THE BALTIC SEA

GEOLOGY AND GEOTOURISM HIGHLIGHTS

NGO GEOGUIDE BALTOSCANDIA

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INTRODUCTION

The Baltic Sea area is astonishingly naturally diverse, a diversity that is closely tied to the marine environment. It is also a politically important region, with the Baltic Sea being bordered by Denmark, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland, and Germany. It is estimated that more than 85 million people live in close proximity to the Baltic Sea and the area is of great importance, not only in terms of environment and economy, but also in terms of energy and transport. Regionally the area offers a variety of possible nature experiences that might include a visit to pristine beaches, water sports and fishing or visiting one of the many islands, each one with its own character. Other recreational activities might include canoeing, horse riding or golfing on excellent golf courses. A relatively mild climate and stunning nature in combination with well-developed tourist facilities, especially related to health and well-being, gives the area an around-the-year appeal. This book intends to give you in-depth knowledge of the geological history of the Baltic Sea and how it came into being, as well as directing you to some of the thematic geotourism-associated activities in the area.

THE BALTIC SEA

The Baltic Sea is about 1600 km long and on average 190 km wide, with a surface area about 386,000 km^2. A bird's eye view of the sea suggests the outline of a dragon that divides and protects continental Europe from the Scandinavian Lion to the north-west. However, if so, it has been singularly unsuccessful, as the Scandinavian Vikings were well-known for their skills in navigating the Baltic and attacking its bordering countries.

Tied to the North Sea via an intricate system of straits (Danish, Kattegat and Skagerrak), the Baltic Sea can be considered as an arm of the Atlantic that intrudes deeply into the continental hinterland. The Baltic Sea, like all seas, fills a depression into the continental crust below present sea level. What the forces that created this depression were, and when it was formed, is still a matter of discussion and controversy. Indeed, considering the complex shape, geological structure, morphology and bathymetry of the Baltic depression, we can be sure that there are no unambiguous or simple answers to these questions. Its formation was the outcome of combined geological processes – erosional, tectonic and glacio-isostatic – which have shaped the earth's crust in this region of the world throughout geological history. This long and complex history means that the depression itself is considerably older than the present day Baltic Sea that currently fills it – a body of water that has only existed since the retreat of the last continental ice sheet some 14,000 years ago.

The present-day Baltic Sea is relatively shallow. One of its shallowest areas is around the Danish archipelago where narrow straits prevent ships with a draft over 12.5 m from entering the rest of the Baltic Sea. The mean depths in the other parts of the sea – the Baltic Proper 65 m, the Bothnian Sea 68 m, the Bothnian Bay 43 m, the Gulf of Finland 37 m, and the Gulf of Riga 26 m – are rather modest, too. However, large depth variations occur as the result of the highly rugged sea floor, expressed in various forms of deeps, valleys and trenches that alternate with plateaus, shallow banks and escarpments. The deepest point measured in the Landsort Deep (459 m), slightly north of Gotland, is considerably deeper than the greatest


Norwegian Sea
White Sea
Bothnian Bay
Lake Ladoga
Bothnian Sea
Gulf of Finland
Åland Sea
northern Baltic Proper
Gulf of Riga
Skagerrak
Gotland Deep
Kattegat
North Sea
MAIN SUBDIVISIONS OF THE BALTIC SEA
Arkona Basin
Bornholm Basin
Gdansk Basin

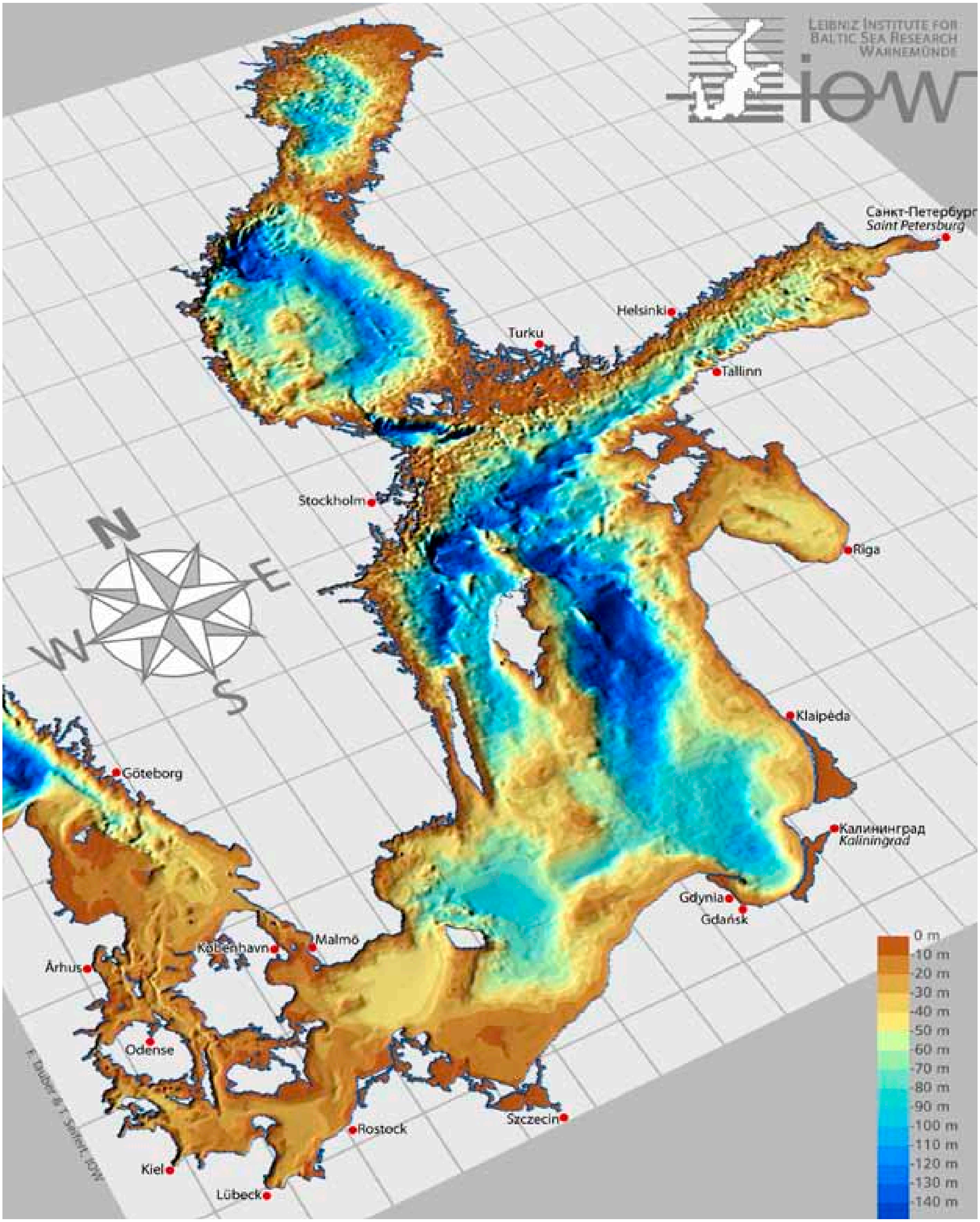
depths in the other parts of the Baltic – Bothnian Bay (147 m), Bothnian Sea (294 m), Åland Sea (301 m), Gotland Deep (245 m), Gulf of Finland (123 m), and Gulf of Riga (67 m). The depth in the southern part of the Baltic remains largely less than 50 m; though it exceeds 100 m in the Gdansk depression (116 m) and in the Bornholm Basin (110 m).

The Baltic Sea is one of the largest expanses of brackish water in the world. The dilution of normal seawater is caused mainly by three factors: the water exchange with the North Sea and, thus, the oceans of the world through the Danish Straits is very limited; its catchment area of about 1.6 million km^2 is drained by more than 250 water courses (including large rivers like the Vistula, Oder, Neman, Daugava and Neva) that contribute about 660 km^3 of fresh water to the approximately 21,000 km^3 total volume of the Baltic Sea every year; the amount of precipitation exceeds evaporation. Thus, despite being connected to the North Sea, where salinity is normally about 3.5%, the surface water salinity of the Baltic Sea decreases steadily from the inflow area of salty seawater around the Danish Straits (0.8 – 1.0%) across the central Baltic Sea (0.6 – 0.8%) towards the east and north. As a result, the most distal areas are practically fresh water, with a salinity of around 0.1%. Indeed, areas such as the head of the Gulf of Bothnia and the Neva River mouth in the Gulf of Finland are inhabited by many fresh-water species including fish such as perch, pike and bream. However, the saltiest water occurs in the deepest areas of the Baltic Sea, where a distinct halocline (rapid change in salinity), at about 50 m and 70 m depth in the northern and southern Baltic, respectively, isolates the deep less brackish waters from the overlying fresher waters. In these places the salinity in the bottom layer can reach as much as 1.5 – 2.0%.

Isolation from the Atlantic Ocean also shelters the Baltic Sea from noticeable tidal currents and sea level fluctuations, though in response to the regional wind situation, changes in water level can occasionally amount to several metres. The long term sea level changes of the Baltic Sea, on the contrary, have been considerable; mainly because of crustal rebound following the diminishing weight of the melting continental ice sheet and water level changes in the world ocean. Today, the southernmost coastline of the Baltic Sea is slightly transgressive (showing relative sea level rise) and its northern part, with the fastest glacio-isostatic rebound, strongly regressive (showing relative sea level drop). The fluctuating sea level in combination with different type of rocks adjacent to the sea, are the main factors responsible for the great variety of coastal types around the Baltic Sea.

The coastal area in the northern Baltic region, which is still gently rising, is largely cut into solid ancient bedrock. This combination of rock type and uplift makes the coastline here highly fretted (meaning that it is deeply cut into by erosion). Often the coast rises remarkably high above sea level, forming outstanding scarps in places. Such intricate and greatly dissected shorelines are particularly typical in the area where Precambrian crystalline rocks crop out, which includes most of the Swedish and Finnish coasts in the region. In these areas, the Baltic Sea is often fringed by groups of low rocky islands, known as skerry guards, each composed of either exposed crystalline rocks, or of such rocks partly covered by glacial drift and marine sediments. These are most numerous in the Saltsjön (Salt Bay) between Stockholm and the open waters of the Gulf of Bothnia and off the southwest coast of Finland.

The most remarkable shoreline-forming escarpments, however, occur in the Cambrian-Ordovician rocks



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Malmö
Århus
Odense
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-70 m
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-90 m
-100 m
-110 m
-120 m
-130 m
-140 m

in northern Estonia and in the Silurian rocks in the north-western parts of the islands of Saaremaa and Gotland. Known respectively as the Baltic and the Silurian klints, these escarpments continue below sea water, and indeed are even better developed there. Thus, they are older than the waters that now cover them. As magnificent natural monuments, the klints provide a glimpse of the pre-glacial erosional processes responsible for the formation of the Baltic Sea basin.

In the gently subsiding southern part of the Baltic Sea, the coastline, which is slowly being submerged, is mainly the outcome of Pleistocene glaciations and of subsequent changes in sea level. It is formed largely out of glacial drift and/or marine sediments. Thus, in contrast to the dramatic coastline of the northern Baltic Sea region, it is relatively smooth, low-lying and featureless. Shallow bays divided by low promontories, shallow straight-sided fjords and shallow inlets are the main features that dissect the coastline. In places, bars capped with moving sand dunes or extensive sandy spits cut off distinctive lagoons from the open Baltic Sea (for example the Szczecinski and Curonian lagoons). Outcrops of solid bedrock are rare, though in a few islands (Møn and Rügen), the remarkably irregular coastlines include chalk cliffs that can reach about 120 m in height (Rügen).

As already mentioned, there are numerous islets and islands, particularly in the shallow near shore areas of the northern Baltic Sea. Many of them, exposed by land uplift, simply represent rugged relief features of the pre-glacial and/or glacial erosional surface. Coastal processes of the transgressing sea in the southern part of the Baltic Sea have created still more.

The Baltic Sea depression – 3D model. Printed with the permission of authors F. Tauber and T. Seifert (Leibniz Institute for Baltic Sea research, Warnemünde)

Widespread groups with numerous smaller and larger islands and distinguished as separate archipelagos occur in many parts of the Baltic Sea (for example the Danish, Stockholm, Åland, Turku and West-Estonian archipelagos). Some of the largest islands of the Baltic Sea are also part of similar groups; Saaremaa and Hiiumaa of the West-Estonian archipelago and Funen (Fyn) and Zealand (Sjælland) of the Danish archipelago are good examples. An exception is in the central Baltic, where a few solitary larger islands occur further off the Swedish coast (for example Gotland and Öland). They, together with Stora and Lilla Karlsö and Fårö offshore Gotland, can be broadly considered to be limestone remnants left behind after a combination of the pre-glacial and glacial erosion together with long lasting tectonic and/or glacio-isostatic processes. The rectangular Danish island Bornholm offshore southern Sweden, however, has a distinct tectonic origin. Placed on a major deep crustal fault zone (the so-called "Tornquist Line"), the core of Bornholm is a detached block of granite. The high cliffs of Bornholm were shaped by faulting and shearing of the rock strata that overly the granite, rather than directly by uplift or erosion.

THE BALTIC BELOW THE SEA

The rocks underlying the Baltic Sea and its surrounding areas tell a long and eventful story about the evolution of the earth's crust in the north-western part of Eastern Europe. This story, more than three billion years long, is about the origin and growth of a particular unit of continental crust called the Fennoscandian continental block, and how it has been later reshaped by alternating periods of erosion and accumulation of sediments. The Fennoscandian block was amalgamated with two similar crustal units called

Regional tectonic setting showing the main tectonic structures in the Baltic Sea area

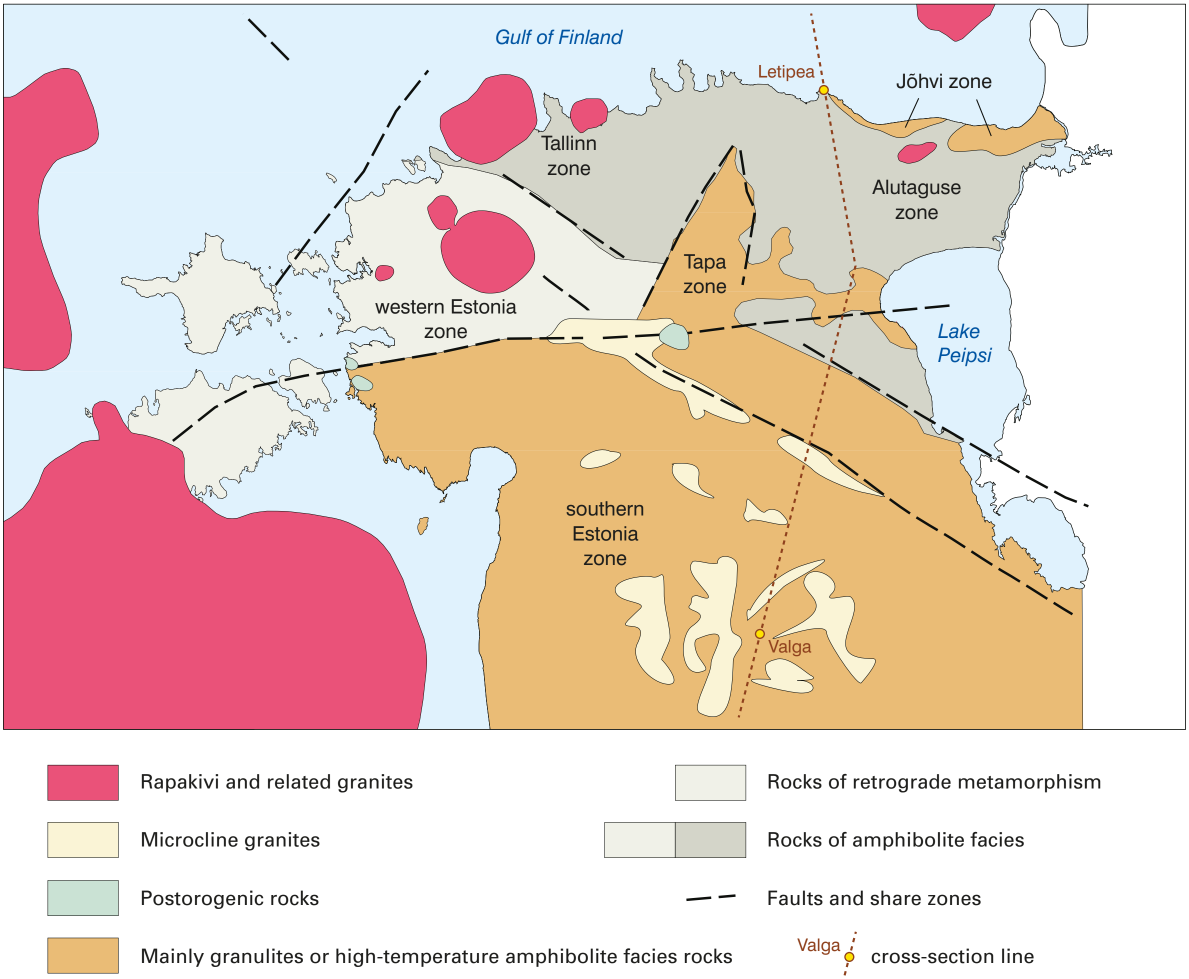
of strongly deformed metamorphic and igneous rocks, which have been formed through orogenic (mountain forming) cycles under high pressures and temperatures. The upper floor of a craton is mostly made up of sedimentary rocks. These rocks largely reflect the time periods when already consolidated basement, during constant drifting and interactions with other lithosphere plates, became inundated by oceans and continental seas. There is always a considerable time gap between the formation of these lithologically and tectonically highly contrasting layers or floors. In areas with uplifted crystalline basement, called the shields, the upper floor of the craton was either never built or, more likely, has been removed by later erosion. Cratons with Precambrian basement (that means rocks older than 543 million years) are considered to be old – they are normally built around cores of the earliest continental blocks of Archaean age (over 2.5 billion years old), called protocontinents, that contain among the oldest known rocks on the earth.

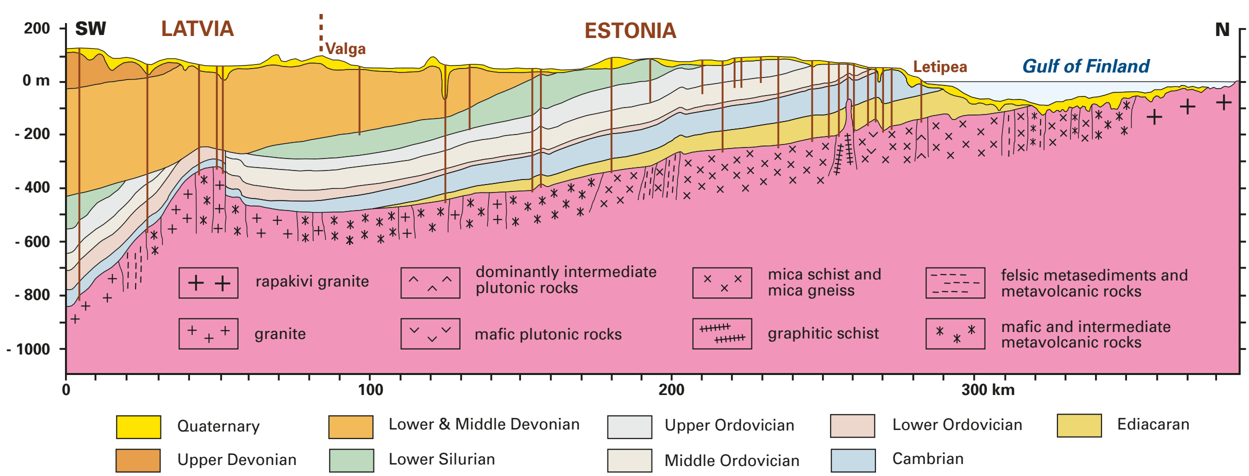
the Sarmatian and the Volga-Uralian blocks, some 2.0–1.7 billion years ago, and all three together are considered to form the so-called "East European Craton" (EEC). Throughout a long period, from deep in the Precambrian into the late Palaeozoic, this large continental block has had its own independent history, and is considered to have constituted a separate continent called Baltica.

A craton is a consolidated, and thus rigid, and tectonically stable part of a continent that can be considered to be built like a two storey building. Its basement is always crystalline, in other words composed

The East European Craton (EEC) is a very old craton, as its Precambrian basement is built around several Archaean protocontinents. Around the Baltic Sea, the Precambrian basement is exposed within the Fennoscandian (Baltic) Shield that surrounds most of its northern and western coastlines. The south-eastern

Right page, top: the major units of Estonian basement rocks. Right page, bottom: a schematic cross-section of the Estonian basement rocks from southern Finland to northern Latvia (modified after Puura & Vaher, 1997)


Gulf of Finland
Letipea
Jõhvi zone
Tallinn zone
Alutaguse zone
Tapa zone
western Estonia zone
Lake Peipsi
southern Estonia zone
Valga
Rapakivi and related granites
Microcline granites
Postorogenic rocks
Mainly granulites or high-temperature amphibolite facies rocks
Rocks of retrograde metamorphism
Rocks of amphibolite facies
Faults and share zones
Valga
cross-section line


200
0 m
- 200
- 400
- 600
- 800
- 1000
SW
LATVIA
Valga
ESTONIA
Letipea
Gulf of Finland
N
rapakivi granite
granite
dominantly intermediate plutonic rocks
mafic plutonic rocks
mica schist and mica gneiss
graphitic schist
felsic metasediments and metavolcanic rocks
mafic and intermediate metavolcanic rocks
0
100
200
300 km
Quaternary
Upper Devonian
Lower & Middle Devonian
Lower Silurian
Upper Ordovician
Middle Ordovician
Lower Ordovician
Cambrian
Ediacaran

and the southern parts of the Baltic Sea, however, are bounded by the East European Platform – by that part of the EEC where the ancient Precambrian rocks are covered by a thick sequence of Phanerozoic sedimentary rocks younger than 543 million years old.

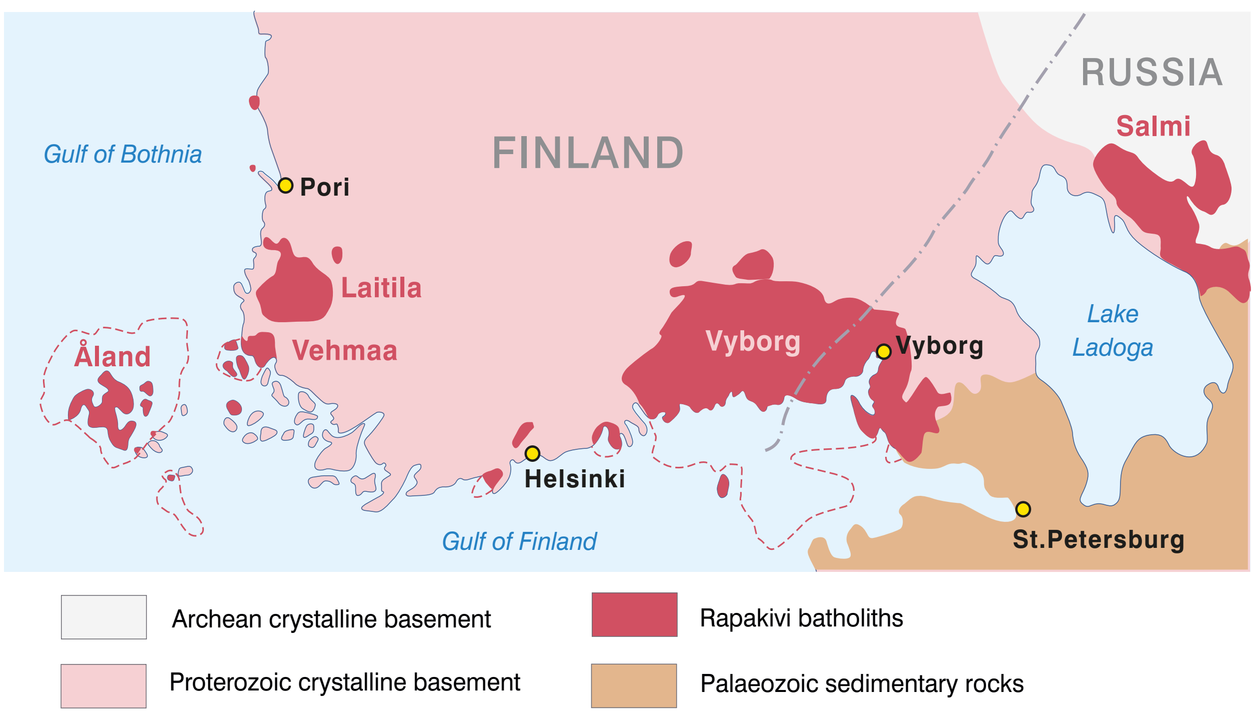
Although much of the Baltic Sea is situated within the boundaries of the EEC, its most south-westerly part extends beyond the south-western border of the EEC that is defined by a trans-European deep crustal boundary, the Tornquist Line. This border, defined by a zone of heavily smashed and faulted rocks welds the EEC together with the much younger West European Craton to the west. The crystalline basement of this craton was consolidated throughout the Phanerozoic orogenic events stretching more than a billion years later than those that formed the EEC.

Major rapakivi intrusions in southern Finland (modified from Lehtinen et al. (eds.) 1998. Suomen kallioperä: 3000 vuosimiljoonaa)

THE CRYSTALLINE BASEMENT

Like a mosaic, the crystalline basement around the Baltic Sea is pieced together from numerous zones and segments of the earth's crust, often delimited by faults, made up of different types of metamorphic and igneous rocks. Each of them tells its own story about the depths, temperatures and pressures of its formation as well as the time and types of geological processes (for example subduction, rifting, collision) that were involved in the long history of successive mountain-building cycles.

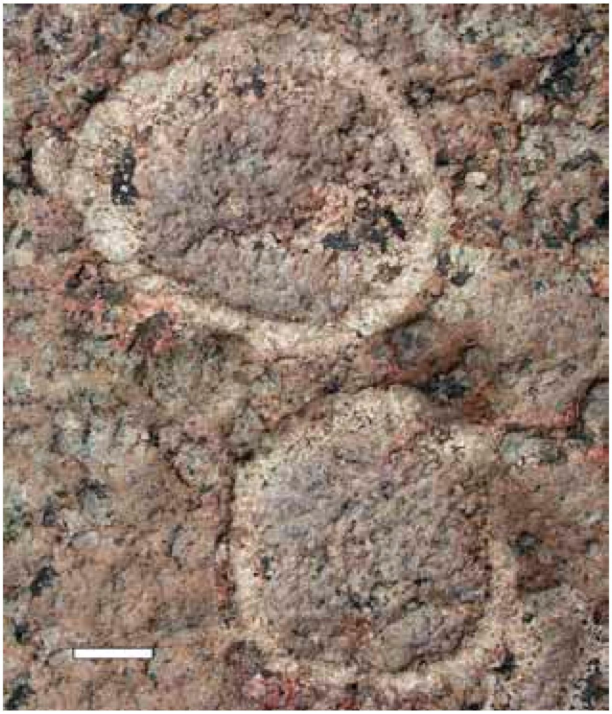
The age of the crystalline rocks around the Baltic Sea reveals three distinctive domains, showing us that the Fennoscandian block grew in an accretionary manner from northeast to southwest. The Archean, so-called Fenno Karelian granite-gneiss-greenstone protocontinent (3.5–2.7 billion years ago) in the far north is the oldest sub-unit of the Fennoscandian block, and is



pounded by the waves of the Baltic Sea only within a very short coastline section in the head of the Gulf of Bothnia. The youngest basement rocks, a mosaic of metamorphosed volcanic arc complexes of the Sveconorwegian orogeny (1.14 – 0.95 billion years ago), adjoin the Baltic coast in its south-westernmost corner around the Kattegat Strait. Within the large area between them, the Baltic Sea rests on the crystalline rocks that were formed during different phases and in different belts of the Svecofennian orogeny (1.95 – 1.75 billion years ago).

The Svecofennian crust, largely a mosaic of successive volcanic arc formations mingled with several smaller continental blocks, reveals an environment typical for active continental margins. The geological scenery at the time it was forming was to a great extent similar to what we can see today in south-eastern Asia (Indonesia, Philippines) – several small plates and volcanic arcs with subduction zones, all fighting for the same space. This led to subsequent collisions of plates and volcanic arcs. As a result, many of the volcanic rocks with the associated sediments that were produced by intense volcanic activity and erosional processes, were subjected to high pressure and temperature. The products of these processes, the large variety of different types of metamorphic rocks (for example gneisses, granulites, amphibolites and migmatites) can be seen along most of the Finnish and Swedish coasts of the Baltic Sea.

Although intrusive rocks are uncommon in this part of the Baltic coast, at least one magmatically active period 1.67 – 1.44 billion years ago with several large granitic rapakivi intrusions, shows its imprint in the Svecofennian rocks. These intrusive bodies tell us about deep crustal processes that triggered partial melting of the upper mantle (the rocks directly below the earth's crust). Rising, hot and swelling magma



Rapakivi in Vyborg batholite is charaterized by large rounded orthoclase crystals mantled with plagioclase rims; scale – 1 cm. Photo: I. Tuuling

melted and pushed up already existing juvenile continental crust, causing its extension and rifting. In general, the scenario was rather like the scenery in the magmatically active east Africa today, where the domed and stretched continental crust starts to collapse and rift valleys are formed along its down-faulted segments.

Most rapakivi massifs are hidden under a thick platform sedimentary cover. However, some of the largest and best known of them, namely the Vyborg and the Åland intrusions, are exposed, and form coastlines in the Baltic Sea, in the Gulf of Finland and Gulf of Bothnia respectively. Like scars of old wounds, many of these ancient rifts, partly filled with lithified and metamorphosed sandy Proterozoic sediments (Riphean-Jotnian quartzites), or even with much younger Palaeozoic rocks, are still clearly preserved in the crystalline basement. Furthermore, having been repeatedly reactivated during a long geological history, these ancient rift structures are also expressed in the present topography; like Lake Ladoga and Lake Onega on the mainland and the Landsort Deep, the Åland Sea, the Bothnian Sea and the Bothnian Bay, below the waters of the Baltic Sea. Thus, looking at the configuration of the Baltic Sea with its two arms, the Gulf of Finland, and the Gulf of Bothnia in particular, to a certain extent trace out ancient, tectonically active rifting zones.

PRECAMBRIAN PENEPLAIN

The huge time gap between the rocks forming the crystalline basement and the overlying platform sedimentary cover around the Baltic Sea is not very informative about the conditions and processes during the intervening period. Still, the upper portion of the crystalline basement under the platform sedimentary cover reveals a long period of intense weathering and erosion. Thus, by the time of the formation of the platform sedimentary cover, a vast area with levelled crystalline rocks, called the Precambrian peneplain, can be seen to have extended across the area of the present Baltic Sea. Some segments of this ancient plain, exhumed in recent geological history, are still discernable in southern Finland and below the Baltic Sea.

Palaeomagnetic data confirm that before the platform cover started to form, Baltica was located in high southerly latitudes, around the present position of Antarctica. Considering the current position of the EEC, its last 650 million years have been the story of a constantly northwards drifting continent, which through interactions with other lithosphere plates and eustatic sea-level changes became here and there occasionally flooded by the world ocean. The spans and extensions of the alternating erosional and sediment accumulation periods in different part of the craton were foremost dependent on the regional structural setting.

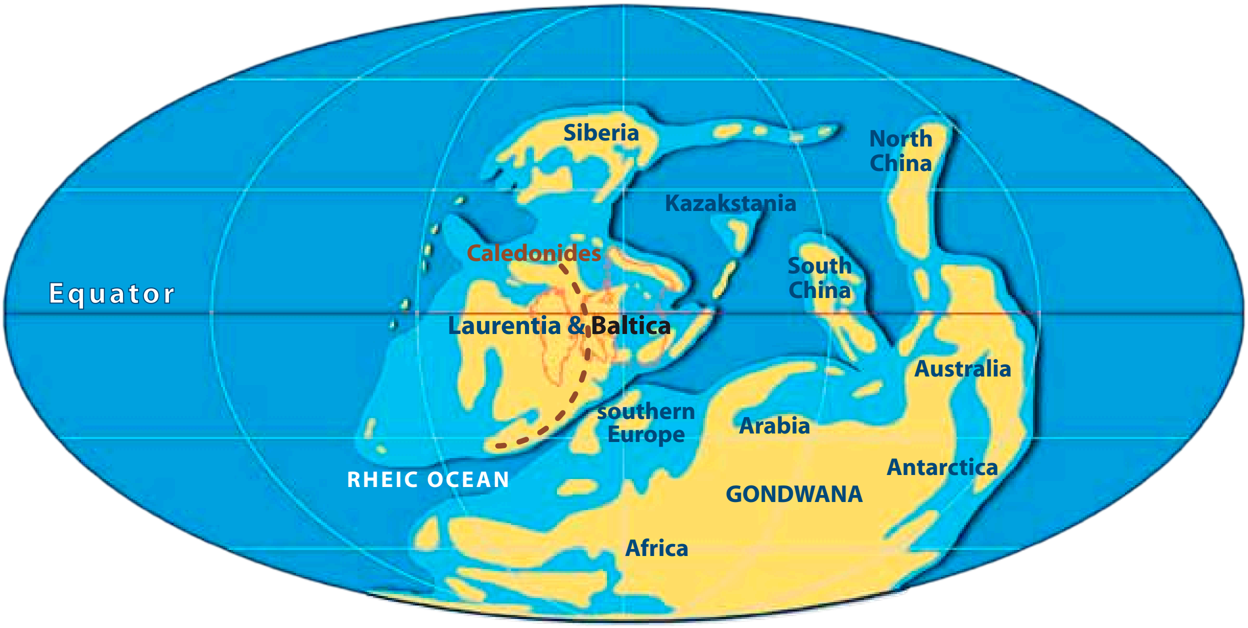
PLATFORM SEDIMENTARY COVER

LATEST PRECAMBRIAN AND CAMBRIAN ROCKS

The first sedimentary basins formed in the Baltic Sea area during the latest Precambrian from the north-east, when Ediacaran (latest Precambrian) sediments were laid down around the Gulf of Finland. At present, Ediacaran clay- and sandstones are exposed on the coast only at the very head of this gulf. In the Cambrian, the seas continued sporadically invading from the east and south and wide areas of the present Baltic Sea became covered with marine sandy and clayey sediments. Nowadays, the Cambrian clay- and sandstones crop out occasionally at the base of the Baltic Klint along the southern coast of the Gulf of Finland and on the Swedish island of Öland, as well as within several coastal sections around Skåne (Scania) in southern Sweden.

CALEDONIAN OROGENY AND FORMATION OF THE BALTIC SYNECLISE

The later development of the sedimentary cover around the present Baltic Sea was strongly influenced by the progressing Caledonian orogeny, which reached its peak when Baltica collided with Laurentia (the North American continental block) at the transition between the Silurian and Devonian periods. The outcome of this collision, the still imposing if some-



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

what eroded Caledonian mountains, form an eye-catching chain in Norway and in Sweden, as well as in North America (meaning the Appalachians). Other crucial but not so easily discernable results of this event were highly differentiated movements of the crystalline basement. As a result, the regions a little further away from the mountains were deflected downwards and flooded by the ocean, whereas the areas next to the Caledonides became gradually even more uplifted. This led to the formation of two large cratonic structures, which in the Ordovician started to play a major role in the formation of the platform sedimentary cover close to the north-western margin of Baltica. The main area of sediment accumulation, called the Baltic Syneclise, formed around a deep depression with its centre in the present southern Baltic Sea. The rising Caledonides with neighbouring Baltic Shield area became the main source area of the sediments that started to fill up this depression.

THE PALAEOBALTIC BASIN

In the Early Ordovician, most of the western margin of the Baltica became inundated by the waters of the Iapetus Ocean (Pre-Atlantic). A stable and long-lasting sea, known as the Palaeobaltic basin, spread almost all over the present Baltic Sea territory. As Baltica edged closer to the southerly equatorial latitudes, the clayey and sandy marine sediments were gradually replaced by carbonate ones. In the middle of Ordovician, the first solitary reef structures appeared. Reefs became widespread by the end of Ordovician, particularly during the Silurian when Baltica crossed the equator. Nowadays, erosion resistant reefs adorn the landscapes in western Estonia, and in particular on the Swedish island of Gotland.

Although short marine transgressions occasionally occurred in the north, the southerly withdrawal of the sea from the Palaeobaltic basin progressed towards

Gamlahamn rauks on Fårö island, north of Gotland, are erosional remnants of Silurian reefs. Photo: H. Bauert

the end of Ordovician. By the end of the Silurian, the sea had retreated from the present Estonian territories. A great quantity of sediments, derived from the mounting Caledonides and the neighbouring Baltic Shield, filled the Baltic Syneclise with up to 0.4 and 1.5 km thick Ordovician and Silurian sequences, respectively. The Silurian and Ordovician rocks form outcrops that border the present Estonian coast, both on mainland and in the West-Estonian archipelago. No less famous are the Swedish islands of Öland and Gotland, where the Ordovician and Silurian rocks respectively form excellent, coast-fringing escarpments, the klints.

Concurrently with the closing and demise of the Iapetus Ocean, a small breakaway fragment from the southern supercontinent Gondwana, called Avalonia, joined the fused Baltica and Laurentia from the south-southwest. As a result, the Baltic Sea area that throughout the Silurian was situated on the western margin of Baltica became an interior region of a new supercontinent Laurussia (which consisted of Baltica, North America and the Avalonia continents) in the Early Devonian. However, new connections to the world ocean opened along the eastern margin of Laurussia and the battle between the land and sea in the present Baltic Sea region continued. On occasion, the southerly retreating Devonian basin advanced once more, and areas exposed previously to intensive land erosion became for short periods once again inundated and buried under new marine sediments. The most prominent evidence of such an event is the Wesenberg escarpment. This up to 30 m high scarp, buried under Middle Devonian rocks, marks an east-west running Early Devonian river that crossed the present Estonian and Russian border a little to the south of the city of Narva.

Across the present southern Baltic region, the slowly retreating Devonian basin left behind a thick sequence of various shallow marine, lagoonal, deltaic and continental sediments. The major part of them represents variable, poorly sorted and cross-bedded sandstones that are often stained red by oxidized iron minerals – just like the well-known Old Red Sandstones in Great Britain. Similar red coloured Devonian sandstones, based on the erosional material derived from the Caledonides, are widespread all over Laurussia, which therefore is also known as the Old Red Sandstone Continent. Around the Baltic Sea these red sandstones crop out in southern Estonia, and particularly widely in Latvia where they also border most of its present coast.

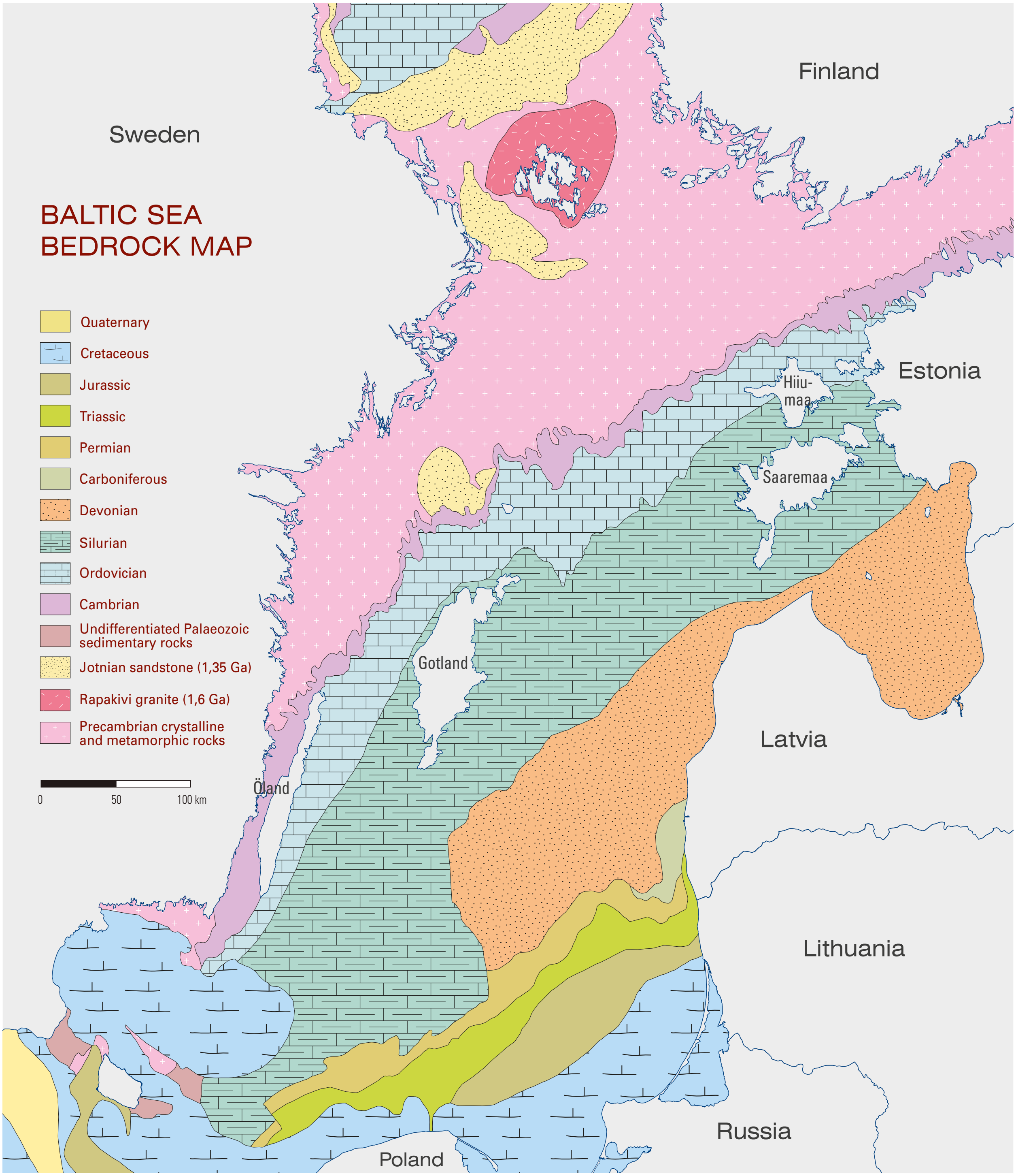
The sequence of the Palaeobaltic basin ends with Lower Carboniferous terrigeneous-carbonate rocks that were only preserved from later erosion in a very restricted area around the Latvian-Lithuanian border. Along an about 10 km long section in southern Latvia, they also border the Baltic coast.

Picturesque Veczemju cliff at Vidzeme coast in northern Latvia formed in the red Burtnieki Formation (Middle Devonian) sandstone. Photo: I. Tuuling

THE VARISCAN OROGENY

Towards the end of the Devonian, during the gradual assembly of the Pangaea supercontinent, the distribution of the seas over the EEC became increasingly dependent on the ongoing collision of Gondwana (and its associated microcontinents) with Laurussia. This complex event of subductions and collisions along the southern border of EEC is known as the Variscan (or Hercynian) Orogeny. The Variscan metamorphic and intrusive complexes comprise the crystalline basement of much of Central and Western Europe.

From north to south across the north-western EEC, the retreating Palaeozoic basin came to its end at the culmination of the Variscan Orogeny during the Carboniferous period. The present Baltic Sea area turned to land, and even in its southernmost extremity, sedimentation was for a short period in the Carboniferous and Permian periods replaced with intensive erosion.



Distribution of rocks of varying ages in the Baltic Sea area (adapted from Ahlberg 1986, Swedish Geological Survey, R&M 47)

THE PLATFORM COVER AROUND THE SOUTHERN BALTIC SEA

Since the latest Palaeozoic (Permian) almost up to the end of the Cenozoic (Pliocene), the EEC has been surrounded to the south by various sedimentary basins, the centres, configurations and extensions of which have been depending on the regional tectonic setting and processes. For most of the time, these basins also inundated to a lesser and greater extent the southern margin of the EEC. Different regions below the present southern Baltic Sea existed as the marginal, shallow-marine portions of these basins. The latest Palaeozoic to early Mesozoic Pangaea supercontinent, its break-up and the subsequent formation of the Tethys Ocean in the second half of the Mesozoic, as well as closing of this ocean during the Alpine Orogeny in Cenozoic – all these periods, with different events, are imprinted into the platform sedimentary cover around the present southern Baltic Sea.

Most of the bedrock adjacent to, and below the southern Baltic Sea consists of claystones, sandstones, siltstones, limestones, dolostones and evaporates of shallow marine, lagoonal, deltaic, fluvial, lacustrine and continental origin. The latest Permian and Triassic rocks crop out only around the Latvian and Lithuanian border, and the Jurassic ones around the city of Klaipeda, in a few places in Poland and in southernmost Sweden. Cretaceous rocks are widely spread along the southern coast of the Baltic Sea where in a few places they form outstanding chalk cliffs (the islands of Rügen and Møn). Cenozoic rocks that occur abundantly along the southern coast of the Baltic Sea are particularly well exposed around the Sambian Peninsula close to the city of Kaliningrad.

Stevns Klint on the east coast of Sjælland island exposes chalky limestones encompassing the Cretaceous-Tertiary boundary. Photo: A. Põldvere

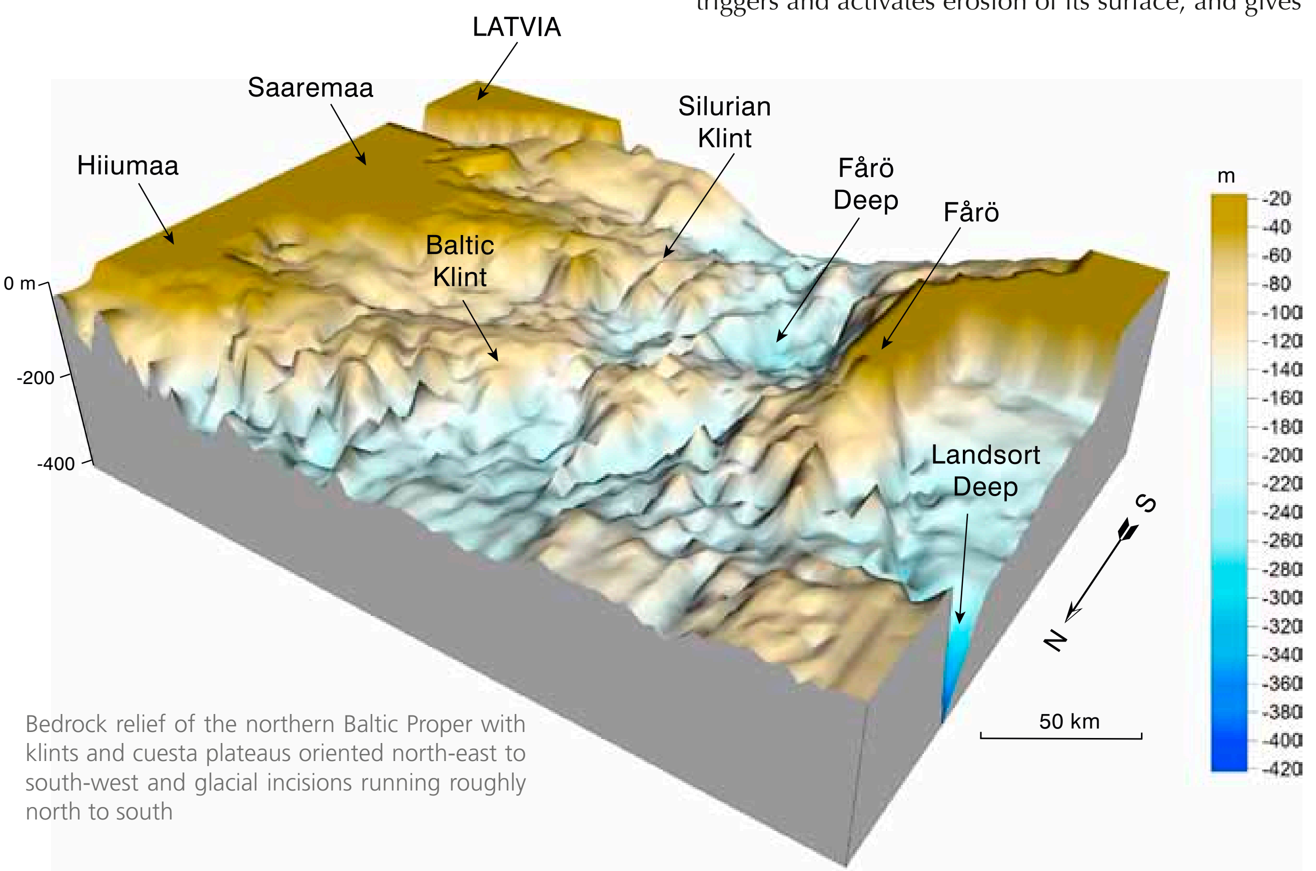
THE PRE-GLACIAL AND GLACIAL EROSION AROUND THE NORTHERN BALTIC PROPER

While the southern part of the Baltic Sea oscillated between marine and non-marine conditions between the latest Palaeozoic to Cenozoic, its northern majority was since the Devonian already shaped by strong and prolonged land erosion. During more than 400 million years of erosion, even high mountains were worn away and any relief largely levelled to a peneplain. Nevertheless, a highly rugged land surface with some remarkable bedrock escarpments catches our eyes around the northern Baltic Sea. Particularly impressive relief, full of different erosional features is hidden under the waters of the Baltic Sea. The north-east to south-west trending cuesta relief, dissected by north to south oriented large glacier valleys, is best expressed only on the seafloor of the northern Baltic Proper.

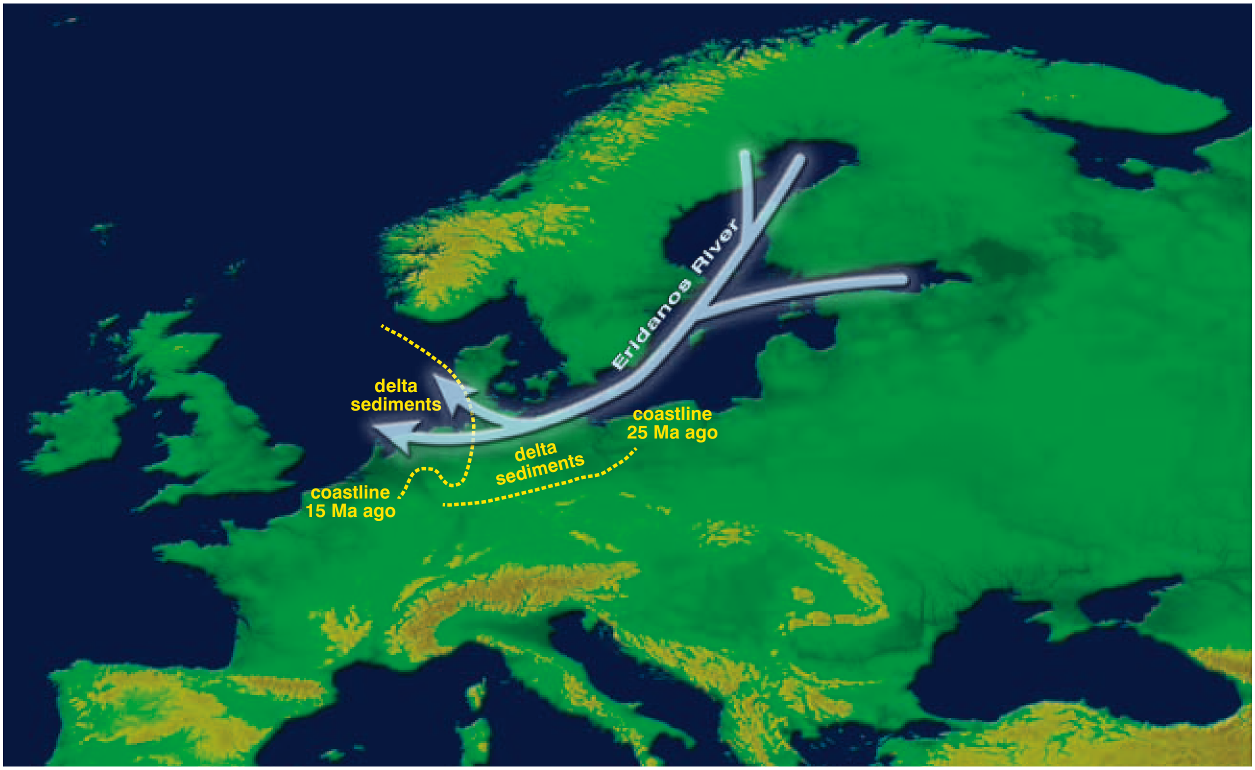
CENOZOIC RIVER SYSTEM

OPENING OF THE NORTHERN ATLANTIC ACTIVATES EROSION

We can only guess how the topography around the northern and central Baltic Sea looked like at the end of Mesozoic and in the Early Cenozoic. Probably it was in the form of a mostly levelled, slightly undulating mainland plateau just above sea level. But refreshing of this old eroded landscape started when this region became once again involved in an active plate tectonics region. By the Cenozoic, the break-up of Pangaea, with the newly-evolving Atlantic Ocean, had finally reached the area surrounded presently by Scandinavia, Greenland and North America. The opening of the northern Atlantic, preceded by continental uplift and rifting, also strongly affected the neighbouring Baltic Shield areas. Uplift of a continent triggers and activates erosion of its surface, and gives



Bedrock relief of the northern Baltic Proper with klints and cuesta plateaus oriented north-east to south-west and glacial incisions running roughly north to south



Proposed flow direction of the over 2500 km long Eridanos River and migration of its delta westwards during the Late Cenozoic

rivers the opportunity to cut deeply into the land surface and gouge canyons. Impressive erosional scenery driven by tectonic uplift can nowadays best be admired from the rim of the Grand Canyon in Arizona.

THE RIVER OF ERIDANOS

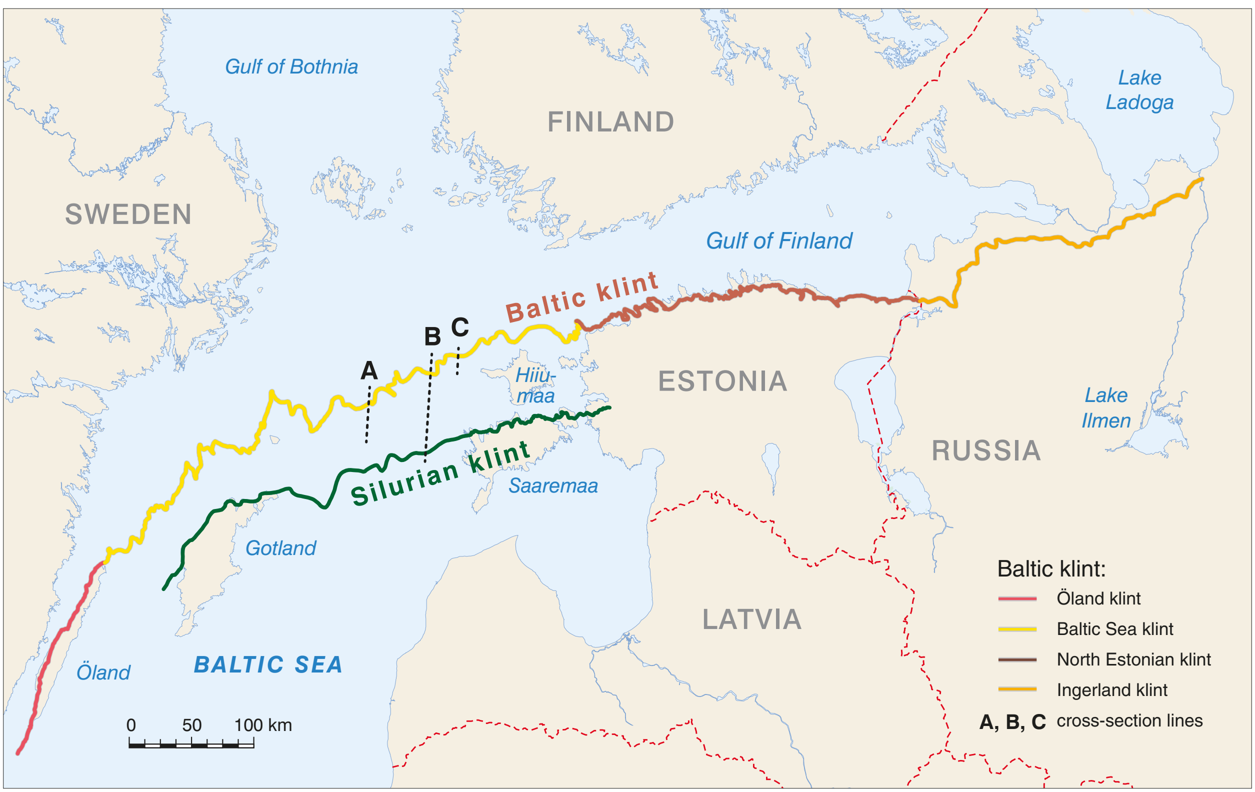
Given the above description of tectonic uplift, where are the canyons in which these rivers ran, and into which seas did they flow? The canyons still exist, but have been reshaped and levelled by the Pleistocene glaciers, filled up and buried under younger sediments, and finally inundated by the waters of the present seas. The solitary pieces of evidence, scattered around and below the Baltic Sea, leave little room for doubt that before the Pleistocene glaciers moved repeatedly forth and back across the north-eastern EEC, there existed an impressive drainage system of rivers with deep (in places canyon-like) valleys.

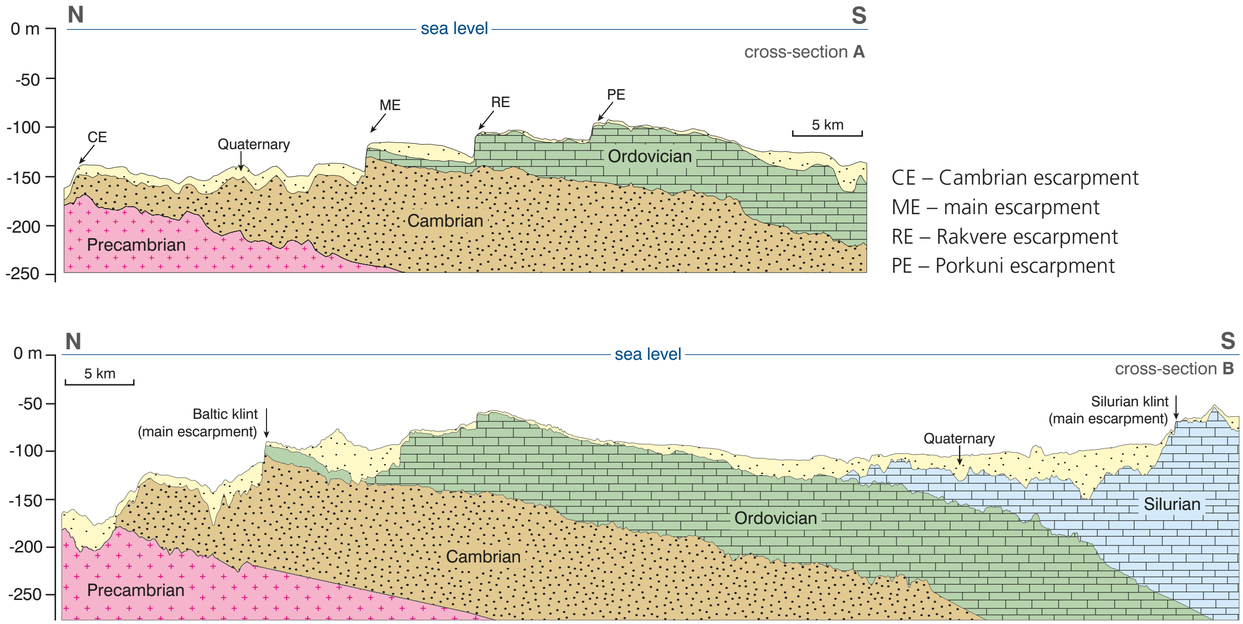
This old set of rivers has been occasionally penetrated by drillings and contoured by geophysical studies around the Baltic Sea. A row of canyon-like buried valleys, cut deeply into the bedrock, is known along the North Estonian coast. Dissecting the Baltic Klint, they run towards the Gulf of Finland. However, if these represent the rivers, then they had to flow into some sea to deposit the material they eroded and transported from the Baltic Shield area. Indeed, the best evidence for this river system is an up to 1.5 km thick complex of fluvio-deltaic sediments found in a Cenozoic basin that bordered the south-western corner of the EEC. The age of these shield-derived sediments is 25 Ma (million years ago) in northern Poland, 15 Ma in northern Germany and 12 – 1.0 Ma in the North Sea, telling a story about a large Miocene river running north-south across the present western Baltic Sea. The enormous quantity of sediments, transported from the Baltic Shield areas, regularly filled up this Cenozoic basin and forced the mouth of this river to constantly bend to the west.

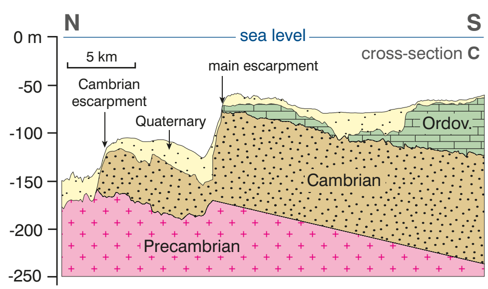
Although we do not know exactly where this river had its source, we have given it a name – the Eridanos. Eridanos was a mythical river of the ancient Greeks somewhere far in the north, where Phaeton, the son of Helios (God of sun), leading the chariot with the sun over the firmament, could not govern the fierce horses, fell down to earth and perished. The tears of his weeping sisters turned to amber. Indeed, it was amber, which occurs profusely in the deltaic sediments in northern Poland that gave rise to the idea to call the carrier of these sediments after the mythological Eridanos River. Amber, as a well-known commodity in the Baltic countries, particularly in Lithuania and in the Kaliningrad district, proves that this precious stone occurred further north of this river delta.

Most probably the Eridanos made its course through the Gulf of Bothnia, which has since the Middle Proterozoic repeatedly acted as a tectonically active and lowered hinge zone close to the western border of the EEC. From the centre of the Pleistocene glaciated region in northern Scandinavia, glaciers advancing towards the south obviously favoured, and thus heavily reworked, this already existing river valley. Because of the depression of the land surface

The extent of the Baltic klint and its subdivisions







Geological cross-sections across the submarine Baltic Klint. The locations of cross-sections A, B and C are shown as dotted lines on the map of the Baltic Klint (see left page)

caused by the huge mass of ice that was present during the Pleistocene and was later removed, the relationship between the isostatically still-rising northern, and the subsiding southern parts of the Baltic Sea, make it difficult to picture what this large north-south running Cenozoic river may have looked like. It is nevertheless most likely that the Gulf of Bothnia was born through tectonic forces combined with the erosion caused by Cenozoic rivers and Pleistocene glaciers.

THE TRIBUTARIES OF ERIDANOS – THE PRA-NEVA AND THE RIVER BETWEEN SAAREMAA AND GOTLAND

Despite not having precise information about the course and the valley of Eridanos, it is, perhaps surprisingly, possible to see the position of two of its tributaries. These are marked by two extensive escarpments – the **Baltic** and **Silurian klints** – that run across the Baltic Sea and border the coast in many places in Estonia and in Sweden.

Although, these large and extensive klints have been interpreted as the scarps along tectonic faults, walls of glacial valleys, or cliffs eroded by the ancient or even by the present Baltic Sea; all these theories are problematic. The only argument that prevents these escarpments being treated as the elements of the Cenozoic river valley system is the difficulty in imagining them as such. Indeed, it is hard to believe that a river can create such a complicated system of alternating escarpments and plateaus with highly rugged

Udria cliff is the easternmost part of the North Estonian Klint. It borders to the southern shore
of the Gulf of Finland, and is therefore subjected to, and eroded by, storms. Photo: H. Bauert

Ninase (Tagaranna) cliff in north-western Saaremaa.
Photo: T. Bauert

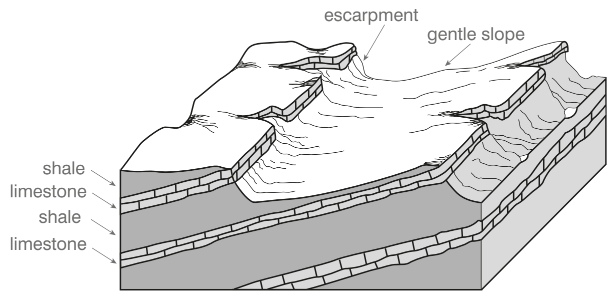
Högklint cliff south of Visby, western Gotland.
Photo: T. Bauert

topography. Still, in order to envisage how this may have looked you should admire one of the greatest natural masterpieces made by a river – the Grand Canyon, cut by the Colorado River in Arizona. Standing at the rim of this canyon full of alternating plateaus, escarpments, erosional remnants and so on, we can imagine ourselves being on the crest of the Baltic Klint and looking down at the Gulf of Finland, from where the waters of the Baltic Sea have been removed.

Of course, it cannot be only one large river that has created such natural wonders. A large river such as the Eridanos would have had plenty of smaller, often temporary tributaries that reshaped the marginal areas of large canyons and redefining the escarpments. And it is self-evident that occasionally, the steep river banks would collapse and slide under the influence of gravitational forces.

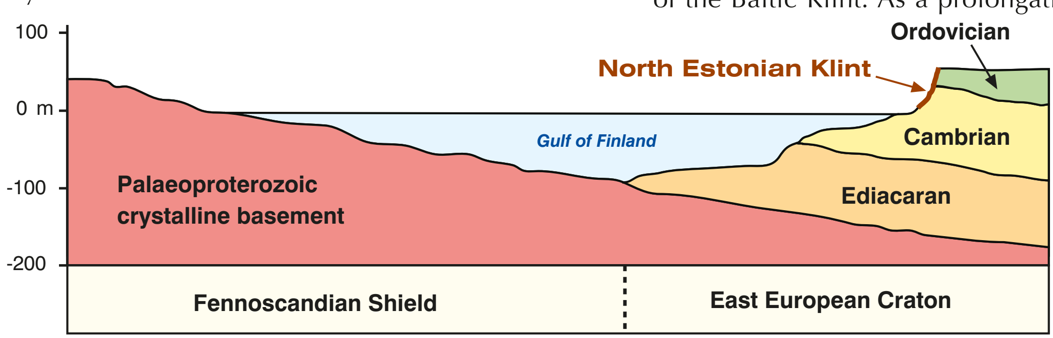
THE CUESTA LANDSCAPE

In fact, these klints above the Baltic Sea are only half of the picture, as the submarine relief on the northern Baltic Proper leaves even less arguments against the klints representing the erosional features made by Cenozoic rivers. The bedrock relief there reveals two excellent asymmetrical cuesta valleys, both having a gently south-westerly sloping plateau, one of them restricted from the south by the Baltic Klint, another by the Silurian Klint.



Cuesta topography developed in gently dipping, alternating hard and soft sedimentary rock layers

A cuesta landscape shaped by rivers is one composed of ridges made by the erosion of tilted layers of rocks with highly contrasting erosive properties. This is exactly what is found on the southern slope of the Baltic Shield. About 10–15 minutes towards the south sloping platform cover that consists of easily erodable clays, sandstones, marls alternating with the hard erosion resistant reef containing limestones and all this is resting on the hardest crystalline rocks. So, we can easily imagine about east-westerly, towards the Eridanos running Cenozoic rivers in front of the Baltic and the Silurian klints. Owing to the southerly tilt of the layers these rivers consistently widened their valleys in the same direction, by erosion of the banks. As the easily erodable rocks were removed, the rivers shaped slightly southwards tilted plateaus along the erosion resistant rocks, simultaneously developing the escarpments in front of them. And the geologists have even a name for the river that once run in front of the Baltic Klint. As a prolongation of the present Neva River it is called the Pra-Neva. Thus, we may say that the Gulf of Finland was largely born from the Pra-Neva.



As we do not know exactly where the river of Eridanos ran, we also cannot say where it met with its tributaries. However, the north-east to south-west deepening bedrock relief on the northern Baltic Proper suggests that the rivers in front of both the Baltic and Silurian klints, surely reached the area around northern Gotland. Further westwards, and around the Swedish islands of Gotland and Öland, the present height relationships do not permit the outlet of any river there. But as we already know, these height relations became distorted by the burden of the Pleistocene glaciers. Moreover, the exposed Ordovician and Silurian rocks on Öland and Gotland, which formed in a much deeper part of the basin than the rocks of similar ages in Estonia, are presently located at the same altitude. As the Eridanos with its tributaries gets trapped around northern Gotland, we cannot even be sure if this river ran east or west of present-day Gotland. If it ran along the eastern side, then the klint on Öland cannot be a part of the escarpment gouged by the Pra-Neva, just like the klint on Gotland cannot be the continuation of the escarpment observed in north-western Saaremaa. In this case, the Öland and Gotland klints would both represent the scars cut by westerly tributaries of the Eridanos. But still, even if we do not know the exact answer to how they were formed, they can even so be considered as two separate magnificent and extensive escarpments. The first one is the about 1600 km long Baltic Klint (cut into Cambrian and lowermost Ordovician rocks) that extends from Lake Ladoga in Russia in the east to the island of Öland in the west. The other is the about 500 km long Silurian Klint (cut into Silurian rocks), that makes its first appearance in the West Estonian lowland and grows to a superb escarpment beneath the waters of the central Baltic Sea and particularly along the north-western coast of Gotland.

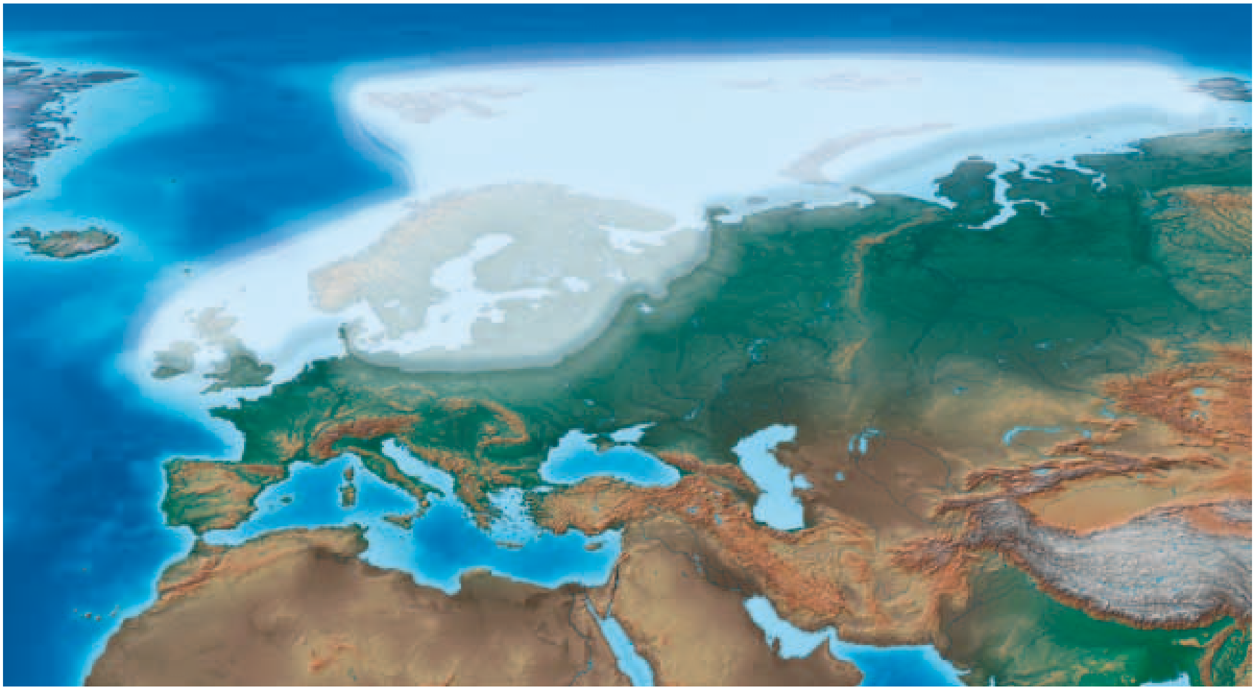
PLEISTOCENE GLACIATIONS

THE EROSIONAL SCARS OF THE PLEISTOCENE GLACIERS

The story about the formation of the Baltic Sea substratum reached its next phase when the reign of the large Cenozoic rivers came to an end and the whole area became covered by a thick ice sheet. During the last 2.5 – 3 million years the Nordic countries have experienced multiple glaciations and intervening warmer interglacials. Mighty glaciers from northern Scandinavia have repeatedly expanded forth and retreated back across the present Baltic Sea area. Each new ice sheet reworked and successively eroded the older, underlying relief and strata. Therefore we know the most about the last glaciation, the Weichselian glaciation (115,000 – 11,500 years ago), with its maximum about 20,000 – 22,000 years ago. This was the period when the ice sheet extended beyond the southern Baltic Sea, when its thickness in the centre of glaciation around the northern Gulf of Bothnia reached, by most estimates up to 3.5 km, and when the water level in the world ocean was about 130 – 140 m lower than it is today.

It is not necessary to rely on guesswork to discover what effect a similar ice sheet with powerful lobes of glaciers stretching out of it might have. The present world is full of examples, starting from the largest ice-covered mainland areas such as Antarctica, Greenland and Patagonia, stunning U-shaped valleys scraped out by the glaciers that once flowed into the low lying seas in the fjords of Norway and in New Zealand, or just having a look at the backyard of the Baltic Sea in Scandinavia. And the glaciers did much to change the Cenozoic appearance in and around the Baltic Sea area beyond recognition.

As highly effective scrapers, the advancing glaciers across the north-western EEC truncated and lev-



Extent of the Late Weischelian glaciation ca 20,000 years ago

elled everything with already existing relief. However, the lobes of the glaciers preferentially moved along former Cenozoic river valleys or tectonic zones with crushed and weakened rocks. Of course, the directions of these valleys had to coincide with the southerly moving glaciers, or otherwise these valleys became hurdles that the glaciers had to fight through or simply grow over them. And for sure, the most troublesome obstacles for the expanding glaciers were the traverse lying, steep and high klints.

Indeed, both klints are full of scars; the pathways of the advancing glaciers. On the mainland, this is best expressed along the coasts in northern Estonia and in north-western Saaremaa, where the dissected klint mingles with the winding coastline sections. The small bays cutting deep into the mainland alternate with northerly protruding capes, which are often terminated by high cliffs. What we cannot see are the glacial valleys beneath these small bays that are inundated by the waters of the Baltic Sea. But there is much more evidence below the waters of the Baltic Sea that tell us about the battle between the glaciers and klints. In fact, the sea bottom shows us unambiguously that the glaciers did a great job in gouging out and deepening the depression of the present Baltic Sea. We just need to look at some of the most impressive examples – the northern Baltic Proper and the Gulf of Riga.

THE NORTHERN BALTIC PROPER

The Cenozoic cuesta relief on the northern Baltic Proper, still with quite imposing klints and plateaus, has been heavily ploughed and made rugged by numerous glaciers. The further one goes towards Gotland, the larger and deeper become the furrows of the glaciers. The widest and deepest pathway is marked with a row of deeps along the easterly coast of Gotland. The best known of them, the Fårö and Gotland deeps, are both among the deepest troughs of the Baltic Sea. But it is not only erosion that marks the routes taken by the glaciers. No less convincing are the thick ridges composed of glacial sediments that occur in many places around northern Gotland. Most of them are hidden below the Baltic Sea. What reaches above the sea level can be admired on the island of Gotska Sandön a little to the north of Gotland.

A thick sequence of glacio-fluvial sediments crops out along the south-eastern escarpment of Gotska Sandön, which in places reaches more than 10 m high. But as the name of the island (island of the sand in Swedish) hints, most of its surface is covered with sand that is, by wind activity, mostly heaped into dunes. Sandy sediments are continuously washed out by the waves from the glacio-fluvial deposits that are gradually rising from the sea. Much sand driven around by the wind is presently in motion and piled here and there into the dunes around the north-western corner of the island.

Thus, just as the Cenozoic rivers lowered the relief from Estonia towards Gotland, so the extent of the glacial erosion increases in the same direction. If the valley of Eridanos existed somewhere around the north of Gotland, then doubtlessly the glaciers that descended along the Gulf of Bothnia largely destroyed it. The most extensively eroded pathways of the southerly advancing Pleistocene glaciers are placed just at the mouth of this gulf around northern Gotland.

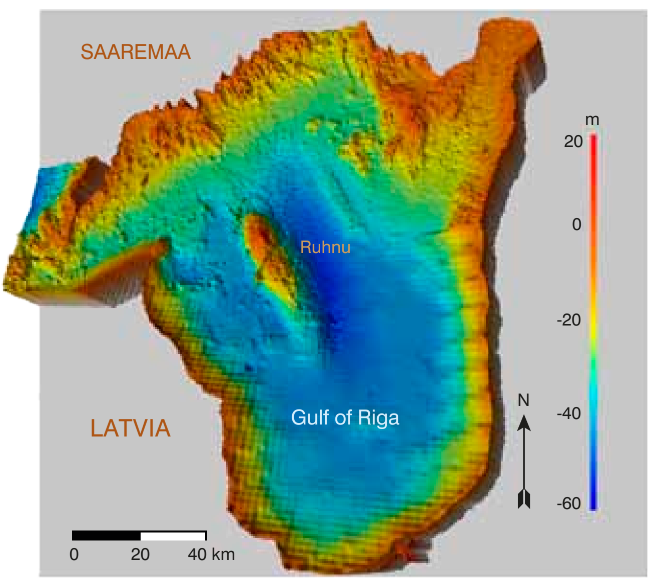
This coastal cliff section at the southeastern coast of Gotska Sandön is formed in a thick sequence of the glacio-fluvial sediments. Photo: I. Tuuling

GULF OF RIGA

In estimating the role of glacial erosion in the formation of the Baltic Sea depression; the Gulf of Riga is without doubt one of the best examples. This gulf, partly enclosed by the West Estonian Archipelago and cut into the Estonian and Latvian mainland, owns its existence largely to the Pleistocene glaciers. Its glacial origin can already be discerned from its shape, but above all its bathymetric characteristics leave little space for other interpretations.

The central part of the gulf, between the largest Estonian island of Saaremaa and the area around the Latvian capital of Riga, stretches across a northwest to southwest elongated symmetrical depression. The depth in the centre of this depression regularly lessens everywhere towards the island of Ruhnu that divides the central deep of the gulf into two sections. The island itself represents the highest point of a larger, northwest to southeast elongated bedrock elevation that rises above sea level. Like the central deep,

Bathymetry map of the Gulf of Riga with a drumlin-like elevation forming the island of Ruhnu

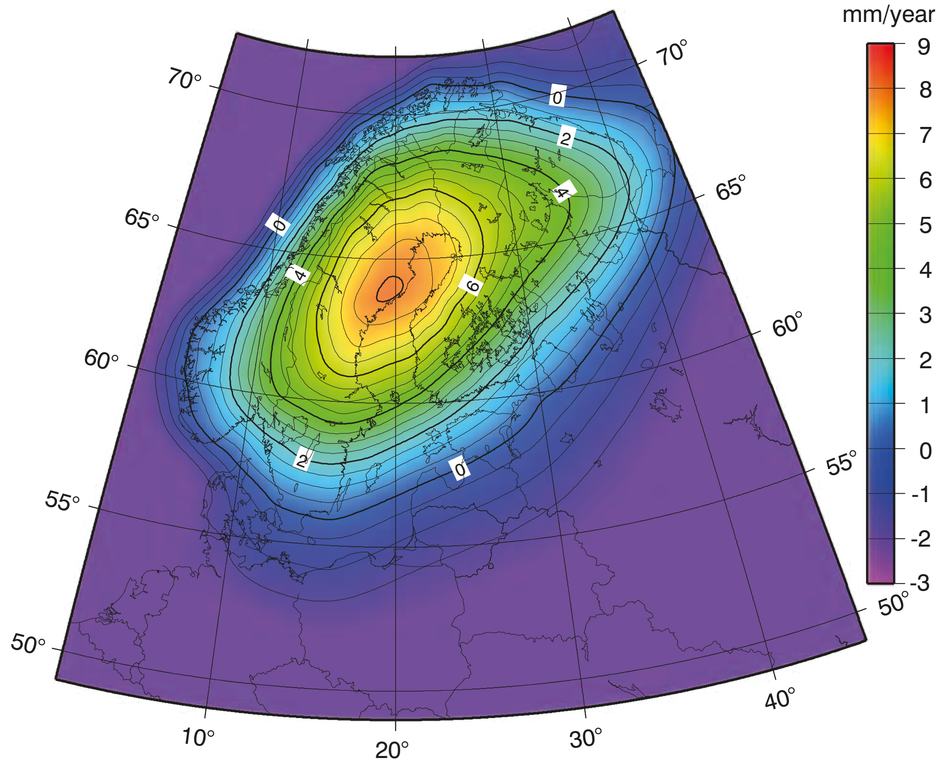


this drumlin-like elevation, with its steeper proximal (closer to advancing glaciers) and more gently falling distal slopes, was largely moulded by south-easterly advancing glaciers. Geologists call the ice flow that once crossed the Gulf of Riga the Riga ice stream or just the Central-Latvian glacier lobe.

GLACIOISOSTACY

In addition to their scraping effect, the Pleistocene ice masses had another, even more powerful influence that profoundly altered Cenozoic topography around the Baltic Sea. Its effect, differentiated glacio-isostatic movements of the earth's crust, is still in progress. Simple successive loading and unburdening of the north-western EEC by the Weichselian ice sheet has been one of the main agents to trigger and direct the development of the Baltic Sea.

To understand the term "isostacy" we have to look deeper into the earth, where a layer the geologists call as the "asthenosphere" exists. This thick layer of low-viscosity rocks beneath the solid and rigid "lithosphere" plays a critical role in plate tectonics. As these rocks rise at the plate boundaries and decompress, and where the ocean floor subducts into and along its upper boundary the outer rigid layer of the earth is broken into separate, smaller and large lithosphere plates. It is at these boundaries that the bulk of magma, the molten rocks, is produced. But apart from these regions, this plastically deforming layer of rocks balances gravitationally (isostatically) all the mass of rocks resting above it. Simply put, the rocks of the overlying lithosphere effectively float in the asthenosphere. Taller regions of the lithosphere, such as mountains, are balanced by deeper roots to the lithosphere. As the tops of mountains are eroded, these roots thus also shrink in order to maintain balance. It is not only the rocks of the lithosphere that float in the asthenosphere. During earth history the burden on the asthenosphere has been in places repeatedly changed by glaciations that redistribute water mass on the planet. During ice ages, some water from the world ocean is locked up in continental ice sheets, which puts an extra load on the ice-covered land areas. As a result, plastically deforming asthenosphere "creeps" away from the regions overloaded by ice, and the surface of the lithosphere below this overburden is warped down. When the ice melts, the burden of the overlying ice is removed and the rebounding asthenosphere triggers uplift of the previously down bended area.



Contour lines (mm/year) for the land uplift. Source: Fig. 4.3 in Ågren, J. & Svensson, R., 2007. Postglacial Land Uplift Model and System Definition for the New Swedish Height System RH 2000. LMV-Rapport 2007:4

How much was an ice sheet with a thickness of about 3 km able to unbalance the earth's crust? It is estimated that at the peak of the glaciation, the lithosphere below the maximum overburden around northern Scandinavia became deflected downwards by about 800–1000 m. However, in congruence with the thinning of the ice sheet towards its margins, the depth of this subglacial depression smoothly decreased towards the southern Baltic Sea. Exactly what the shape of this depression was and how far to the south it extended, is a matter of discussion and several different hypotheses on the subject exist. Some scientists think that the asthenosphere, pushed aside by the ice sheet, formed a bulge, and thus uplifted the surface of the earth outside the Scandinavian ice front.

Widening of the depression generated by the ice sheet below and around the Baltic Sea could be halted, and the rebound of the pushed-aside asthenosphere could only commence, after the glaciers had finished their final advance around the southern Baltic about 15,000–16,000 years ago. Further glacio-isostatic rebound with concurrent land uplift was in accordance with the deglaciation pattern and rate around the Baltic. At the beginning, when very slow melting occurred only on the very periphery of the ice sheet, the land uplift was insignificant. How-

Massive beach ridges of sandstone boulders formed on the slopes of Lauhavuori, western Finland after deglaciation of the area. Due to glacioisostatic land rise, these can now be observed at 150 metres from sea level. Photo: H. Bauert

Location map of the Kvarken Archipelago World Heritage site

ever, it speeded up notably when the final retreat of the ice sheet with rapid deglaciation started in central Scandinavia around 11,000 years ago. Based on the shore level changes seen around the Baltic Sea, the highest estimated land uplift at that time reached far more than 10 cm per year. At present this value does not exceed 9 mm per year.

In all, it is thought that in the centre of the glaciated region the total rebound of the earth surface so far reaches about 650–800 m, of which some 120 m has taken place during the last 7000 years. But it may well take some 7000–12,000 years more to raise the area around the northern Baltic Sea a further 100–150 m to equilibrate the crust around Scandinavia that was unbalanced by the Pleistocene glaciers. Others think, however, that the glacio-isostatic rebound already reached almost zero about 5000–3000 years ago, and the present land uplift simply has a neotectonic origin. No matter what the reason is for these differentiated glacioisostatic movements, the ever-increasing north-south tilt of the land surface means that the southerly driven waters of the Baltic Sea are constantly attacking and inundating the land areas around its southern coastline (Poland, Germany and Denmark).

THE HIGH COAST AND KVARKEN ARCHIPELAGO

Slightly north of the Baltic Sea lies an area that is known worldwide as an area of outstanding natural beauty. Included in the UNESCO list of World Heritage Sites, the formation of the High Coast and Kvarken archipelago is a direct result of post-glacial isostatic uplift whereby the land rises slowly as the ice that has previously weighed down the land melts away. In historical times this area has been affected by three major ice ages of which the centre of the last one lay directly over the High Coast area. Thus the area is continuously rising from the sea at rates that are among the highest in the world: since the final retreat of the ice some 10,000 years ago this area has experienced an uplift of close to 300 metres. As a consequence islands form and unite, peninsulas expand, and lakes evolve from bays and develop into marshes and peat fens and finally to dry land. At present the High Coast/Kvarken archipelago is experiencing an uplift that is averaging 8–8.5 mm per year. At this rate the Bothnian Bay, which is only 25 m deep in its shallowest part, will rise above sea level and form a land bridge that connects Finland and Sweden within 2500 years.

The High Coast is located in north-eastern Sweden and is characterized by steep-sided forested hills with flat tops and a cliffy coast. For someone interested in geology and how glaciers shape the landscape the High Coast is exceptional. It is an example of how geological processes can alter an area over a relatively short time period. The bedrock consists of various types of magmatic and metamorphic rocks such as granite, gneiss and gabbro with an overlying cover of easily-studied Quaternary deposits. The glaciers that formed the landscape were mainly oriented in a northwest to southeast direction and as they moved across the landscape they eroded and shaped the bedrock forming deep valleys with steep sides. Following the retreat of the ice the area was submerged and only the highest peaks were above water. This level is called the highest coastline and rocks and sediments above it are mainly unaltered by the sea: these glacial deposits provide the best soils for farming. Below the highest coastline many surfaces were affected by later wave action that washed out the sediments bringing fine-grained sediments to the lower parts of the valley. For those interested in hiking the

The high rate of land uplift in the Kvarken area exposes thousands square metres of new land every year. Photo: H. Bauert

area is full of trails that bring you close to nature and magnificent scenery.

The changing topography and variety in soil gives the High Coast a diverse floral community. Dominated by boreal forest, spruce and pine on poorer soils the vegetation becomes combined with deciduous forests on the plateau tops. As a consequence, the area can be considered to represent a vegetational boundary zone where southern and northern boreal plant species meet with western oceanic and eastern continental species, with the occasional alpine species also represented in the highest parts. The terrestrial fauna includes lynx, brown bear, deer and elk, whereas the mix of marine, brackish and fresh water habitats gives a range of fish, seal and snail communities living together with other macrofauna. Birdlife is well represented: for example all seven woodpecker species recorded in Sweden are found here.

On the Finnish side of the northern extension of the Baltic Sea the Kvarken archipelago comprises more than 5000 islands and islets in an area that extends 70 km east to the west and 70 km north to the south. Just like the High Coast the area is completely shaped by glacial and post-glacial activity, but the two areas are topographically very different. Where the High Coast is ancient, stable and steeply hilly the Kvarken archipelago consists of recent low-lying islands and islets formed in a very active and dynamic environment. The major geomorphologic features are unusual glacial ridges called De Geer moraines. They are formed perpendicular to the movement of the ice and consist of blocky ridges that can be several hundred metres long, 10–50 m wide and up to 5 m high. In addition, the archipelago exhibits other glacial features, most notably drumlins and flutings as well as transverse-, hummocky-, and terminal moraines.

As the coastline is continuously rising the emerging shores are rapidly colonised by opportunistic plant species that are gradually replaced by other species as the land continues to rise and the conditions change. This results in a very diverse and heterogeneous plant community protected under the Natura 2000 initiative. The landscape provides good conditions for wetlands in various stages of development. Additionally the archipelago is on a major and important migratory route for several birds, and also provides excellent breeding sites. Black guillemots, razorbills, Caspian and Arctic terns, eagles and ospreys are some of the birds that you can get a glimpse of.

The High Coast/Kvarken archipelago has a unique natural value owing to its geological and geomorphological history. The ongoing land uplift provides constant environmental changes that in turn are reflected in floral and faunal evolution as well as landscape development. The aesthetic value of both areas are well-known, and they are visited by hundreds of thousands of Swedish and international visitors each year.

FORMATION OF THE BALTIC SEA

Now being familiar with the geological background of the Baltic Sea, one might want to ask: How old is this sea? But it should be clear from the above that this very young water body rests on a much older depression and on a very ancient substratum. There can be no doubt that the depression in the ancient rocks below the present Baltic Sea already existed long before it started to fill up with the melt waters of the Weichselian ice sheet. Moreover, there is much evidence to confirm that the same depression has repeatedly hosted older seas, which existed during earlier warm stages between the different Pleistocene glaciations. Most of the known facts about these earlier seas concern the Eemian interglacial that preceded the Weichselian glaciation about 130,000–115,000 years ago. In general, the Eemian Sea was more extensive than the present margins of the Baltic Sea and was connected via Karelia to the present White Sea in the northeast.

The Baltic Sea was, as mentioned above, born from the melt waters of the Weichselian ice sheet about 13,000–14,000 years ago. But really it was not a sea, but a big fresh water lake. Its development was largely governed by the melting and retreating of this ice sheet and by the land uplift caused by deglaciation. All this was combined with the rapid sea level rise in the world ocean caused by ice melting. As a result, the connection(s) of the evolving sea in front of the retreating Scandinavian ice sheet with the world ocean changed several times. The fresh water periods of isolated lake(s) alternated with more brackish water stages when the Baltic Sea had a good salt-water inflow from the Atlantic.

The Baltic Ice Lake just prior to the maximum extension and final drainage at ca 11,700 years ago. Printed with permission of Thomas Andrén

THE BALTIC ICE LAKE

To understand what the Baltic Sea looked like in its early stages, you can turn to some of the numerous ice lakes that are present around the world today. One of the best places to study contemporary ice lakes is in Patagonia, Argentina where mighty lobes of glaciers, tens of kilometres in width and around 100 m in height, are bordered by huge glacial lakes.

Such a glacial lake was also developed in front of the receding ice sheet in the Baltic area more than 10,000 years ago. This glacial lake consisted in the very first phase of several isolated ice lakes located at different altitudes. The lake started to increase in volume as the amount of the accumulating melt waters in front of the retreating Weichselian glacier gradually increased. The oldest evidence of a similar ice lake in southernmost Sweden is dated at about 16,000 years ago. It is thought that the margin of the ice sheet extended from southernmost Sweden towards Estonia. Gradually decaying and retreating glaciers increased both the area and the volume of these lakes that finally combined into one large Baltic Ice Lake. In its earliest stages, the Baltic Ice Lake had only one outlet, a mighty waterfall around the present Öresund area in southern Sweden. The Baltic experienced different rates of uplift in different parts and the Öresund area emerged faster than the water level in the lake, a process that gradually shallowed the outlet. This in turn increased the velocity of the out-flowing water,

The Yoldia Sea at the end of the brakish phase ca 11,100 years ago. Printed with permission of Thomas Andrén

which substantially increased the rate of erosion. Erosion ceased as the hard bedrock was reached and the Baltic Ice Lake was gradually dammed up and started to widen towards the south. The end of this ice lake about 11,600 years ago was extremely dramatic. In an event known as the Billingen Catastrophe, the Baltic Ice Lake became rapidly emptied until the water levels equalled that of the world ocean. It is estimated that the water levels in the lake may have dropped by up to 25 m in just a couple of years.

The reasons for this catastrophe were very simple. The gradually decaying ice sheet retreated across the Billingen bedrock ridge between the two large Swedish lakes Vättern and Vänern that formed the western barrier for the Baltic Ice Lake. A much lower area that was suddenly exposed north of this ridge, the South-Central Swedish Lowland, opened the gate and the waters of the Baltic Ice Lake rushed towards the sea in the west. This rapid drainage had enormous effects on the landscape at the time as new land areas emerged out of the water around the Baltic Sea and new coasts were exposed. To give you an idea of the scale of the changes involved: the northward shift of the coastline in what is now Poland was about 30 – 40 km; Denmark became a united terrestrial area; and the formation of a large land bridge between Denmark and Sweden facilitated rapid immigration of plants, animals and humans into southern Sweden.

THE YOLDIA SEA

Following this sudden change of the palaeogeography in response to a warmer climate the evolution of the Baltic Sea reached the next stage in its formation. This stage is called the Yoldia Sea (it lasted approximately between 11,600 – 10,700 years ago) and it is named after a bivalve called *Portlandia (Yoldia) arctica* that is found in the sediments of the South-Central Swedish Lowland (the presence of which indicates brackish conditions instead of fresh waters). This stage in development began once the ice lake had reached the same level as the surrounding ocean, and in the first half, the Yoldia Sea had a rather good connection with the ocean. At that time, owing to the fast melting of glaciers around the world, the water level in the oceans rose significantly. This supported the inflow of the salty waters into the Yoldia Sea and a rapid, up to 10 – 12 m, sea level rise in the southernmost Baltic. In the northern part of the sea, large areas of Sweden and Finland were exposed from under the retreating ice, but were still lying under water. However, owing to the continuing rapid land uplift in south-central Sweden, the sounds between the sea and the ocean got regularly narrower and shallower towards the end of the Yoldia Sea stage. As a consequence the water in the Yoldia Sea became less salty as it was progressively isolated from the ocean – until a new damming stage with fresh-water was introduced in the development of the Baltic Sea.

The Ancylus Lake during the maximum transgression at ca 10,500 years ago. Printed with permission of Thomas Andrén

ANCYLUS LAKE

This new lake phase lasted approximately between 10 700 and 9800 years ago and is called the Ancylus Lake, after the presence of a fresh water snail called *Ancylus fluviatilis*. Triggered by the continuing melting and subsequent retreat of the glaciers, the same tendencies continued in and around the evolving Ancylus Lake. New areas were freed from the ice in the north, the volume of fresh water in the lake grew and the land uplift, particularly around the ice-freed northern Baltic Sea, increased.

As a result, at the beginning of this new phase, the southern coast of the Ancylus Lake, which experienced little or even no uplift, was significantly flooded, as the water level there increased more than 20 m. At the same time, new land areas emerged from the sea around the present Gulf of Bothnia, where the land uplift was greater than the rise in water level. The boundary line between the extending and shrinking seas passed through the south-western extremity of Finland. From a large number of ^{14}C dates of the submerged pine trees and peat deposits from the southernmost Baltic, this transgressive phase in the Ancylus Lake lasted about 500 years. The end of the Ancylus transgression with its highest water level is marked by distinct beach ridges along the Swedish, Latvian and Estonian coasts as well as on the island of Gotland.

The southerly expansion of the Ancylus Lake was followed by its sudden and large drainage, when a new outlet to the ocean, a complex river system with river channels, levées and lakes, was opened by the rising water level and erosion through the Danish Straits area. This might have caused an initial lowering of the Ancylus Lake on the order of 5 m. Large expanses of dry land became exposed, particularly around the northern Baltic Sea. The saltwater of the world ocean could penetrate all the way through this complicated river system into the Baltic only when the sea level in the Kattegat had reached the level of Ancylus Lake. The first sign of the salty water about 9800 years ago marks the end of the fresh water Ancylus Lake and introduces a new brackish water stage called the Littorina Sea.

LITTORINA SEA

The Littorina Sea stage is named after the mollusc *Littorina littorea*. By this stage, Scandinavia had become free from permanent ice, and ceased supplying the Baltic Sea with fresh melt-waters. However, a rapid raise of the global sea level continued, boosted by rapidly melting ice masses in North America and Antarctica. This guaranteed a steady transgression (a sea level rise) in the Littorina Sea during its first 3000 years of existence. At the same time, local land uplift governed the water level fluctuations and the salinity increase in the Littorina Sea. New mainland emerged north of the Stockholm – south Finland area, where the land uplift overtook the Littorina transgression. South of this area, the coasts of the Baltic Sea once again became inundated; the sea level rise in the southernmost Baltic Sea reached at least 10 m.

Steady transgression with constantly inflowing saline ocean water was occasionally speeded up by suddenly collapsing huge ice shelves of the Antarctic Ice Sheet. A distinct turning point in the Littorina transgression appears to have occurred sometime between 5000 – 6000 years ago. From that point onwards, the sea level rise stopped and the influx of the saline water into the Baltic started to decrease. Its further development became entirely dependent on a complex pattern of the isostatic uplift, which was still mainly controlled by a fast uplift rate in the northern, and slow or no uplift in the southern part of the sea. This stage of development of the Baltic Sea with decreased salinity is still ongoing and is also known as the Limnea Sea.

The present day land movements are at the moment +9 mm in the northern and -2 mm per year in the southern extremities of the present Baltic Sea, which reveals a regularly southwards-increasing tilt of the land surface below the sea. This forces the waters of the Baltic Sea to spread southwards, whereas new land areas are emerging in its northernmost part. This differentiated glacio-isostatic rebound, with about

150 m more expected land uplift around the head of the Gulf of Bothnia, is also the main factor controlling the possible future scenarios for the Baltic Sea. Still, as the northern majority of the sea is rising and only its southernmost edge is slightly sinking, the retreat of the shoreline and shallowing effect would be expected in most of the present Baltic Sea area. Fortunately the deepest parts of the Baltic Sea, below 150 m, occur mostly in its northern areas, which are the ones with the highest uplift rates.

However, given recent trends and future predictions about sea level rise and climate change, scenarios for the future evolution of the Baltic Sea based purely on glacio-isostatic models may never be realized. For the past century, a global sea level rise has occurred at a mean rate of 1.8 mm per year. However, more recent satellite altimetry estimations, from 1993–2010, have shown that this rate has been about 3 mm per year. Some people think that similar sea level rise is the best proof for the greenhouse effect and the global warming; others however are convinced that warming of the Arctic during the last century is caused merely by rearrangement of the current circulatory system, most importantly the Gulf Stream in the northern Atlantic at the turn of the twentieth century.

The Littorina Sea during the most saline phase at ca 6500 years ago. Printed with permission of Thomas Andrén

No matter what the reasons are for the global sea level rise – thermal expansion of the warming sea water, increasing water amount through melting of mountain glaciers, ice caps and ice sheets, or changes in the shape of the oceanic basins and in land/sea distribution – most scenarios predict rising sea levels over the course of this century. Worst-case scenario predicts an up to 9 m sea level rise, although it is also plausible that it may not exceed more than 1 m. So far, the recent couple of warm ice-free winters with stormy weather have put extra pressure on the shorelines around the whole Baltic Sea.

GEOTOURISM DESTINATIONS AROUND THE BALTIC SEA COASTS

As you are now aware, the present Baltic Sea coasts have evolved during the last 10,000 years when continental glaciers of the last ice age retreated from this area. Palaeo-coastline changes of the Baltic Sea show a remarkable shift in land-sea distribution during the last few thousands of years. This development has been mainly controlled by climatically driven eustatic sea level change and by vertical crustal movements. Knowing the crustal movement data, together with data from modelling the future sea level change, can be used to calculate scenarios of relative sea level development. All this is needed for long-term planning of human activities in the Baltic Sea coastal areas.

Land uplift is still on-going in the northern Baltic, where coastline advancement is well observable within a human generation. For example, comparing the topographic maps published in 1922 and in 1998, one can see that the shoreline near the town of Vaasa in western Finland has changed by half of kilometre within 77 years and the land uplift has been about 70 cm. In the areas of land rise, the sea bays are gradually transformed into coastal lakes which further will develop into mires and eventually into land areas.

While the coastline in northern Baltic is still advancing and new land is continuously emerging from the waters, the scenario is totally different in the southern Baltic. Here a long term eustatic sea level rise up to 70 cm may seriously affect the low-lying German and

Polish coasts and cause a considerable submergence of coastal areas.

The key factors involved in developing the coastline that can be seen at present were Pleistocene continental glaciations that heavily eroded the crystalline basement and Palaeozoic bedrock surface; the glacioisostatic rebound of the surface of the earth from areas once covered by thick glaciers; and advances/retreats of various Baltic Sea water bodies that reworked and redeposited sediments left behind by glaciers. These key factors have resulted in the formation of various coast types bordering the Baltic Sea.

Shores of the small Vekara island in the Gulf of Bothnia (off the Uusikaupunki town in western Finland) expose a variety of crystalline rocks, sculptured by glaciers of the last ice age. Photo: H. Bauert

TERMINOLOGY: COAST, SHORE AND BEACH

Coast (also coastal zone) defines the area between mainland and the open sea. This term is used in a quite informal manner in the general central Baltic region to describe the landscape that forms islands with their surrounding waters together with adjacent parts of the mainland. In Estonia, the coast encompasses the strip of land and the portion of sea floor where ancient coastal formations can be traced. The Integrated Coastal Zone Management in the European Union defines the coastal zone limits as a strip including 3 kilometres inland and 300 metres offshore.

Shore (also shore zone) is the narrow strip of land immediately bordering a sea or large lake which is

subjected to wave action, in other words, the zone between high water and low water.

Beach is the part of the shore that stands between the mean shoreline and high water level resulting from storm surges. It is usually covered by sandy or pebbly material.

SHORE TYPES IN THE CENTRAL BALTIC AREA

According to the primary topography, the geology of the bedrock and the prevailing coastal processes, the following abrasional and depositional shore types in the coastal zones have been distinguished.

ABRASIONAL SHORE TYPES:

1. **Cliffed shore** is characterized by the presence of an abrasional sharp cut developed in resistant Palaeozoic rocks (carbonate or clastic rocks).

2. **Scarp shore** is an abrasional bluff developed in loose Quaternary deposits (for example sands, gravels and tills).

3. **Rocky shore** is an abrasional sloping shore usually developed in hard crystalline rocks, but on a few occasions also in weather-resistant carbonate rocks (see photo on p. 46–47).

4. **Till (morainic) shore** is an abrasional sloping shore developed in tills, often exhibiting a protective cover as boulder lags or cobble pavement.

DEPOSITIONAL SHORE TYPES:

1. **Shingle shore** (also known as a coarse clastics shore or pebble shore) is a depositional shore with beach ridges formed mostly with pebbles and small- to medium-sized cobbles (2–200 mm in size).

2. **Sandy shore** is a depositional shore with sand ridges and often backed by foredunes and dunes towards the inland.

3. **Silty shore** is a depositional shore composed of silty sediments. Usually it is very flat and often overgrown by vegetation (see photo on p. 52 – 53).

Next we will be taking a closer look at some shore types that are most attractive to geotourists are have the highest value as recreational areas.

CLIFFED SHORES

Present-day cliffed shores can be observed at those spots along the Baltic and Silurian klints that are still in reach of storm surges and thus subject to wave erosion.

The part of the Baltic Klint that borders the southern shore of the Gulf of Finland in Estonia is known as the North-Estonian Klint. This klint represents the most outstanding natural monument in Estonia and exposes a sequence of Lower Cambrian to Middle Ordovician siliciclastic and carbonate rocks covering a time span up to 70 million years. The maximum heights of the North Estonian Klint in north-western Estonia are 30 – 35 metres (Türisalu and Rannamõisa cliffs), but may reach to 56 metres above the sea level at Ontika in north-eastern Estonia. The easternmost part of the North Estonian Klint, exposed directly at the shore, can be visited at Udria where it reaches 22 metres in height. Further east of Udria, the klint turns away from the sea, but still continues towards the east under Quaternary sedimentary cover.

Cliffed shores along the Baltic Klint

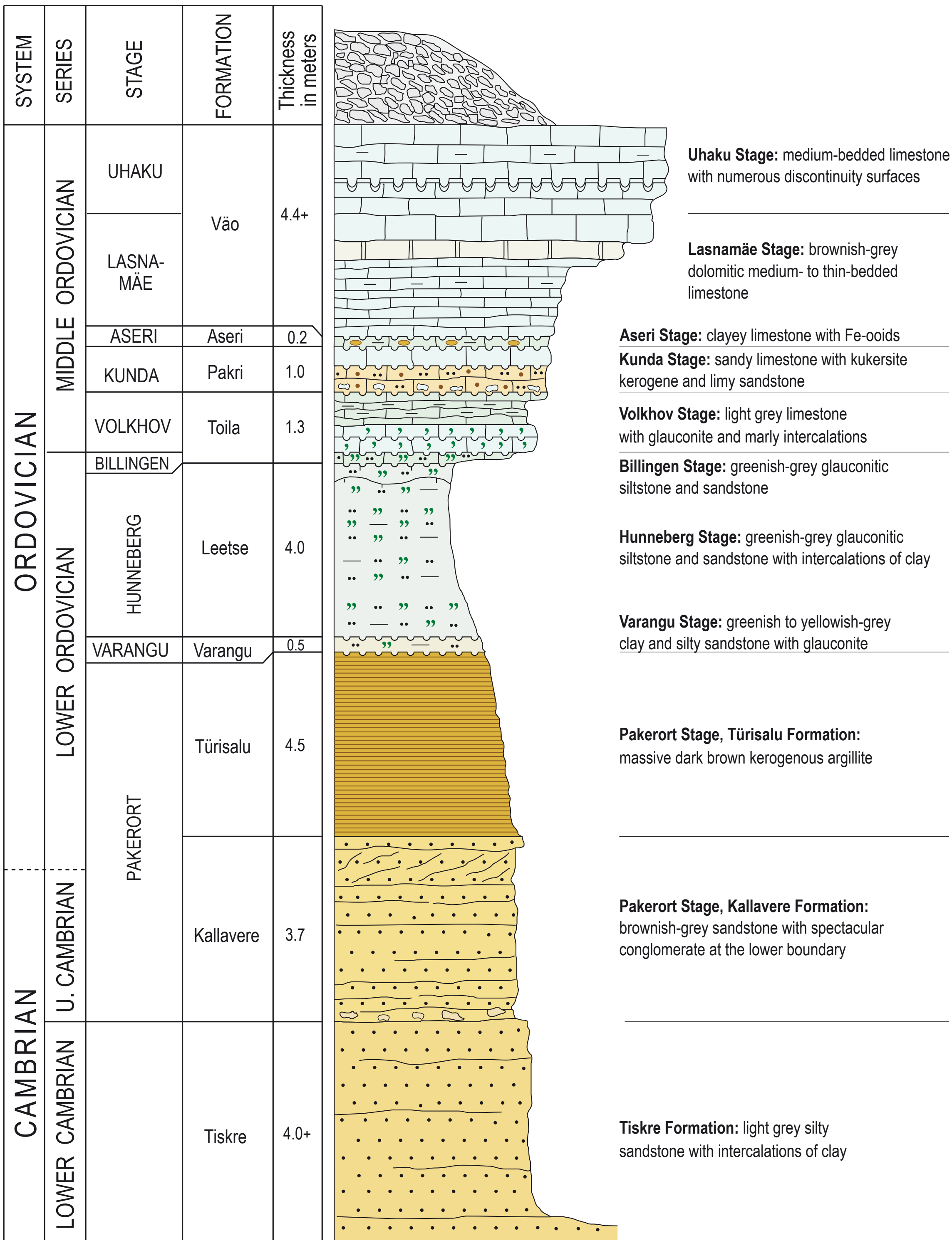
The best places to get acquainted with the geology of exposed cliff walls of the Baltic Klint and to enjoy stunning vistas from the cliff edge in Estonia are (moving from east to west):

• **Udria cliff** (Lower Cambrian – Middle Ordovician, north-eastern Estonia), see photo on p. 24 – 25

Boulder lag on the till (morainic) shore at the tip of Pedassaare cape in northern Estonia. Photo: H. Bauert

A giant erratic boulder sitting on the silty shore of Vahase island, off-shore southern Saaremaa, attracts nature tourists. Photo: T. Bauert

Pakri cliff (composite section)



- **Valaste cliff** (Lower Cambrian – Middle Ordovician, north-eastern Estonia)
- **Saka cliff** (Lower Cambrian – Middle Ordovician, north-eastern Estonia)
- **Kakumägi cliff** (Lower Cambrian, north-western Estonia)
- **Rannamõisa cliff** (Lower Cambrian, north-western Estonia)
- **Tilgu cliff** (Lower Cambrian, north-western Estonia)
- **Ninamaa-Suurupi cliff** (Lower Cambrian, north-western Estonia)
- **Türisalu cliff** (Lower Cambrian – Middle Ordovician, north-western Estonia)
- **Uuga cliff at Pakri cape** (Upper Cambrian – Middle Ordovician, north-western Estonia)
- **Pakri islands** (Lower – Middle Ordovician, north-western Estonia)
- **Osmussaar island** (Middle Ordovician, north-western Estonia)

The composite cliff section at the Pakri cape, north-western Estonia

The klint section on the Pakri cape has been studied by geologists over two centuries.

The composite section given here is a generalised account based on geological sections exposed at three key localities on the Pakri cape:

- **Pakri cape tip section** (N59° 23′ 13.68″, E24° 2′ 7.52″) – located next to the lighthouse;
- **Leetse section** (N59° 21′ 33.82″, E24° 9′ 18.7″) – located on the eastern coast of the Pakri cape, near Leetse village;
- **Uuga cliff section** (N59° 22′ 16.33″, E24° 2′ 12.7″) – located on the western coast of the cape, about 1 km northwards from the northern limits of Paldiski town. This section is most easily accessible to geotourists and displays a wide variety of rocks, starting from the base of the Lower Ordovician dark brown kerogenous argillite of the Türisalu Formation to the Middle Ordovician hard limestones of the Väo Formation that form a massive, partly overhanging cliff ledge.

Description of the composite section (from base to top):

Lower Cambrian

Tiskre Formation

The exposed thickness in the Pakri cape section is 4 m. Lithologically, it is composed of light grey silty sandstone with intercalations of argillaceous siltstone and clay.

Furongian (Upper Cambrian) – Lower Ordovician:

Pakerort Stage

The thickness of the Pakerort Stage is 8.5 m and it is represented by sandstones of the Kallavere Formation (thickness 4 m) overlain by monotonous black shale of the Türisalu Formation. The lower boundary of the Kallavere Formation is variable along the klint. About 200–300 m east of the Pakri cape tip section, it is marked by distinct lenses of basal conglomerate, incorporating pebbles of different ages and sources and even boulders from the underlying Tiskre Formation. These lenses may contain fragments of the lingulate brachiopod Ungula ingrica (Eichwald). The early planktonic graptolites Rhabdinopora flabelliformis flabelliformis and R. cf. R. flabelliformis desmograptoides have been recovered from the basal part of overlying dark brown kerogenous argillite of the Türisalu Formation,

The boundary between the Cambrian and Ordovician systems is lithologically indistinguishable at the Pakri cliff section. Based on indicative findings of graptolite

Uuga cliff at Pakri cape exposes a succession of Upper Cambrian to Middle Ordovician sedimentary rocks. Photo: M. Veisson

fossil in the kerogenous argillite and conodont fossils in the underlying sandstones, this boundary seems to be hidden somewhere in the uppermost part of the Kallavere sandstones.

Lower Ordovician

Varangu Stage

The Varangu Stage is 0.5 m thick. In the Uuga Cliff section, the Varangu Stage is represented by greenish-grey to beige clay and silty sandstone with green glauconite grains.

Hunneberg Stage

The Hunneberg Stage is 3.9 m thick. In the Uuga Cliff section, the Hunneberg Stage is represented by greenish-grey fine-grained glauconitic sandstone, with intercalations of light grey clay.

Billingen Stage

The Billingen Stage is 0.3 m thick. It consists of greenish-grey glauconitic silty sandstone that is replaced upwards by calcareous silty sandstones and glauconitic packstone.

Middle Ordovician

The Middle Ordovician sequence in the Pakri cape is very condensed in comparison to the klint sections in northeast Estonia (for example at the Valaste waterfall). The Middle Ordovician carbonates, mainly packstones and wackestones, formed in a marine environment (on shallow to middle ramp settings) with low sedimentation rate conditions.

Volkhov Stage

The Volkhov Stage is 1.3 m thick. In the Uuga Cliff section, the Volkhov Stage is represented by light grey limestone grains with intercalations of marls. Both rock types contain some glauconite. The lower boundary of the Volkhov Stage is marked by a distinct discontinuity surface.

Kunda Stage

The Kunda Stage is 1 m thick. The Kunda Stage is here lithologically represented by the Pakri Formation which is composed of kukersite-containing sandy limestone and limey sandstone. The rocks of the Pakri Formation are brecciated and penetrated by limey sandstone injections. The lower boundary of the Pakri Formation is marked by a series of discontinuity surfaces, with rounded, flat pebbles found on top of these. The uppermost 0.1 m is represented by a light-grey fine-grained limestone with phosphatic discontinuity surfaces. The upper boundary is marked by an even discontinuity surface with deep vertical burrows.

Aseri Stage

The Aseri Stage varies between 0–0.2 m thick. It consists of argillaceous limestone with intercalations of marl, and includes brown iron ooids.

Lasnamägi Stage

The Lasnamägi Stage is 2.4 m thick. The main lithology is brownish-grey, dolomitic, thin- and medium-bedded limestone.

Uhaku Stage

The Uhaku Stage is about 2 m thick. It is composed of medium-bedded limestone with numerous discontinuity surfaces.

Cliffed shores along the Silurian Klint

Well-developed cliffed shores at the foot of the Silurian Klint can be observed in the Baltic Proper, along the northern coasts of Muhu and Saaremaa islands in Estonia as well as along the northern and western coasts of Gotland. The Silurian Klint is relatively low (from a few to 20 m) on Estonian islands, but may form striking shore cliffs on north-western Gotland with the cliff heights reaching up to 40–50 metres.

Püssina cliff on the north-eastern coast of Muhu island. Photo: H. Bauert

The most outstanding and picturesque sections/cliffs along the Silurian Klint can be examined and admired at these localities:

• **Püssina cliff** (Muhu island, western Estonia; see photo on p. 58–59)

• **Pulli cliff** (north-eastern Saaremaa)

• **Panga cliff** (northern Saaremaa)

• **Ninase cliff** (north-western Saaremaa), see photo on p. 26–27

• **Suuriku cliff** (north-western Saaremaa)

• **Hallshuk** (northern Gotland)

• **Ireviken** (north-western Gotland), see photo on p. 62–63

• **Korpklint** (western Gotland)

• **Högklint** (western Gotland), see photo on p. 28–29

Apart from the classic Silurian Klint that can be followed at about the same stratigraphical level (at the boundary of the Llandovery and Wenlock layers) across the Baltic Sea from Saaremaa to Gotland, there are many other cliffs in the different layers of the younger Silurian rocks that border the Baltic Sea. However, their height normally does not exceed several metres and most of them have very limited lateral extension (for example Soeginina, Elda, Kaugatuma and Ohesaare cliffs on Saaremaa). Exceptionally, there are two islands made up of Silurian limestones, Lilla and Stora Karlsö, offshore western Gotland, which are both bordered to the north by magnificent cliffs. Breath-taking panoramic views can be experienced from the several kilometres long klint on Stora Karlsö that at its highest points reaches about 30 m above the sea level.

Magnificient vistas can be enjoyed from the cliffs on Stora Karlsö. Photo: T. Bauert

Panga cliff at northern Saaremaa (N58° 34′ 15″, E22° 17′ 22″)

Panga cliff near Võhma village is the highest (20 m) and the most prominent landform on the northern coast of Saaremaa island, and runs about 3 km along the seashore. The cliff is exposed at the northern tip of an arch-shaped cape and offers a stunning panoramic view that is enjoyed by almost every tourist visiting Saaremaa for the first time. The cliff is cut into the various limestones of the Jaani and the Jaagarahu stages that were subjected to secondary dolomitization.

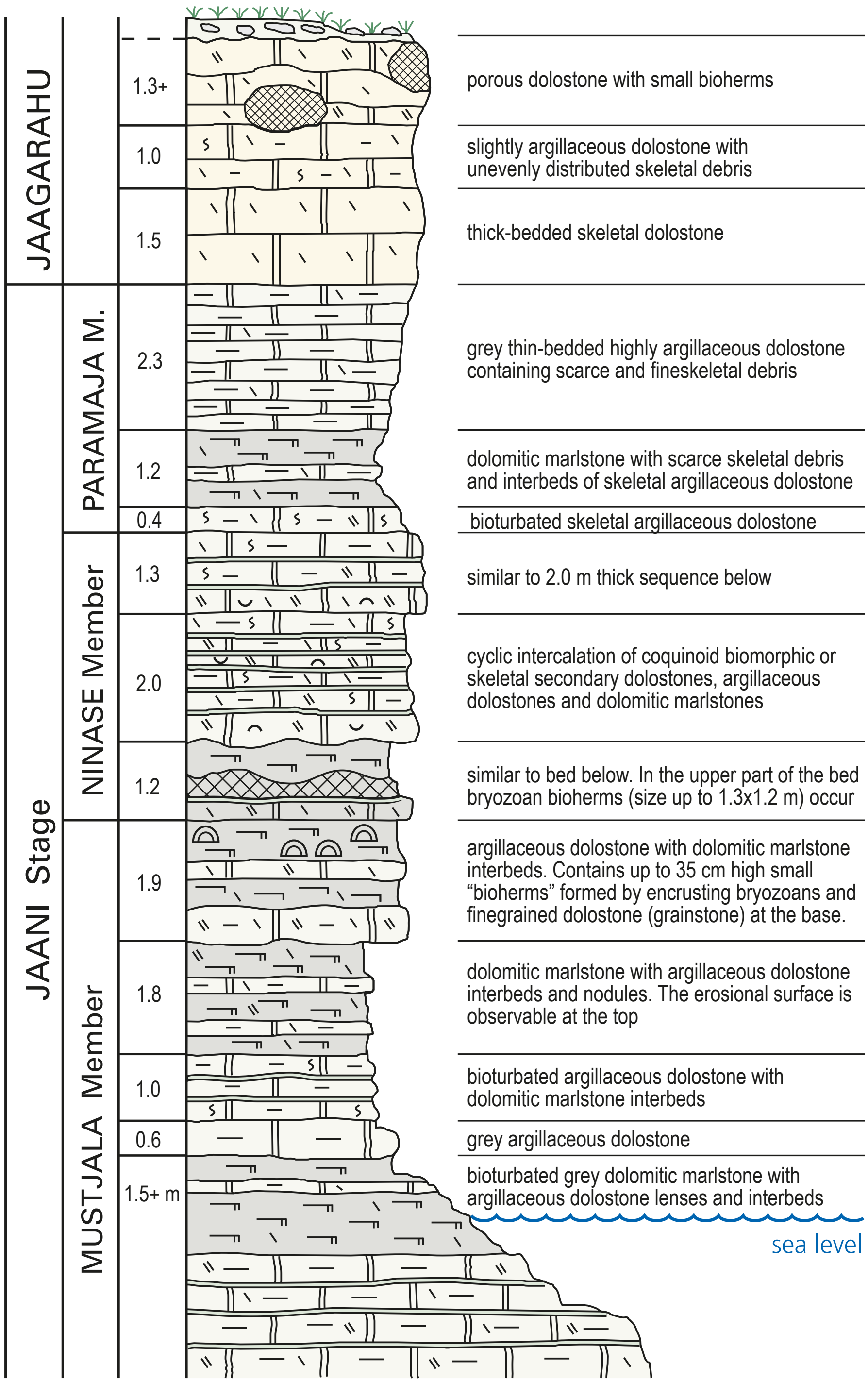
The exposed outcrop consists of two escarpments. The lower escarpment on the sea shore is composed of marlstones and variably argillaceous limestones of the Jaani Stage. Its crest is made up of the hard erosion resistant dolostones of the Jaagarahu Stage. The smaller, less conspicuous and up to few metres high upper escarpment can be observed landward of the shore cliff. This one is cut into porous dolostones of the Vilsandi Beds (Jaagarahu Stage) containing rare small bioherms. Actually, there is also an approximately 10 m high underwater escarpment, marked by an active surf zone that borders a wide wave-cut platform north of the shore cliff. The underwater cliff is cut into highly argillaceous, dolomitized limestones and dolomitic marlstones.

The described and figured cliff wall represents the eastern part of the outcrop (from base to top):

Mustjala Member, Jaani Formation

1. 10 m – underwater part of the cliff; according to the samples taken at metre intervals it consists of grey bioturbated dolomitic marlstone containing argillaceous dolostone nodules, lenses and interbeds.
2. 0.6 m – grey argillaceous dolostone.
3. 1.0 m – bioturbated argillaceous dolostone with dolomitic marlstone interbeds.
4. 1.8 m – dolomitic marlstone with argillaceous

PANGA cliff


JAAGARAHU
JAANI Stage
PARAMAJA M.
NINASE Member
MUSTJALA Member
1.3+
porous dolostone with small bioherms
1.0
slightly argillaceous dolostone with unevenly distributed skeletal debris
1.5
thick-bedded skeletal dolostone
2.3
grey thin-bedded highly argillaceous dolostone containing scarce and fineskeletal debris
1.2
dolomitic marlstone with scarce skeletal debris and interbeds of skeletal argillaceous dolostone
0.4
bioturbated skeletal argillaceous dolostone
1.3
similar to 2.0 m thick sequence below
2.0
cyclic intercalation of coquinoid biomorphic or skeletal secondary dolostones, argillaceous dolostones and dolomitic marlstones
1.2
similar to bed below. In the upper part of the bed bryozoan bioherms (size up to 1.3x1.2 m) occur
1.9
argillaceous dolostone with dolomitic marlstone interbeds. Contains up to 35 cm high small "bioherms" formed by encrusting bryozoans and finegrained dolostone (grainstone) at the base.
1.8
dolomitic marlstone with argillaceous dolostone interbeds and nodules. The erosional surface is observable at the top
1.0
bioturbated argillaceous dolostone with dolomitic marlstone interbeds
0.6
grey argillaceous dolostone
1.5+ m
bioturbated grey dolomitic marlstone with argillaceous dolostone lenses and interbeds
sea level

dolostone interbeds and nodules. The top is marked by an erosional surface.

Ninase Member, Jaani Formation

5. 1.9 m – similar to bed 3 but contains up to 35 cm high small "bioherms" formed by encrusting bryozoans and fine-grained dolostone (grainstone) at the base.

6. 1.2 m – similar to bed 5. The bryozoan bioherms (in size up to 1.3 x 1.2 m) occur in the upper part of this bed.

7. 2.0 m – cyclic intercalation of coquinoid biomorphic or skeletal secondary dolostones, argillaceous dolostones and dolomitic marlstones.

8. 1.3 m – similar to bed 7.

Paramaja Member, Jaani Formation

9. 0.4 m – bioturbated skeletal argillaceous dolostone.

10. 1.2 m – dolomitic marlstone with scarce skeletal debris and interbeds of skeletal argillaceous dolostone.

11. 2.3 m – grey thin-bedded highly argillaceous dolostone containing scarce and fine skeletal debris.

Jaagarahu Formation

12. 1.5 m – thick-bedded skeletal dolostone.

13. 1.0 m – slightly argillaceous dolostone with unevenly distributed skeletal debris.

14. 1.3 m – porous dolostone with small bioherms.

Ireviken cliff in north-western Gotland (N57° 50′ 28″, E18° 34′ 45.5″)

Here a fine sequence of Lower Visby, Upper Visby and Högklint formations is exposed.

There are four protruding cliffs consisting of huge isolated Högklint bioherms southwest of Ireviken bay. These patch reefs are named successively Tretrivsklint, Millingsklint, Gautuklint and Snipklint (Snipan). The reefs consist mainly of stromatoporoids and tabulate corals, but also of bryozoans, crinoids, and calcareous algae. Owing to the steep cliff, the reefs are dif-

The southern part of Panga cliff. Photo: H. Bauert

Silurian cliff at Ireviken, northwestern Gotland.
Photo: H. Bauert

ficult to access, but many large boulders on the beach can be studied.

The reefs are surrounded by a well-bedded to wavy-bedded limestone-marl alternation. This alternation differs strongly from the underlying Upper Visby Formation. The approximately 10 cm thick bioturbated limestone beds have a slightly silty appearance, show a brownish colour, and sometimes have a bituminous smell. The interbedded marls are dark-brownish and are strongly compacted. Whereas the thickness of the limestone beds remains more or less constant around 10 cm throughout the section, the thickness of the marl layers decreases from 20–30 cm in the lower part to less than 5 cm in the upper part of the section.

Several fossilized volcanic ash beds (K-bentonite beds) can be observed in the lower part of cliff section. The bentonite beds are easily tracked as they form layers that are impermeable to the rainwater draining down through the carbonate rocks, thus forcing it to seep out on the cliff surface along their upper boundaries.

A prominent marker in the Ireviken section is a halysitid biostrome (a bed rich in chain corals) close to the top of the Lower Visby beds.

ROCKY SHORES

Rocky shores prevail in areas bordering the Baltic Proper where Precambrian crystalline rocks are exposed. They are particularly well-developed in an area of the Scandinavian Archipelago that includes about 90,000 islands, islets and skerries. It is located between eastern Sweden (the Stockholm Archipelago or Stockholm Skärgård) and south-western Finland (the Turku Archipelago or Åboland Archipelago) with the Åland islands (Åland Skärgård) in the middle. This region, studded with thousands of islands, is unique within the Baltic.

The evolution of the Scandinavian Archipelago shores is mainly controlled by the geology of ancient structural and glacial formations, and the littoral zone is usually poorly developed because of the recent rapid uplift of the land. The rocky shores are largely composed of ice-polished landforms known as roches moutonnées and whalebacks.

Such easily accessible bare bedrock surfaces offer a great opportunity for hard rock scientists on learning about the formation of the earth's crust as well as giving hints to Quaternary geologists about landforming and land-shaping processes by continental glaciers. These glacially-striated roches moutonnées surfaces are particularly well preserved because they were sheltered by the waters of the Baltic Sea against weathering until they recently emerged above the sea.

The rocky shore on Keistiö island, Turku Archipelago has been smoothened and polished by glaciers during the last ice age. Photo: H. Bauert

Besides its geoscientific value, the Scandinavian Archipelago is also of outstanding international importance because of the very specific biological conditions in its terrestrial and marine environments.

Roches moutonnée – *a rock hill shaped by the passage of ice to give a smooth up-ice side and a rough, plucked and cliff-girt surface on the down-ice side. The upstream surface is often marked with striations. The roche moutonnées are aligned roughly parallel to ice flow.*

Whaleback – *a bedrock knoll smoothed and rounded on all sides by a glacier. The whalebacks have a smooth lee side, whilst roche moutonnées have a cliffed lee side. Whalebacks often show striations on all surfaces, indicating that abrasion has scoured the entire surface of the bedrock rock bump.*

The Åland Archipelago (Åland Skärgård)

Åland is separated from the Stockholm Skärgård by the Åland Sea, which is up to 290 m deep. There are 5275 islands larger than 1 hectare and 13497 skerries smaller than 1 hectare, that together form a mosaic in the Åland Sea. The highest rock hill in northern Åland has an altitude of 129 m, and the deepest sound is more than 100 m deep. The sculpturing activity of continental glaciers has left behind a landscape of roche moutonnées and drumlins, oriented parallel to the movement of ice sheets. These drumlins extend mainly in a north-south direction while striations on rocks surfaces are from north-northwest to northwest.

The spectacular nature seen on Åland islands, with its smooth bedrock coastlines, lush meadows and windswept stunted pine trees, attracts a great number of nature tourists to these islands in summer. The bedrock consists mainly of the red rapakivi granite that is visible almost everywhere in the landscape, but especially along the coastlines and on the islands. But even if you are not interested in rocks at all, sitting on a barren whaleback, warmed by the sun with nothing but the sea and horizon in front of you, gives you a pleasant feeling that you will never forget.

The Åland islands are perhaps most fascinating in the spring and early summer when the meadows are in full blossom with hepaticas, wood anemones, cowslips, buttercups and different orchids. Nature and hiking trails are a nice way to discover the Åland islands on your own and there are close to 30 different trails around them. Some of them are nature trails with signposted information about the local flora and fauna, while others provide insights into Åland's history and culture. Åland's paths and trails range from easy to moderate in terms of difficulty. They cross meadows and woods, but the sea is never far away.

The medieval Kastelholm castle (Kastelholms slott) is now in use as a museum of Åland cultural history. Photo: E. Lepik

The ruins of Bomarsund fortress (built 1832 – 1854) is one of Åland's most remarkable historical monument. Photos: E. Lepik

Bomarsund sea level gauge. Photo: E. Lepik

Besides the unforgettable terrains and nature on the Åland islands, they also boast a rich cultural heritage. There are around 50 museums and attractions to discover on Åland. One of the best known sights is Åland's only medieval castle – Kastelholm castle. This castle was built in the 14th century and is one of only five surviving Finnish medieval fortresses. Another magnificent ancient monument is the Bomarsund fortress that was built in 1832 by Russia but destroyed only 22 years later in 1854 in the Crimean War by a British-French fleet. Both the Kastelholm castle and the remains of the Bomarsund fortress are great examples of local building stone use.

In a small cove next to the ruins of the Bomarsund fortress, it is possible to visit the Bomarsund sea level gauge – the oldest preserved such gauge in the world which was most probably established as long ago as winter 1822. The gauge consists of a vertical scale, carved directly onto the bedrock and onto the cut stone that was placed on top of it.

Today the Bomarsund gauge would be an excellent site for scientific studies of long-term sea level changes as it was carved directly into the bedrock. The only problem is that because of the continued postglacial uplift, there is no longer any sea water around to measure!

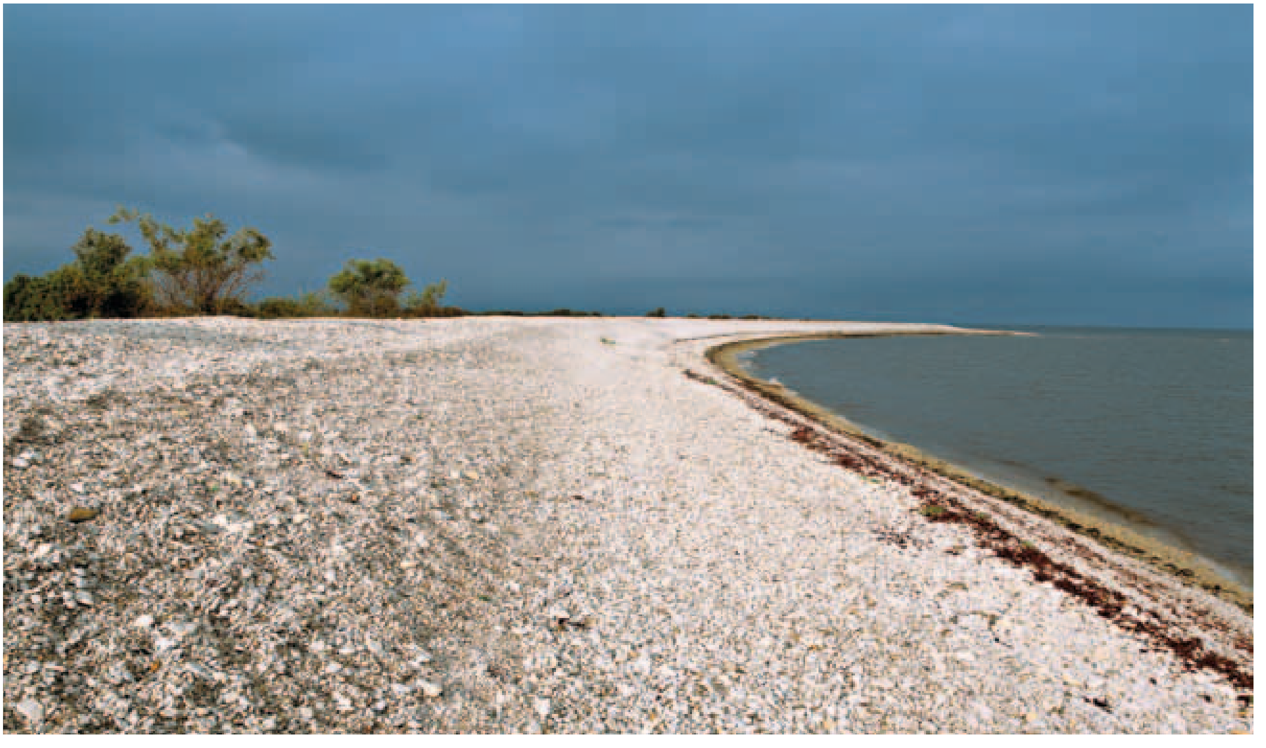
SHINGLE AND PEBBLE SHORES

The shingle shores occurring on coasts of the central Baltic Proper are mostly made by pebbles (4–64 mm) and by small- to medium-sized cobbles (64–192 mm). Such beaches are typically steep, because the water of wave splashes easily percolates through the coarse shingle heaps, thus decreasing the effect of backwash erosion and increasing the formation of steeply sloping beach ridges.

The main possible sources for beach pebbles in the Baltic Sea area are either underwater or shore cliff erosion or reworking of former glacial deposits exposed on the seafloor or in the swash zone. The abraded material is then carried on by longshore flows induced mainly by high-energy storm surges. The longer the transport route, the higher the degree of rounding and sorting of pebbles.

The accumulative shingle shores in Estonia are most common on Saaremaa island where adjacent cliffed

Right page, top: Shingle beach on the west coast of Ninase cape. Right page, bottom: Spectacular, massive shingle beach ridges on Osmussaar island. Photos: H. Bauert



shores developed in Silurian carbonate rocks are the major source for pebbly material. Particularly well-developed shingle shores made up by carbonate pebbles can be seen in north-western Saaremaa (on western shores of Ninase and Panga capes), but the largest beach ridges areas and the highest ridges can be encountered on Osmussaar island offshore north-west Estonia.

A unique pebble-cobble shore consisting mostly of crystalline pebbles and cobbles can be visited in the south-western edge of Harilaid cape, on the north-western tip of Saaremaa. The core of Harilaid cape is a northwest-southeast trending glacial ridge that has been subjected to intense reworking by waves and storm surges in an area of ongoing uplift. Owing to reworking of former glacial drift deposits on the seafloor, sandy material has been winnowed and transported away, leaving coarse pebbles and small cobbles to be concentrated and piled up by heavy storms during high sea stands onto a series of beach ridges. These steeply-sloping beach ridges can reach as high as 2.5 metres and be more than 1 kilometre long, but only 25–50 metres wide, as exemplified by the narrow bow-shaped Kelba spit. Comparing this spit today with data from older topographic maps shows that the spit gained over 87,000 m^2 of new area from 1955 to 2005. During this time, the spit has lengthened some 890 metres which makes about 18 m longer per year on average.

SANDY SHORES

The sandy shores of the Baltic Sea are the most attractive of all beach types to people for leisure activities and from a recreational viewpoint. There are long stretches of sandy shores along the eastern coast of

Sandy beach on the south-eastern coast of Naissaar, Tallinn Bay. Photo: H. Bauert the Baltic Sea – from Pärnu in south-western Estonia down to the Polish and German coasts in southern Baltic. The two largest islands in the West Estonian Archipelago, Saaremaa and Hiiumaa, also have several strips of nice sand beaches developed. The majority of the sand originates from glacial drift sediments, especially from glacio-fluvial deposits that formed eskers and outwash plains at the edge of glacier tongues during the retreat of the ice cover.

The major strips of sandy coasts on Hiiumaa and Saaremaa worth visiting by nature tourists, holidaymakers and various wind- and kite-surf enthusiasts are:

- **Tahkuna cape** (northern Hiiumaa)
- **Ristna cape** (western Hiiumaa)
- **Harilaid cape** (north-western Saaremaa)
- **Järve beach** (southern Saaremaa)

The largest sandy beaches can be seen on the Tahkuna cape, in northernmost Hiiumaa – these mainly consist of sand washed in from a large sandy glacio-fluvial delta deposit on the adjacent seafloor. The fine sandy beaches are backed up towards the inland by beach ridges covered with a heath pine forest.

Järve beach, about 6 km long and located some 10 to 15 km south of Kuressaare, is the most visited sandy beach by holidaymakers and kite surfers. At Järve, the sandy beach is fed by material eroded from a 3 – 4 m high coastal escarpment cut into Limnea Sea sandy deposits with some gravel and shelly coquina beds. Sandy material derived from abrasional scarps drifts further northward to form a new accumulational beach there. The southern part of the Järve beach, however, is a classic example to show the severity of erosion on sandy shores that might happen in a few decades elsewhere – here the high-voltage power line

poles which used to run on top of a shore ridge are now exposed directly on the beach.

Storm surges have severely eroded the sandy Järve beach in southern Saaremaa. Photo: H. Bauert

Even more drastic sandy shoreline changes have been observed over the past 40 years at the tip of the Harilaid cape in north-western Saaremaa. Here the glacial drift deposits have been largely reworked by wave action on an emerging seafloor. The mostly sandy material has been dumped onto the shore, forming extensive shore ridges and aeolian sand plains next to the former Kiipsaare lighthouse. However, intensified shore erosion processes on the western shore of the cape have led the cape to migrate north-eastwards and to change its shape considerably as well. Comparing the coast outline on old topographic maps with recent measurements shows that the tip of Kiipsaare cape has migrated northeast about 30–35 metres in the first half of the 20th century, while during the last 50 years the coastline shifted by about 75–90 metres.

This rapid coastline shift can be easily visualized by reference to the 25 m high, slim concrete Kiipsaare lighthouse that was built in 1933. The original location of the lighthouse on the cape with regard to the coastline is unknown; however on the 1:10000 map from 1955, it is positioned in the middle of the cape – about 100–120 m from the shoreline. Owing to the very fast retreat of shoreline on the second half of the 20th century, the Kiipsaare lighthouse already stood on a sloping sandy shore in 1995 and because of the unstable ground properties of a beach slope, it was leaning about 7 degrees west towards the sea. At the present day, the Kiipssaare lighthouse sticks out of waters of the Baltic Sea more than 30–40 m from the shoreline. Supported now by a stable seafloor, being in equilibrium around the lighthouse, it has straightened up once again.

Due to large-scale sandy coast migration on the tip of Harilaid cape, the former Kiipsaare lighthouse now sticks out of the waters of the Baltic Sea. Photo: T. Bauert

LIGHTHOUSE TOURISM IN THE CENTRAL BALTIC

One relatively new kind of tourism links together both nature and cultural tourism – lighthouse tourism. The primary significance of lighthouses as navigational aids has considerably diminished in the Baltic Sea region in recent decades because of advanced technology. At the same time many of them retain their value as maritime heritage sites or as sightseeing sites for nature travellers that can offer stunning panoramic vistas. As interest in visiting lighthouses by tourists is showing an increasing trend in the region, many lighthouse premises have been converted into tourism destinations offering various cultural, accommodation and dining services.

The main challenges in the preservation of lighthouses as maritime cultural monuments is to find sustainable restoration methods; to explore new uses of these buildings for opening them to the public, and to integrate all this on a large scale with the development of coastal areas and coastal societies.

LIGHTHOUSE TOURISM IN FINLAND

The most remarkable success in this field in the Nordic countries has been achieved by the Finnish Lighthouse Society, founded in 2003, to promote the protection and preservation of the Finnish lighthouses and related cultural inheritance. There are about 60 lighthouses along the Finnish coast, of which one third are either historically renowned or architectur-

Bengtskär lighthouse. Photo: T. Bauert

Kylmäpihlaja lighthouse. Photo: T. Bauert

ally recognized. A few of those lighthouse have been renovated and opened to the public – Bengtskär, Utö, Isokari, Kylmäpihlaja, Tankar, Söderskär, Marjaniemi, while several others are under renovation.

Bengtskär lighthouse (built in 1906) on Hiittis island, outside Hanko town has been a pioneer of lighthouse tourism in Finland. It rises 52 metres from the sea level and is the tallest lighthouse in the Nordic countries. Since it was opened to the public in 1995, it has been a very popular tourist attraction. Things to see and experience at the Bengtskär lighthouse include the first lighthouse museum in Finland, the home of the lighthouse keeper, several maritime exhibitions, a chapel, a lighthouse post-office, cafe and souvenir shop as well as accommodation and conference rooms for 24 persons. The Bengtskär lighthouse is visited each summer by about 10,000 people.

Utö lighthouse (the first one was built in 1753, but the present one was erected in 1814) on the small Utö island is Finland's oldest lighthouse. This is the southernmost year-around inhabitated island in Finland which besides the lighthouse has a pilot station, a small guest harbour, a hotel, a shop and a post-office.

The third level of the lighthouse building houses the church which is a popular place for weddings, although the island is quite remote. The lighthouse church is probably the oldest in the world and is mentioned for the first time in 1841. The Utö lighthouse can be visited during guided tours.

Isokari lighthouse off the coast of Uusikaupunki town can be visited by arranged tours between June 1st and

August 16th. Visitors can stay overnight on the island and there is also an exhibition about local nature and culture. This red-white striped lighthouse was finished in 1833 and stands about 50 metres above sea level.

Kylmäpihlaja lighthouse is located on a small island in the Bothnian Sea – about 10 km west from the mainland and the town of Rauma. The lighthouse was built in 1953 to guide ships entering the port of Rauma. The lighthouse was opened to the public in 2002. Nowadays there is a hotel (11 rooms) with conference facilities and a restaurant (40 seats) that is open during the summer. Private boats can use a small marina that is well protected from gusting winds by wavebreakers.

Tankar, the lighthouse island outside Kokkola, invites you to an unforgettable adventure in the Gulf of Bothnia. When the visitor arrives to the island, they will immediately recognize the slender red and white coloured Tankar lighthouse. The former lighthouse buildings are used as holiday cottages. This lighthouse has served ships and sailors since 1889. In the middle of the island, you can find a charming chapel with its belfry. The chapel was built in 1754 to serve as a church for fishermen. The oldest private cottage on Tankar is the so-called "Sjöbloms bastu" (Sjöblom's sauna), built in 1768. The seal hunting museum holds a collection of sealing equipment and boats. There is also an ornithological station situated in the western part of the island where seafowl are ringed and examined by birdwatchers.

The 38 m high **Söderskär lighthouse** sticks up on the rocky Söderskär island which lies in the outer archipelago of Porvoo, against the open sea. It was completed in 1862.

Söderskär island can be reached by the Royal Line cruises from Helsinki marketplace from late June until mid-August. A guided tour in the lighthouse starts at the bottom of the tower, and continues all the way up through five floors, which are all decorated with historical pictures and objects that tell the visitors stories about the history of shipping and the lighthouse. In the café you may enjoy pancakes, coffee, tea, oat biscuits and other refreshments.

Marjaniemi lighthouse is located in the village of Marjaniemi (about 50 kilometres west of Oulu) at the westernmost point of Hailuoto island in the Gulf of Bothnia. This lighthouse was first lit in 1872. A pilot station was built next to the tower: it currently serves as a hotel. The village of Marjaniemi hosts a versatile holiday and activity centre called Luotokeskus with several accommodation and dining facilities. Nature travellers can enjoy an interactive exhibition here of the Baltic Sea provided by Finnish National Board of Forestry. The University of Oulu uses the former lighthouse keepers' buildings as a research and field centre.

LIGHTHOUSE TOURISM IN ESTONIA

The IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) list of 100 world lighthouses as historic and architectural monuments contains six Estonian lighthouses – Kõpu, Ruhnu, Tahkuna, Keri, Pakri, and Suurupi. There are 61 lighthouses in Estonia, but only three – Kõpu, Tahkuna, and Ristna lighthouses (all located in the north and west of Hiiumaa island) – are presently open for visitors. However, several other Estonian lighthouses have a great potential for geotourism development. Visiting the Sõrve lighthouse located at the southernmost tip of Saaremaa would certainly be popular with tourists, as well as visiting the lighthouses located on some of the small islands (Kihnu, Ruhnu,

Kõpu lighthouse, Hiiumaa. Photo: T. Bauert


Tahkuna lighthouse, Hiiumaa. Photo: T. Bauert

Vormsi, Vilsandi, Naissaare, Osmussaare). Opening these lighthouses for visitors in summers would certainly add another tourist attraction to the list of local sightseeing. If for some reasons, a lighthouse cannot be opened or if it is not worth opening for the public, it could still be a part of a hiking trail offering a spectacular sea view from its base with the info panels providing information about local maritime history.

Kõpu lighthouse in western Hiiumaa is 36 metres high and reaches 102 metres above the sea level. It is the third oldest working lighthouse in the world and the first one built in the Baltic Sea region. The beacon became a lighthouse in 1649, when they started to burn wood on its platform. The lighthouse has been renovated several times during the past century. Since 1999, it has been open to visitors. There is a café and a souvenir shop at the parking lot next to the lighthouse.

Ristna lighthouse is located about 9 kilometres northwest of Kõpu lighthouse, on the western coast of Kõpu peninsula in Hiiumaa. It was built partly to safeguard the boats passing the Hiiu shallows from the west. The 29.5 metre high lighthouse was bought from Paris and erected in 1874. It was severely damaged in 1915 during World War I, when it was bombarded by German ships. The lighthouse was opened to the public in 2007. A small café is located just next to the lighthouse.

Tahkuna lighthouse was bought from France at the same time as the Ristna lighthouse, and its erection in northern Hiiumaa was completed in 1875. The lighthouse building is 43 metres high and can be seen from as far as about 30 km away. The lighthouse was opened in 2006, offering visitors a stunning panoramic view to the surroundings.

In the coming years, more cooperation will be seen between the Nordic countries in the aim of developing lighthouse tourism in the Baltic Sea area. The goals of these kinds of activities include exchange of experiences in preservation and alternative usage of lighthouses as a valuable maritime heritage, development of lighthouse tourism products and promoting them through joint marketing channels.

Kylmäpihlaja
Gulf of Bothnia
Vekara
FINLAND
TURKU
GÄVLE
Åland
HELSINKI
Keistiö
Bomarsund
MARIEHAMN
Gulf of Finland
UPPSALA
Bengtskär
Naissaar
SWEDEN
TALLINN
Pakri cape
Osmussaar
STOCKHOLM
Tahkuna
ESTONIA
Hiiumaa
Kõpu
BALTIC SEA
Püssina
Panga
PÄRNU
Ninase
Harilaid
Saare-
maa
Gotska Sandön
Järve beach
Vahase
Gulf of Riga
Hallshuk
Ireviken
Veczemju
VISBY
Högklint
Stora Karlsö
Gotland
RIGA
Öland
LATVIA

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