the so-called Grimstorp series of K-bentonite beds. It is also the youngest exposed K-bentonite in the Ordovician of Estonia: younger beds are observed only in core sections.

The vertical section does not look very promising with respect to fossils but there are extensive bedding planes exposed at the water level, just next to the section with K-bentonite, and further to the south, where the sea floor may locally look like a stepped plateau. The most common fossils on these bedding planes are *Diplotrypa petropolitana*, *Sowerbyella (Sowerbyella) trivia*, *Ristnacrinus* sp. and *Mastopora concava*, but this list is far from being complete, as this is one of the most fossiliferous coastal sections in mainland Estonia.

Throughout the section hemispherical colonies of the bryozoan *Diplotrypa petropolitana* may occur on bedding planes. This is a common fossil in the lower part of the Upper Ordovician. Complete fossils can be recognized by their nodule-like shape on the bedding planes, mostly with a diameter of 2 – 3 cm. In cross section the massive colonies of this species display a radial structure, the lower surface displaying a concentric pattern. The same species also occurs quite often in loose debris, being mainly preserved because of its massive structure making it stronger than the argillaceous rock matrix.

Accumulations of valves and shells of *Sowerbyella (Sowerbyella) trivia* occur more often in the southern part of the section. This is a small brachiopod, with the hinge line mostly 12 – 16 mm long, of trapezoid outline, finely costate, and it can be rather abundant on some bedding planes.

The same bedding planes, but also the vertical surfaces in the northern part of the section, may also expose echinoderm fossil remains. These are circular

Ristna cliff in northwestern Estonia

massive columnals of the crinoid *Ristnacrinus marinus* that may occur as accumulations in some layers. The same species can also occasionally be rather abundant in the northern part of the section, where it can occur as accumulations of columnals or even as stem fragments of variable length. The species was named after the Ristna section, and the type specimen was also found here. It is very well-preserved crinoid specimen, with the nearly complete theca and a long coiled stem attached to it. Specimens of such quality belong to the II category of protection (see page 48).

The bedding planes in the northernmost part of the section may also reveal *Mastopora concava*. Fossils of *M. concava* are nearly circular but not very regular, with a diameter of 3 – 4 cm, with a finely but distinctly reticulated surface. Although the colours of pigments are not really preserved in fossil material it is suggested that *M. concava* represents a type of Ordovician green algae.

The accessibility to particular fossils may change, because of local changes that are difficult to forecast. This is because of relocation of loose sediment and redistribution of accumulations of recent algae that may temporarily cover a very considerable part of the bedding planes.

This section was somewhat neglected 1960 – 1990, partly because of access restrictions in the so-called border zone of the former Soviet Union. Today it is an important geological site visited by numerous geological excursions.

About 10 kilometres southwest of the section (road distance about 21 km) are the Nõva sandy beaches that offer a fine opportunity for refreshment on a sunny summer day.

Well-preserved crinoid *Ristnacrinus marinus*, horizontal field of view – 8 cm. Courtesy of GMUT

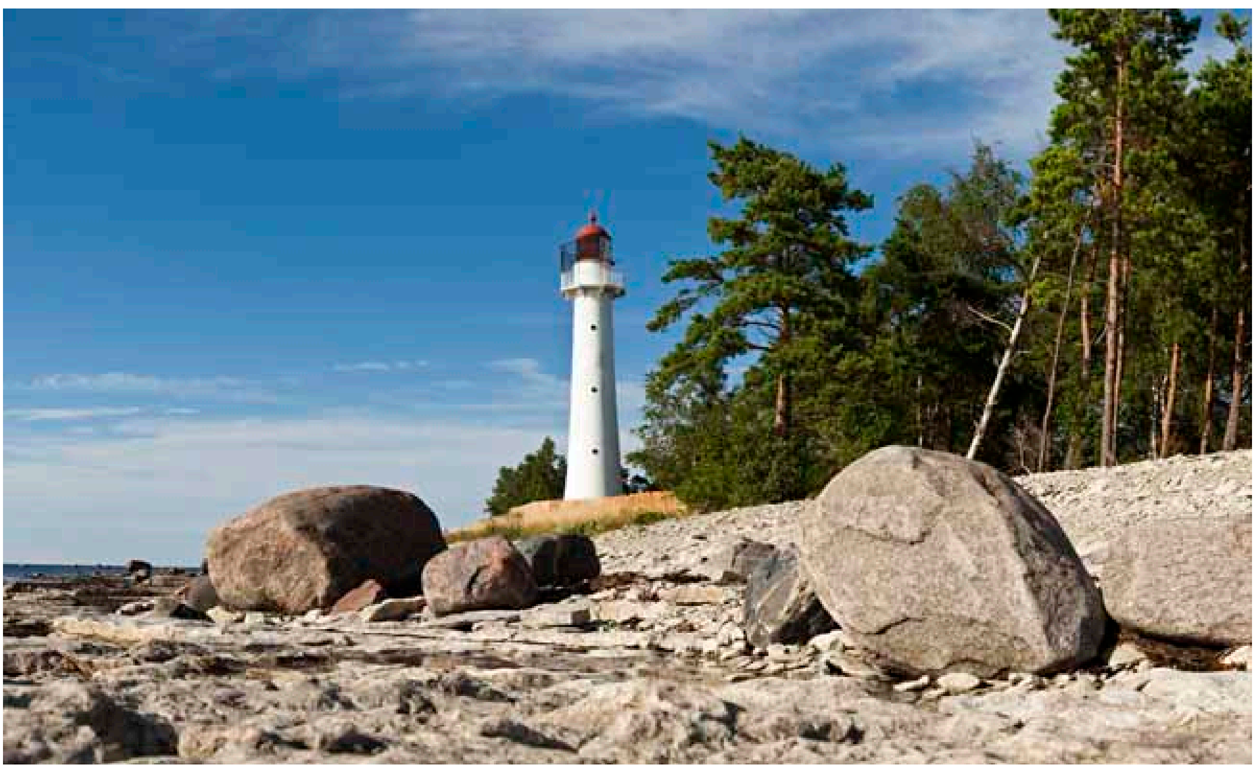
Getting to Ristna cape: Ristna cape is located in northeastern mainland of Estonia, 75 km west of Tallinn (not to be confused with the westernmost point of Hiiumaa that bears the same name). Drive 1.4 km north of Keibu village, turn left and after 170 m left again, 400 m to the northwest, take a left turn again and keep northwest on the small roads, driving about 1 km. The best exposure is located right of the road, a few hundred metres north along the coast.

SAXBY COASTAL EXPOSURE, VORMSI ISLAND (59° 01.614, E 023° 07.023)

The island of Vormsi is the fourth largest island of Estonia, located west of Noarootsi peninsula, not far from Haapsalu. The island is relatively young and flat, having risen from the Baltic Sea only about 4000 years ago.

Exposure on the Saxby coast is very much dependent on relative water level in the Baltic Sea. During lowstands, extensive and almost continuous bedding planes may occur above the water level; during highstands the section may easily be discontinuous and even mostly flooded. Low water levels mostly occur in spring and may sometimes last until midsummer. During July and August, the water level is mostly higher. The situation is very much dependent on weather conditions (persistent high pressure usually results in lower water levels).

The section is a good example of the upper part of the Upper Ordovician in Estonia. The section is nearly 2 kilometres; most of the section is located south of Saxby lighthouse. The section exposes grey to bluish-grey slightly argillaceous micritic limestones of



Coastal exposure of Upper Ordovician limestones next to Saxby lighthouse on Vormsi.

the Kõrgessaare Formation, overlain by almost pure brownish-grey micritic limestones of the Moe Formation, which is a little more thick-bedded than the underlying unit; it crops out near the southern end of exposure (comprising perhaps about 300 m of the section). The position of the boundary is not so easy to find, as this particular part of the outcrop is quite often buried under loose sediment. Finding subtle differences in the rock succession is also complicated because of weathering of the rock surface all over the section.

The bedding planes and loose debris are a rich source of fossils, even though no dense accumulations of fossils are usually present. Brachiopods, trilobites, tabulate and rugose corals, gastropods, stromatoporoids, and algae can all be found.

Some of the fossils found here can be remarkably large. One of those is *Equirostra gigas*, a large pentamerid brachiopod species, with a diameter of up to eight centimetres. Complete specimens are not so common, however. Shells of this brachiopod may also rarely contain a rarity – yellowish crystals of the mineral fluorite. This is the only known location of this mineral in the sedimentary bedrock of Estonia.

Coral fossils, rather large colonies on the bedding planes and their fragments in debris, are quite common in the section. A very characteristic species is *Sarcinula organum*, with its widely spaced corallite openings of about 3 mm diameter, covering large (often about ten centimetres in diameter) colonial fragments with distinct horizontally laminated complex tissue visible in cross section of a colony. Several species of favositid tabulates, with densely packed corallites looking like miniature honeycombs, are also common but the species are almost impossible to distinguish with certainty without making thin sections. *Catenipora tapaensis* is a common halysitid tabulate, distinguished according to its fine (about a millimetre-size) corallites joined end to end in wandering palisades, with large irregular matrix-filled cavities between them. Rugose corals are also common; it is easy to find *Streptelasma (Kenophyllum) siluricum*, one of the solitary species characterized by a very deep calyx.

The complete list of taxa found in this section is very long. Relatively large (over ten centimetres) ortho-

Pulli cliff in northeastern Saaremaa attracts geology students all-year-around.

cone nautiloids can be found on the bedding planes and isolated siphons from broken shells occasionally are found in the debris. Rather common is the gastropod *Subulites subula*, an elongated narrow cone-shaped gastropod, which often occurs in the debris. The list of brachiopods, apart from *Equirostra gigas* mentioned above, is remarkable, including species of *Vellamo*, *Triplesia*, *Platystrophia*, etc. The rocks are also rich in microfauna. Looking westward, when the weather is good, some small islands (Harilaid, Kadakalaid) are visible, on the background of the northeastern coast of Hiiumaa.

The island of Vormsi (Ormsö in Swedish) was an island of mainly Swedish population throughout the centuries, like several other smaller Estonian islands in the northwestern coastal areas of Estonia. In 1944, many people left the island for Sweden. This part of the history is explained in the Vormsi Farm Museum (Pearsgården) located in Sviby village, one km from the harbour.

Getting to Saxby: To get to the island, visitors must take a 10 km ferry trip from Rohuküla harbour to Sviby harbour. The Saxby coastal exposure, the type section of the Vormsi Regional Stage, is located on the western coast of the island, near Saxby lighthouse, at a distance of 15 km from Sviby harbour, the only landing place on the island. Drive 6 km northwest of Hullo, keep west in Kersleti (formerly Kärrslätt) village and take a right turn in Saxby village, 1.5 km west-south-west of the previous turning point. After 1.7 km of driving, you will reach the coast and the middle part of the coastal exposure.

PULLI CLIFF, SAAREMAA (N 58° 36.969, E 022° 56.947)

This section exposes the contact between the Jaani and Jaagarahu formations. Like all sections in the eastern part of Saaremaa and on Muhu, the carbonate rocks are dolomitized and not very exciting from the palaeontological point of view. The structure itself is still worthy of examination, as the rocks were originally (and still are) of very different composition. The lower part of the section exposes argillaceous dolomites and domerites, overlain by massive dolomite units. The lower unit of bedded bluish-grey cavernous dolomite is of irregular thickness and its contact with the underlying strata is irregular and wavy. The upper part of the section comprises a lenticular body

of grey cavernous dolomite without regular bedding and uneven fracture surface, with small irregular inclusions of more dark-coloured dolomite or related rock types. Although the upper unit is dolomitized, its general shape and lack of distinct internal bedding suggest it to be a former reef or bioherm – an elevation on the sea bottom formed as an organic build-up. Such lenticular bodies are often related to irregular bedding features. The younger, overlying beds often dip towards the flanks of a bioherm (being deposited on the slopes of an elevation), and the underlying (older) beds are often deformed, dipping toward the centre of the biohermal unit.

Reef limestones are common on Saaremaa; in several cases they are well preserved and non-dolomitized, but the Pulli cliff is probably one of the best sites to observe the related irregularities in bedding.

Getting to Pulli cliff: Pulli cliff in the northeastern part of Saaremaa is located about eleven kilometres northwest of Orissaare settlement. Take the northwestern direction from Orissaare, until you reach the crossing with the road heading south to Taaliku. The coastal outcrop is located north of the crossing.

UNDVA CLIFF, SAAREMAA (N 58° 31.007, E 021° 55.148)

Undva cliff is located 54 kilometres northwest of Kuressaare, being the northernmost point of the Tagamõisa peninsula in the northwestern part of Saaremaa. The bedrock exposure extends nearly 100 metres west and about 400 m east of the northern point of the peninsula. Further to the east, the section is buried under loose sediments. The westernmost part of the exposure is formed as a series of bedding planes, and further to the east it comprises a cliff, locally up to 3 metres high. Access to the section is slightly dependent on the water level. Higher water level may reach the lowermost part of the cliff, making it impossible to pass under it. Usually there is still enough room to walk and look at the section.

The rocks exposed in the escarpment comprise marlstones with interbeds and nodules of micritic limestone in the lower part, overlain by massive grainstones, occasionally with small bioherms in the upper part of the escarpment. Both units are assigned to the Jaani Formation. Although the grainstones represent an entirely biogenic rock, largely composed of fragmented echinoderm material (mostly columnals of

Undva cliff in northwestern Saaremaa

crinoids), its primary component (i.e. fossil material) is quite fine grained and can therefore not be identified. Still, small complete echinoderm calices have occasionally been found in the Undva section.

The uppermost unit in the section is rather fossiliferous, with brachiopod and bryozoan fossils. This unit does not crop out in the eastern part of the section, being better exposed right to the west of the northern point of the peninsula. The bioherms, mostly confined to the same part of the section, also contain abundant bryozoans, rugose corals, brachiopods, echinoderm columnals, and, rarely, trilobites also. The westernmost part of the sections comprises the grainstones only, as the marlstones do not crop out there. The best exposure of the argillaceous strata occurs about 200 m east of the northern point of the peninsula. Ripple marks can be observed on the top of escarpment at almost the same location.

The locality contains a coral fauna of high variability, with several favositid species ("honeycomb corals") which, however, are very difficult to distinguish in the field. *Halysites senior* with wandering corallite palisades and irregular matrix-filled cavities between them represents another common morphotype. Solitary rugose corals are rather abundant. Stromatoporoids can also be found in the section. The bryozoan bioherms contain abundant *Ceramopora* sp. and *Lioclema* sp. Identifying this material with certainty requires detailed investigation of microstructure, as is the case for tabulate corals and stromatoporoids as well.

The brachiopod fauna is so rich and diverse that it would deserve a special chapter. A common species is *Rhynchotreta gracilis* – a small (up to 13 mm long) biconvex brachiopod of a narrow fanlike shape and 10–13 rounded costae. Representatives of *Stegerhynchus estonicus* are larger and relatively wider (but still less than 2 cm), biconvex, with a very characteristic sub-pentagonal outline and 12–17 sharp-edged costae. Collecting in the loose debris can be very productive as well-preserved smaller fossils are often "prepared off the matrix" in a process of natural weathering. The loose material which can be collected may originate from different parts of the section.

Walking south of the westernmost end of the section, a discontinuous series of bedding planes can be traced further in conditions of low water level. The situation may change because of mobile loose sediment and algal masses. A specific feature of this part of the section is occasional silicification of rocks that can be observed as occasional small (centimetre-scale) spots of bright white very fine-grained silicate mass in the rocks.

The Tagamõisa peninsula is an area of rather low population density. It offers several sightseeing opportunities. It is an important botanical site: the Tagamõisa wooded meadow is the largest of its kind in Saaremaa and the third largest in Estonia. Oak is a very common tree species here and various species of orchids occur (all protected by law). The botanical richness of the area may be well characterized by the fact that the number of species which can be identified on a square metre may reach more than fifty here. The Tagamõisa peninsula is also a reasonably good site for bird watching, as the surrounding sea is an important stop-over site and wintering grounds for many water birds.

Getting to Undva cliff: Drive north of Tagamõisa village and follow the main road to the northwest, until reaching the northernmost point of the peninsula, about 8 km from Tagamõisa. Park to the right of the road and walk to the coast and you will reach the western part of the escarpment.

KATRI COASTAL EXPOSURE, SAAREMAA (N 58° 14.128, E 021° 58.336)

The coastal exposure at Katri is technically a cliff, like many other coastal sections on Saaremaa. However, because of the very limited height of the escarpment, it would be more correct to term it simply a "coastal exposure". In former years, the section was up to 1 metre high, but the situation changed dramatically a few years ago. A large storm covered the main part of the escarpment with sand and debris, leaving only a few tens of centimetres of its uppermost part exposed.

Most of the exposed section comprises a biostrome which is exposed over a distance of several hundreds of metres. The richly fossiliferous limestone is mostly pure, but in some places it may also be argillaceous or contain occasional interbeds and lenses of light brownish-grey micritic limestone. All these rocks are considered as the Paadla Formation (Lower Ludlow) and likely comprise the upper part of the formation. The rocks were largely similar throughout the one metre interval that was formerly exposed. The rocks contain a very abundant shallow marine fauna. The material includes various groups of corals, brachiopods and algae. Cephalopods may be common in the southern part of the section.

Among corals, a common species is *Favosites pseudoforbesi pseudoforbesi*, a "honeycomb-coral", with the diameter of individual corallites up to 2 mm in a moderately large corallum. The locality is also rich in rugose corals and in stromatoporoids, both impossible to identify with certainty in the field. It is known that the diversity of stromatoporoids is very high, comprising not less than nine species.

Among well identifiable taxa, a rather common one is *Didymothyris didyma*, a small (up to 2 centimetres long) heart-shaped smooth biconvex brachiopod. The bivalve species *Ilionia prisca* is not very common but may be remarkably large; its nearly circular, flat, weakly biconvex valves may reach about 5 centimetres in diameter. Trilobites are also found here.

Between the Katri section and Karala village, the small island Naistekivimaa can be seen, situated a few hundred metres from the coast. This is a strictly protected bird site.

Katri coastal exposure in western Saaremaa

Loose debris from the Katri coastal exposure is full of corals

Getting to Katri: Katri is located about 4 kilometres southeast of Karala village, however, the driving distance is about five kilometres and the road quality may be variable and depend on weather conditions. Drive 300 m west of Karala bus stop, turn right (to the south), continue 2.4 km, until you see the sea and keep to the left (east) parallel to the coast. After about 4 km, the road will almost reach the coast. Make a stop, walk to the coastline and keep left.

KAUGATUMA CLIFF, SAAREMAA (N 58° 07.222, E 022° 11.432)

Kaugatuma cliff is situated in the northern part of the Sõrve peninsula, on its western coast, southwest of Kuressaare town. The driving distance from Kuressaare is about 26 kilometres and from Salme village about 7 kilometres.

Kaugatuma cliff is located at a distance of about a hundred metres from the sea. It reaches over 2 metres in total height, but the exposed section is less than two metres. The very basal part comprises greenish-grey argillaceous micritic limestones, with bioclasts of various fossil groups common. The main part of the section is composed of yellowish-grey coarse grainstone. This material is thought to have been deposited in a fore-reef high-energy sedimentary environment. The bioclastic material is of crinoidal origin; the size of individual grains varies from bed to bed. The beds also comprise the type section of the Kaugatuma Formation and the Kaugatuma Regional Stage.

The lower, poorly exposed unit is rich in different fossils. Large colonies of *Syringopora blanda*, a tabulate coral species with nearly-parallel but loosely spaced corallites with a diameter of nearly 2 millimetres, have been reported from this unit.

The most exciting area to look at is the outcrop right at the water level, about 300 m north of the cliff, which is accessible in conditions of lower water level only. This is an irregular limestone surface which displays locally very thick (up to two centimetres in diameter) and up to ten centimetres long crinoidal stem fragments. This material could be identified as *Crotalocrinites* sp. but most likely belongs to *Crotalo-*

Kaugatuma cliff in western Saaremaa

crinites rugosus, a species which is particular characteristic of the Ludlow and lower Pridoli in Estonia. The columnals are relatively thin-walled, compared to their diameter, and the density of large fragments can locally be fairly high. Occurrence of the larger fragments of crinoids is not very common, as a crinoidal skeleton usually falls apart rather quickly after the death of the animal. There is no clearly dominant orientation in the material, suggesting that the burial of the stem fragments mostly took place close to the life and disaggregation position, without substantial later transportation by current or wave action. An even rarer feature is the occasional occurrence of stem fragments with their lower ends preserved. The lower end of a stem gradually thickens (reaching a diameter of about 3 centimetres) and displays a number of large scars of broken lateral root-like branches of the stem.

The accessibility of this part of the Kaugatuma locality is very much dependent on various factors: higher water level may make the site inaccessible and movements of sediment and algal masses may change the conditions of observation quite unexpectedly, over a short time.

The area is a landscape reserve and as such the cliff is protected by law and should not be hammered on.

Getting to Kaugatuma cliff: Drive 1.6 km south of Salme village and, after passing Läätsa village, turn right. Kaugatuma cliff is located at a distance of 4 km from the crossing, just right of the road.

LÕO CLIFF, SAAREMAA (N 58° 05.416, E 022° 10.161)

The section comprises a low cliff, about 250 m in length. The total thickness of the exposed strata is about 1.5 metres. Coarse bioclastic grainstones, similar to those in the Kaugatuma cliff section, are intercalated with marlstones that are richly fossiliferous. Ripple marks are occasionally preserved on the bedding planes. Similarly to the Kaugatuma cliff section, the rocks in this locality are attributed to the Kaugatuma Formation, comprising the upper part of it.

The marlstone unit contains abundant *Syringopora blanda* colonies (see the description of Kaugatuma cliff and the photo) but are also rich in other invertebrate fossils. A stromatoporoid species of a rather specific morphology called *Parallelostroma tuberculatum* makes its first appearance in these strata. A variety of brachiopods are common. Relatively large (about 2 mm) beyrichiacean ostracods valves, with a distinct lobation, can occasionally be observed on the bedding planes when using a hand lens. Ring-like large isolated columnals of the crinoid *Crotalocrinites* sp., as well as small brachiopods and other fossils can easily be collected from the debris.

A characteristic feature of this section is the frequent occurrence of *Ptilodictya lanceolata*. It represents a brown elongated, leaf-like, parallel-edged very finely sculptured fossil of notably brown colour, assigned to erect (cryptostomate) bryozoans. This fossil is characteristic of the area, being found in several sections of southern Saaremaa.

Walking northwards, it is possible to see large ripple marks. They are observable in a very shallow water or right at the sea level (when the sea level is low). The ripple marks have roughly east-west orientation and the crests of individual ripples are spaced at half a metre, or locally even more.

Lõo cliff is a part of the landscape reserve, together with Kaugatuma cliff. Another important object in the vicinity is the Lõo alvar. This alvar is the largest in Estonia and belongs to the list of important botanical sites, being renowned for its specific and diverse calcophilous plant community.

Getting to Lõo cliff: Lõo cliff is situated about 2 kilometres south of Kaugatuma cliff. Drive 1.8 km south of Kaugatuma cliff and turn right. The section is located in walking distance.

Lõo cliff in western Saaremaa

OHESAARE CLIFF, SAAREMAA (N 57° 59.953, E 022° 01.103)

Ohesaare cliff exposes the youngest Silurian strata to crop out on Saaremaa. The cliff represents a 600 metres long escarpment that reaches up to 4 metres in height. The thickness of the upper Pridoli in this section reaches about 3.5 metres and most of it is well exposed in the northern part of the cliff. The upper part of the succession can be followed far to the south. Still, the youngest part of the succession is accessible only in the middle part of the long north-south oriented interval of the cliff, and can be recognized according to specific lithologies. Walking south of the northern end of the cliff, a small dislocation can be observed at a distance of about 200 m.

The section comprises an intercalation of thin-bedded limestones and marls. The limestones are very rich in coarse bioclastic material, being classified as packstones or grainstones. Occasionally, some cross-bedding can be observed in lens-like intercalations of skeletal grainstones in the middle part of the succession. The marls are richly argillaceous and may in places grade into calcareous clay interlayers. The succession is topped by a finely cross-bedded calcareous siltstone, underlain by a thick layer of silty skeletal grainstone bearing ripple marks at its top. Although the section looks rather monotonous at first glance, and the thicknesses of the individual layers tend to demonstrate a remarkable lateral variation, occasional distinct marker beds can still be recognized in nearly all parts of the section.

The section is richly fossiliferous. The most common macrofossils are probably brachiopods. Bryozoans are relatively abundant and several bivalve species present. A peculiarity of the sections is a lack of stromatoporoids.

Geology students looking for fossils in the marly limestones of the Ohesaare cliff, western Saaremaa

The middle part of the Ohesaare section is characterized by the frequent occurrence of tentaculitids. Tentaculitids are small ribbed conical tube-like shells of problematic affinities. They may sometimes concentrate on the bedding planes, and loose slabs covered with tentaculitids are commonly found in northern part of the outcrop. In *Tentaculites scalaris* the narrow tube-like shell is about 2 centimetres long and almost completely and regularly ornamented with distinct rings. The shell in another species, *Lowchidium inaequale*, is usually slightly smaller and bears a different sculpture: the ornamental rings are equally spaced in the narrower end of the shell whereas in the wider part (in the other half of the shell) the rings are grouped in pairs.

A marly interbed in the upper part of the section contains abundant shells of the bivalve species *Grammysia obliqua*. It is an elongated, narrow biconvex and slightly asymmetrical shell, up to 5 cm in length. Occasionally fine striation on its surface may be preserved. The shells are buried in living position in this bed.

Corals are largely confined to the middle part of the section only, along with the tentaculitids, and the fauna is not of high diversity. The section is also well-known as a locality of small fragments of various Silurian fish.

The southern, main part of the section was very well exposed in 1980s and 1990s, with almost no loose debris at its base. The situation changed rapidly about ten years ago.

Ohesaare cliff is located close to the southernmost point of Saaremaa, the tip of Sõrve (Sõrve Säär), a narrow strip of land with a lighthouse. This place is a "bottleneck" of bird migration and therefore a famous bird watching site.

Getting to Ohesaare cliff: Ohesaare cliff is located in the southwestern part of Sõrve peninsula, about 20 km southwest of Kaugatuma cliff and nearly 2.5 km southwest of Jämaja church. Drive southward from Jämaja village keeping right (destination Sääre) at the next crossing. 0.5 km south of the crossing, turn right towards the sea, stop about 0.5 km after the turn and just walk to the coast line and further to the south.

APPENDIX: COLLECTIONS OF FOSSILS IN THE CENTRAL BALTIC REGION

The principal collections of material from the region are found in the following institutions:

Estonian Museum of Natural History (EMNH): Collections and limited exhibition (www.loodusmuuseum.dyndns.org).

Evolutionsmuseet Uppsala: Uppsala University's Museum of Evolution (www.evolutionsmuseet.uu.se).

Geological Museum, University of Tartu (GMUT): Large collections and exhibition (www.natmuseum.ut.ee/399535).

Gotlands Museum, Visby: Particularly good collections of Gotland material (www.gotlandsmuseum.se).

Institute of Geology at Tallinna University of Technology (IGTUT): Large collections but small exhibition (www.geokogud.info/git/collections.php).

Loona Fossil House, Visiting Centre of the Vilsandi National Park, the Loona Manor, Kihelkonna, Saaremaa: A special exhibition of local rocks and fossils.

Naturhistoriska Riksmuseet, Stockholm (NRM): The Swedish Museum of Natural History in Stockholm has large collections from Gotland in particular (www.nrm.se).

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Limön
Billudden
GÄVLE
TURKU
HELSINKI
Åland
MARIEHAMN
UPPSALA
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SWEDEN
TALLINN
Pakri cape
Ristna cape
STOCKHOLM
Saxby
ESTONIA
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