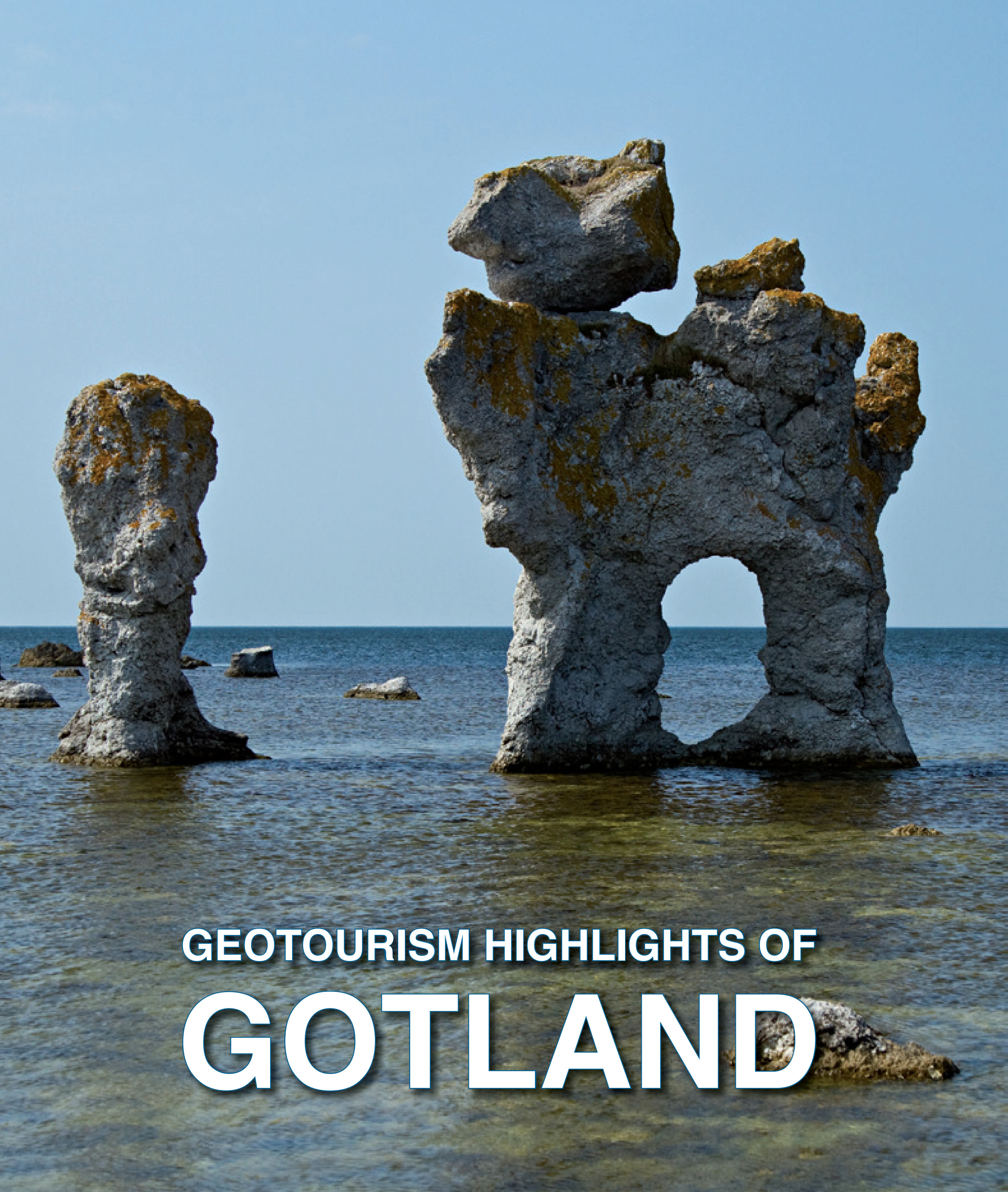


GEOTOURISM HIGHLIGHTS OF GOTLAND

NGO GEOGUIDE BALTOSCANDIA
DEPARTMENT OF EARTH SCIENCES, UPPSALA UNIVERSITY
GOTLANDS MUSEUM

GEOTOURISM HIGHLIGHTS OF GOTLAND

Tallinn, 2010

Geotourism highlights of Gotland.
NGO GEOGuide Baltoscandia. Tallinn, 2010.

ISBN 978-9985-9973-4-5

Compiled by:	Sara Eliason Michael G. Bassett Sebastian Willman
Proof-reading:	Graham E. Budd
Layout:	Heikki Bauert
Photos & Illustrations:	Heikki Bauert, if not otherwise stated
Cover photo:	Sea stacks at Gamlahamn, western Fårö

E-mail: baltoscandia@yahoo.com

Acknowledgements: Gotlands Museum, National Museum of Wales, Raymond Hejdström, Lars Holmer, Paula Knapman, Jan Olsson, Henrik Reintz, Michael Streng, Hanne Ödin, Gun Westholm

CENTRAL BALTIC
INTERREG IV A
PROGRAMME
2007–2013

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
INVESTING IN YOUR FUTURE

Release of this book was co-financed by European Regional Development Fund, Environmental Investment Centre, and NGO GEOGUIDE BALTOSCANDIA. It was accomplished within the framework of the CENTRAL BALTIC INTERREG IVA Programme 2007-2013.

Disclaimer: The publication reflects the authors views and the Managing Authority cannot be held liable for the information published by the project partners.

KIK
ENVIRONMENTAL INVESTMENT CENTRE

CONTENTS

Introduction 5
Geological History of the Baltic Sea Region 6
The Silurian Bedrock and the Geology of Gotland 11
The Sedimentary Rocks of Gotland 13
Gotland Fossils 22
Landscapes of Gotland today 27
The Baltic Sea and the Sea Coast 30
The Inland 35
History and Cultural Heritage of Gotland 37
Industrial History of Gotland 40
Geotourism Destinations 42
- Visby Surroundings 42
  - Högklint and Rövar Liljas Håla 42
  - Snäckgärdsbaden and Korpklint 44
  - Lummelundsbruk and Lummelunda Cave 46
- Northwestern Coast 47
  - Lickershamn 47
  - Ireviken 50
  - Bläse Limeworks Museum 54
- Fårö 55
  - Digerhuvud 55
  - Avanäset 56
  - Langhammarshammar 58
- Northeastern Coast 60
  - Lergrav 60
  - Kyllaj 61
  - St Olofsholm 65
- Northern Inland 66
  - Tingstäde – Hejnum area 66
- Eastern Coast 70
  - Gothemhammar 70
  - Grogarnshuvud 71
  - Kuppen and Snabben 73
- Southeastern and Southern Coast 74
  - Uggarderojr 74
  - Holmhällar 75
  - Husrygg and Hoburgen 78
  - Kettelvik 80
  - Kettelvik Sandstone Museum 81
- Stora Karlsö and Lilla Karlsö 84

INTRODUCTION

The island of Gotland, situated in the centre of the Baltic Sea on the eastern periphery of Sweden, is the largest of the Baltoscandian islands, with an area of 2994 km^2, compared with Öland (1347 km^2), Saaremaa (Estonia, 2673 km^2) and Bornholm (Denmark, 588 km^2). There are only 57 600 inhabitants of Gotland, but about 800 000 visitors come every year, mostly as tourists in the summertime.

Gotland is renowned for its beautiful scenery, especially along the coast where the wonderful sandy beaches attract people who want to swim and sunbathe. There is also a rich cultural heritage, with numerous ancient monuments and 92 impressive churches throughout the island. The largest town, Visby, was a prominent trading town of the Hanseatic League in the 13th and 14th centuries, and this importance is reflected in its rich architectural heritage. The magnificent town wall and some 200 well preserved medieval buildings of Visby are particular attractions.

Apart from these rich human cultural attractions, Gotland has many rich natural features that make it different from other regions of Sweden, related especially to the limestone bedrock that occupies much of the island. The rich flora, noted mainly for its rare orchids, the sedge fens and flush fens, the rocky limestone ground, the magnificent coastal and inland cliff scenery, and the remarkable sea stacks (rauks) are all features of the geological heritage. They owe their origin to the fact that the rocks of Gotland were formed as sediments in a warm, shallow tropical sea more than 400 million years ago. Human livelihood derived from farming, forestry, cement production and the stone industry has been governed by the prevailing types of bedrock and soil. The Visby town wall and numerous churches mentioned above would not have existed without the local supplies of building materials. Even the renowned natural light of Gotland, which has inspired so many artists, is a result of the interaction between the sea and the beautiful grey limestones.

But the bedrock also has another special aspect. It tells the story of life on earth long before humans appeared, and records changes of climate and environments over the course of millions of years. The study of fossils increases our knowledge of how animals and plants have developed through time, and how all these factors have been affected by large scale geological processes.

Gotland plays a prominent role internationally in our understanding of geological processes. The island has some of the world's best preserved shallow sea sediments and richest fossil associations from its period of formation and development. The bedrock sequence is essentially uninterrupted through its thickness of close to 450 metres, recording some 10 million years of the evolution of life on earth. Considerable painstaking research has been undertaken into the description and interpretation of these sediments and their fossils, from as far back as 1741 when Linnaeus spent just over one month on the island in June and July of that year and later described some fossils and geological features in various publications. Detailed mapping of the geology of Gotland was carried out as early as the first half of the 20th century, and over 600 publications have been produced by researchers from all over the world since 1970 alone.

GEOLOGICAL HISTORY OF THE BALTIC SEA REGION

If you picture a map of the Baltic without any of the water in the Baltic Sea, and instead include the sea bottom in a geological map of the region, the position and age of Gotland and the other Baltic islands will be more clearly understood. The northern Baltic Sea islands (Åland, Swedish and Finnish archipelago) belong to the crystalline basement whilst the Estonian (Saaremaa and Hiiumaa) and Swedish islands (Gotland and Öland) represent the northwestern margin of the overlying sedimentary rock layers.

At the beginning of the Cambrian Period some 543 million years ago, the Baltic region, European Russia and some other areas of central and northern Europe formed its own continental mass commonly known as Baltica. The border ran through northern Germany and Poland, across Russia, down to the northern part of the Black Sea and then north through the present Ural Mountains. The Baltic Sea region was a depression in the continental crystalline basement. The land of Baltica had been exposed above sea level for a long time, and had experienced a long period of erosion that gave rise to a low-lying peneplaned surface. As the Cambrian commenced, Scandinivia and the Baltic Sea basin began to be flooded, starting from the south. From the Cambrian up to the end of the Silurian period, a shallow sea lay here, with subsequent variations in land borders and depth. During these 135 million years Baltica gradually moved from a position far down in the southern hemisphere northwards towards the equator.

The climate that prevailed at the different latitudes Baltica passed through on its long journey northwards are reflected in the sediments that were almost continuously deposited on the sea floor, and are now preserved in widespread areas of Scandinavia and the Baltic Sea Region. At certain times, the shallow sea stretched well up what is known today as the Scandinavian peninsular. The oldest Cambrian sediments consist of fairly pure, well-sorted sandstones. They comprise remains of the disintegrated land surface that has been washed and sorted by waves and currents in the shallow cold water, so that sand grains of the hard mineral quartz are almost all that remain. All organic elements have been consumed in the oxygen-rich water. Large numbers of trace fossils of

Geological Time Scale

IUGS ICS Geological Time Scale 2004 (www.stratigraphy.org)

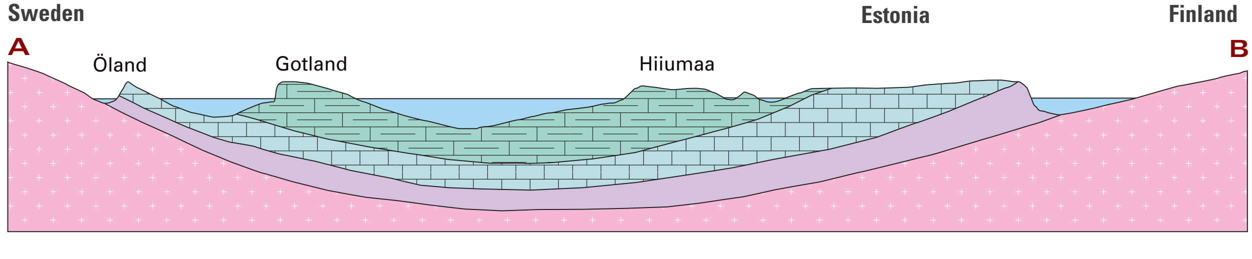
EONOTHEM/EON	ERATHEM/ERA	SYSTEM/PERIOD	SERIES/EPOCH	Age Ma
				0,00
PHANEROZOIC	CENOZOIC	QUATERNARY	Holocene	0,0115
			Pleistocene	1,806
		NEOGENE	Pliocene	5,332
			Miocene	23,03
		PALEOGENE	Oligocene	33,9 ± 0,1
			Eocene	55,8 ± 0,2
			Paleocene	65,5 ± 0,3
	MESOZOIC	CRETACEOUS	Upper Cretaceous	99,6 ± 0,9
			Lower Cretaceous	145,5 ± 4,0
		JURASSIC	Upper Jurassic	161,2 ± 4,0
			Middle Jurassic	175,6 ± 2,0
			Lower Jurassic	199,6 ± 0,6
		TRIASSIC	Upper Triassic	228,0 ± 2,0
			Middle Triassic	245,0 ± 1,5
			Lower Triassic	251,0 ± 0,4
	PALEOZOIC	PERMIAN	Lopingian	260,4 ± 0,7
			Guadalupian	270,6 ± 0,7
			Cisuralian	299,0 ± 0,8
		CARBONIFEROUS	Pennsylvanian	318,1 ± 1,3
			Mississipian	359,2 ± 2,5
		DEVONIAN	Upper Devonian	385,3 ± 2,6
			Middle Devonian	397,5 ± 2,7
			Lower Devonian	416,0 ± 2,8
		SILURIAN	Přidoli	418,7 ± 2,7
			Ludlow	422,9 ± 2,5
			Wenlock	428,2 ± 2,3
			Llandovery	443,7 ± 1,5
		ORDOVICIAN	Upper Ordoviciam	460,9 ± 1,6
			Middle Ordovician	471,8 ± 1,6
			Lower Ordovician	488,3±1,7
		CAMBRIAN	Furongian	501,0±2,0
			Middle Cambrian	513,0±2,0
			Lower Cambrian	542,0±1,0
PROTEROZOIC	NEOPROTEROZOIC	EDIACARAN		630
		CRYOGENIAN		850
		TONIAN		1000
	MESOPROTEROZOIC	STENIAN		1200
		ECTASIAN		1400
		CALYMMIAN		1600
	PALEOPROTEROZOIC	STATHERIAN		1800
		OROSIRIAN		2050
		RHYACIAN		2300
		SIDERIAN		2500
ARCHEAN	NEOARCHEAN			2800
	MESOARCHEAN			3200
	PALEOARCHEAN			3600
	EOARCHEAN			~4500

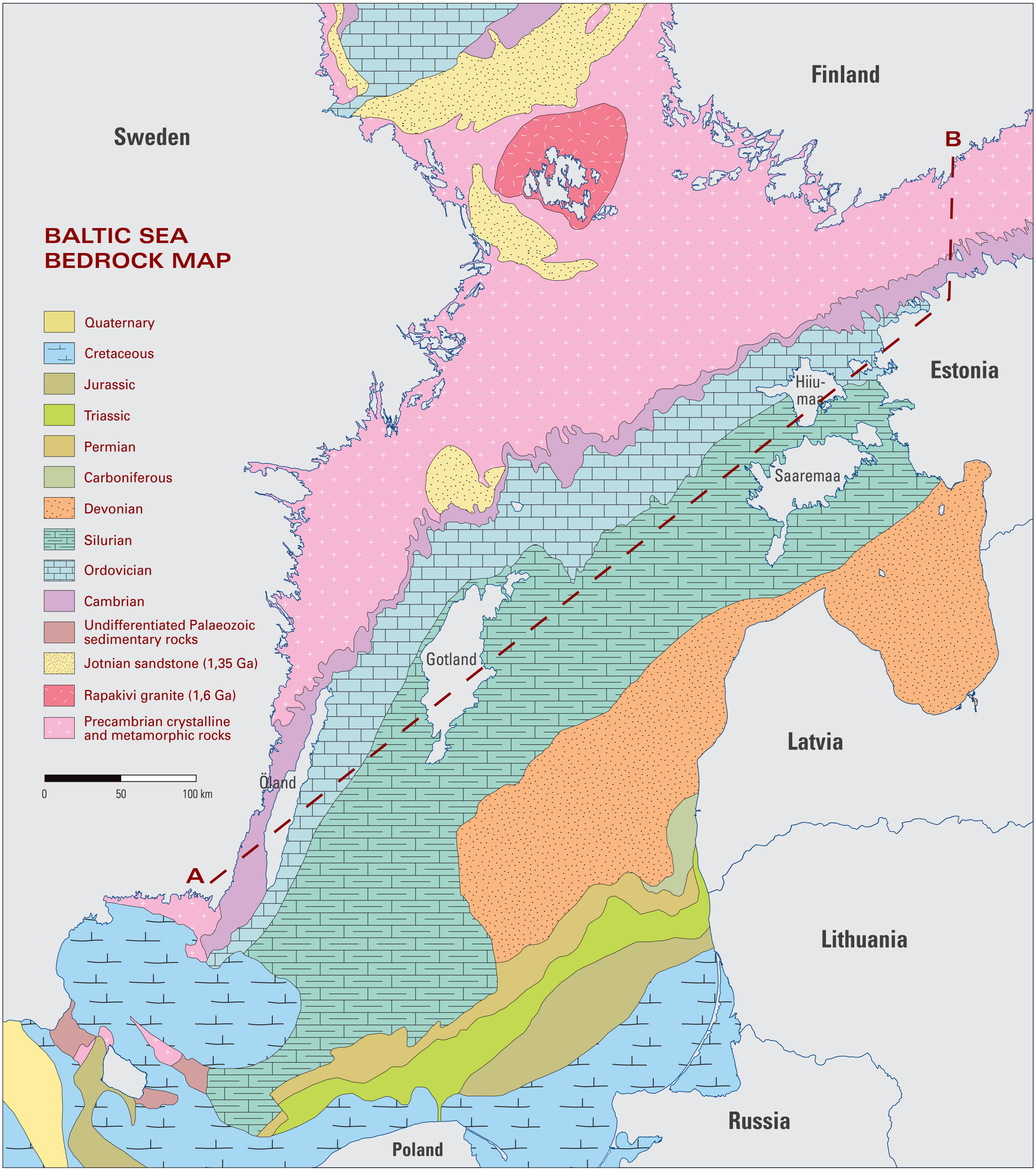
burrowing tracks left by organisms like worms, indicate abundant former life, though remains of shells are rare. At the beginning of the Cambrian, Baltica was probably on the 60–70 degree southern parallel, where it was then (and still is) cold and windy.

Gradually Baltica moved northwards and the sea level continued to rise. The sediment from the mid- and latest parts of the Cambrian has now consolidated to dark shale. Clay shale is the type of rock once deposited as a clayey mud in very calm, usually deeper water beyond the reach of waves and currents. The upper Cambrian so-called alum shale is black owing to a high content of organic material (carbonized disintegrated remains of animals and plants) and the iron-rich mineral pyrite. The oxygen deficiency on the sea bed, just as on the present-day Baltic Sea floor, meant that the decomposition of the organisms' organic parts was only partial; and few animals could live on the sea floor. Therefore the remains of animals such as the freely-swimming trilobites that accumulated, have been well preserved. The alum shales contain quite a lot of bituminous calcium in the form of black, disc-shaped nodules, known as anthraconite. The Cambrian strata are exposed in a narrow belt along the sea bottom and crop out in, for example, Skåne, on Bornholm, in the Kalmarsund, and in northern Estonia.

The deposition of the black clay sediments continued into the next period, the Ordovician, although the sediment became lighter in colour. In Skåne the clay sedimentation continued throughout the period, while further north and east, in the shallower regions of the sea, lime sedimentation occurred, indicating a warmer climate. This orthoceratite limestone (named after the fossil shells of the cephalopods contained within it), which can be found for example on Öland and Hiiumaa islands, is red to light grey in colour and rich in fossil shells, such as those of trilobites, cephalopods and brachiopods. It was in the next period, the Silurian, that reef formations first became common in the shallow coastal areas, indicating a more tropical climate.

During the Silurian period, beginning 444 million years ago and ending 416 million years ago, Baltica was at, or just south of the Equator. Approaching from the west was Laurentia, consisting of present day North America and Greenland. During the Silurian period the two continents finally converged. The enormous force pressed together and crumpled up the thick layers of sediment that had been deposited over a long period of time in the deep sea trench that had formed along the western edge of Baltica, when the sea floor was subducted under present day Norway. The Caledonian convergence boundary that we can see today in the central Scandinavian mountain range (part of the Caledonian mountain chain) emerged. South of Baltica and Laurentia lay the enormous Gondwanaland, consisting of Africa, South America, Antarctica, Australia, Madagascar, India and New Zealand.





Cross section of the rocks in the Baltic Sea area showing the similarities between Gotland and Saaremaa (left page). Distribution of rocks of varying ages in the Baltic Sea area (adapted from Ahlberg 1986, Swedish Geological Survey, R&M 47).

Palaeogeography of eastern Laurussia in the mid-Silurian – Wenlock, 425 Ma (adapted from Cocks & Torsvik 2005).

During the Silurian Period, the climate at the equator was warm, just like today. The Baltic Sea Region and southern Scandinavia were covered by a shallow sea, and land lay in the north and the west. The absence of a vegetation cover and the tropical climate meant that the land surface was subjected to intense weathering. Rain water flushed clay via rivers out to sea, where the small clay particles were held in suspension until the water flow had slowed. Near land – where Gotland's bedrock was just being formed, for example – the shallow sea beds were rich in oxygen, and sunlight could reach the seafloor, providing favourable conditions both for myriads of animals living on the bottom (benthic), and for free swimming ones (nektonic), as well as for the growth of algae. Organic reefs similar to today's coral reefs were periodically formed by sessile animals with calcareous skeletons. Enormous amounts of fragmented shells piled up on the sea beds around the reefs, and these eventually consolidated into stratified limestone. At other times large amounts of clay sediment were deposited. These were combined with calcareous material and formed thick, fossil-rich marlstone layers. Further away from the coast, in deeper and calmer water, almost pure clay was deposited. This has now been transformed into light clay shale, which can be seen in Skåne, for example.

Even in Skåne, reef-like calcareous knolls were formed at the end of the Silurian Period, indicating a regression (the retreat of the sea). The very youngest Silurian layers there consist of red sandstone, sediment that bears witness partly to an environment very close to land, possibly even continental, and partly to the fact that the buckling of the Caledonian mountains had taken place and that this newly-born mountain range had already been subjected to weathering. Sand was also deposited in the Gotland region towards the end of the Silurian period.

At the beginning of the next period – the Devonian – the entire area emerged above sea level, where it probably remained even during the two subsequent periods – the Carboniferous and Permian. There are no sediments from these periods in Scandinavia, but in southeastern Baltic Sea, as well as in southern Estonia, Latvia and Lithuania there are some continental sandstones, mostly of Devonian age. Elevation above sea level was probably caused by the sinking of the oceanic ridges in the spreading centres of the oceans, and thus of the sea level, due to the interruption of tectonic movement following the continental convergence. When plates move swiftly, on the other hand, magma pushes up the ocean floors at the spreading centres, causing them to rise.

At the beginning of the Silurian period, there is little evidence for extensive land life. The sea, however, contained abundant vegetation and animals. Every main group of animals existing today was already represented at that time. Some time during the Silurian Period, plants started colonising the land, and during the next period, certain fish developed the ability to move onto the land.

THE SILURIAN BEDROCK AND THE GEOLOGY OF GOTLAND

The exposed bedrock of Gotland consists of reef limestone, stratified limestone, marlstone and a lesser expanse of sandstone, as well as finer-grained silt. The strata, attaining an impressive thickness of 500 m, were deposited in a coastal shallow-water area within one single geological period – the Silurian. Beneath the Silurian beds, drilling has revealed older sediments of Ordovician limestone, Cambrian shale and sandstone, as well as Precambrian layers resting on the crystalline basement 700–1000 metres beneath the ground surface.

After millions of years of sediment accumulation, the deposits were compressed by their own weight and gradually consolidated to the rock that today forms Gotland's bedrock. Normally only the topmost layer (the youngest layer), would be exposed, but since all the strata dip about 2 degrees southeastwards, and erosion, mainly by the inland ice has scoured away much of the sediment at an oblique angle to the dip of the strata, each layer protrudes and is more or less accessible, from the oldest in the north west, towards the increasingly younger layers in the south east of Gotland. This largely uninterrupted fossiliferous sequence of layers reflects the development of the earth and of life spanning some 10 million years.

Gotland can be very roughly divided into three limestone areas, with marlstone areas in between. Limestone, which is harder and thus less prone to erosion, forms the higher (30–80 metres above sea level) areas in the north, in the central region of the island and in the very south. A closer look at the stratigraphy on Gotland provides a more complicated picture, difficult to interpret. At one and the same point in time there were obviously different depositional environments, depending on the depth of water, reef formation, rate of sedimentation, etc, within the region of Gotland, which is reflected in the fact that deposits of equal age can differ in appearance and fossil content. Similarly, deposits at different levels in the stratigraphic column, and which differ chronologically by several million years, can be largely identical in appearance as the depositional environment was identical. Another complicating factor is that the deposition of large amounts of sediment caused the displacement of the shoreline, thus shifting the focus of deposition towards the south east.

Reef Formation During the Silurian

An organic reef is an ecosystem in the sea, consisting of a fixed core of skeletal material from dead reef-building organisms, to which living generations of these animals and algae are attached. Free living animals are found in the crevices on the surface and around the reef.

Present day tropical coral reefs are the marine equivalent of the tropical rain forest, and are one of the ecosystems on earth richest in species. 430 million years ago the biodiversity in the reef was also enormous, although the main reef-builders differed from recent ones. Today, corals constitute the core of the reef, whereas in the Silurian the reefs were mainly dominated by stromatoporoids, a sponge-like animal, though in some cases by calcareous algae and tabulate corals. The large reefs such as in the Östergarnslandet area, were mainly formed by stromatoporoids, whilst the two small – and also oldest – reefs in the marlstone on the northwest coast of the island were mainly dominated by tabulate corals.

Present day reef formation requires a water temperature of about 22 – 28 degrees and not too great a depth, normally not more than 20 metres, so that sunlight can penetrate to the sea floor. Most modern corals live symbiotically with green algae, thus requiring light in order to grow. It is widely believed that these prerequisites could also be applied to Silurian reef formation.

Certain periods have provided favourable conditions for reef formation. At a suitable depth, sessile organisms with calcareous skeletons began to grow on the sea bed. Gradually as these died, new animals established themselves on the hard surface of the calcareous skeletons. As new generations of skeletons accumulated, the reef grew in an upwards direction. Its rate of growth was fast at first, but decreased as it approached the surface of the water, where surf shattered the skeletons. The estimated average growth rate of a modern reef is one metre per 1000 years. Many nektonic, and benthic crawling and sessile animals like cephalopods, snails, brachiopods and bryozoans thrived in a reef environment where they could seek food and shelter among the reef builders and in the cavities.

Sea lilies (crinoids) were sessile animals, often found in large numbers on reef slopes. When they died their calcareous skeletons were piled up against the sides of the reef. Today these skeletal deposits can be seen as coarse-grained fragmental limestone next to the reef limestone, consisting almost entirely of reddish sea lily fragments. This crinoid limestone is estimated to have been deposited at the rate of 0.5 m per 1000 years.

Further out from the reef, shattered smaller skeletal parts of reef dwellers were deposited. These can now be found in the stratified limestones that succeed the fragment limestone further out from the reef limestone. On the sheltered landward side of the reef there was a shallow lagoon where a rich animal life thrived, and where calm waters enabled the sedimentation of the finest particles. The marlstone formed in this way may have been deposited at a rate of 10 cm per 1000 years.

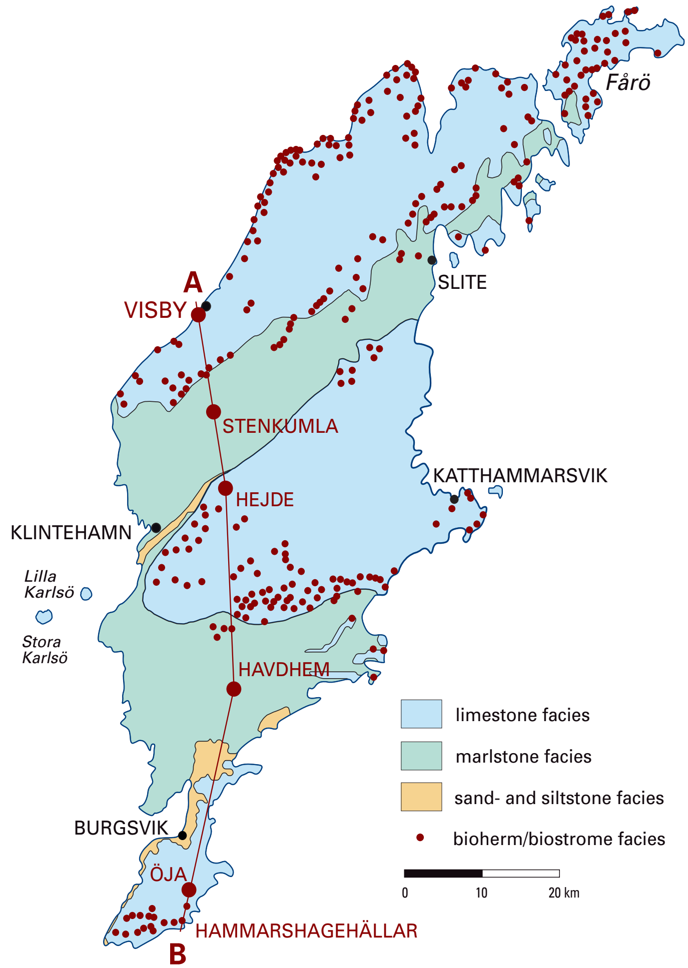
When the environment altered, owing to silting up or water turbidity caused by increased sediment discharge from land, the reef community was destroyed. When conditions once again became favourable for reef-building, the new reefs were formed further towards the south east, since silting up caused the displacement of the coast line – and thereby the optimal depth for reef formation – in that direction. Five such periods of reef formation occurred in the

Gotland area during the Silurian. These reef generations can now been seen as parallel northeast-southwesterly stretches of reef limestone.

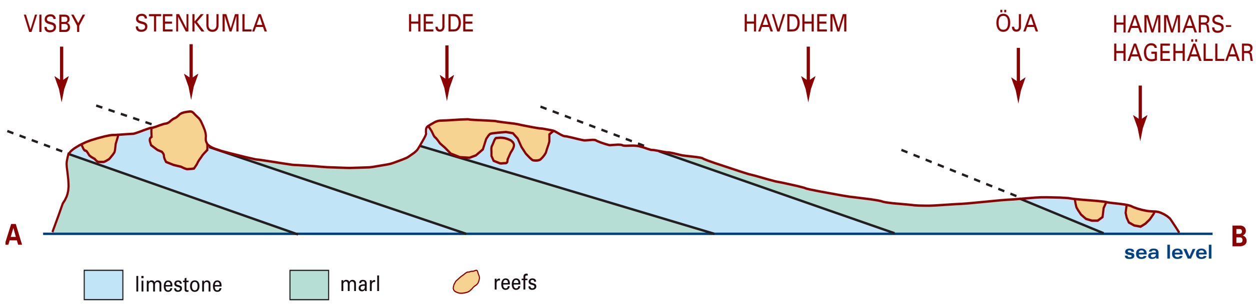
The reef generations on Gotland differ from each other in several ways. They have been divided into three main types, named after the locations from which they have been described: the Visby reef type is less than 10m² in area and is dominated by corals and algae. The Hoburg reef type is up to 100 m² and contains a large number of species; stromatoporoids, corals and calcareous algae are dominant reef builders here. The Holmhällar reef type is dominated by stromatoporoids and calcareous algae, but otherwise has few species. It is up to 1000 m² and is considered to be equivalent to today's barrier reefs, such as the Great Barrier Reef off Australia.

THE SEDIMENTARY ROCKS OF GOTLAND

A meticulous survey of the bedrock of Gotland was conducted by the geologist Johan Ernhold Hede at the beginning of the 20th century. The island had, however, been visited by a British geologist at an earlier date. Sir Roderick Impey Murchison, mainly known for having given the Silurian system its name, spent a couple of days on the island in 1845. He realised that the strata dipped gently to the south east, and concluded that the oldest rocks were in the north west of Gotland, whilst the youngest were in the south east.



Simplified map of the bedrock of Gotland and schematic cross-section showing the dip of the different sedimentary rocks. Note that the lower parts generally consist of easily eroded marlstone and elevated areas of resistant limestone (adapted from Eliason 1999).



Loose slab at cliff foot in Tunguhuvud, Fårö showing a typical fossil assemblage associated with a reef.

Mapping was delayed, however, owing to difficulties in interpreting the bedrock.

Hede divided the sediments of the island into 13 stratigraphic units, and each unit was named after a local place or parish. Obviously, considerable geological research has been undertaken on Gotland since then, but Hede's classification is still largely used to this day.

Lower and Upper Visby Formations

During the Llandovery, the first quarter of the Silurian period, calcareous clay was deposited in the Gotland area. This can now been found as a reddish marlstone in the sea along the north west coast of the island.

The oldest formations exposed on Gotland today were formed at the end of the Llandovery, and are called the Upper and Lower Visby Formations. These fossiliferous marlstones become increasingly calcareous towards the top of the sequences. In the Upper Visby Formation, the earliest reef-like formations can also be found. These reefs – evidence of shallowing water – have been interpreted as the result of isostatic uplift. The alternation of argillaceous (calcium-poor) and calcareous limestone is a frequent occurrence in the Gotlandic stratigraphy. A recent alternative interpretation of these cyclic changes is that global fluctuations in climate, which influence the temperature and chemical content of the sea, as well as the rate of erosion of the land, are responsible for the interstratification and the difference in faunal content of the argillaceous and calcareous strata.

The Visby formations are together 24 metres thick, and they can be seen in the lower part of the cliffs in the north west of Gotland. They are thin, horizontal bands of soft, blue-grey marlstone, with embedded nodules or lenses of grey limestone. The sediment is highly fossiliferous, and when the cliff wall crumbles, the well-preserved corals, brachiopods, gastropods, etc. are washed down onto the beach, where they can be collected with ease.

When the marls of the Visby formations were formed, intense volcanic activity was in progress both in the island arc situated south of the continent and in the north west, where the collision with the North American plate was just taking place. Ash from the volcanic eruption was spread over large areas. When the ash settled on the sea floor, the fauna there was probably wiped out. It has now been consolidated into light grey bentonite clay, and can be seen at several horizons in the marl. Bentonite is most easily discernible following rainfall. Under a knife-sharp horizontal boundary, the cliff is dark-coloured, due to dampness. Above, it is quite dry. Rainwater flows down in the cracks in the rock, but when it meets a bentonite bed, penetration is not possible, since damp bentonite swells and becomes dense. The water must find an alternative escape route out to sea along the top of the bentonitic band, then down the cliff walls.

The small, less than 10 m^2, reef knolls that occur in the younger parts of the Upper Visby Formation are dominated by tabulate corals and algae.

Högklint Formation

Resting on the marls is the protective cap of the harder Högklint Formation. These strata, roughly 35 m thick, are largely formed of more or less connected reefs, up to 100 m^2 in size, with surrounding layers of limestone. Stromatoporoids, corals and calcareous algae were the dominant reef-builders, whilst crinoidal limestone can be found along the sides of the reefs. The Högklint Reef stretched along the coastline in a SW–NE direction. This might indicate that the contemporaneous coast north of the area ran in the same direction, since the optimal depth for reef formation occurs at a specific distance from the land. The Great Barrier Reef in Australia is a present day example of a reef that runs parallel with the coastline. The youngest Högklint strata were deposited as inner offshore, shallow water sediments. The *Pterygotus* beds, in which fossils of sea scorpions and even scorpions have been found, are examples of these.

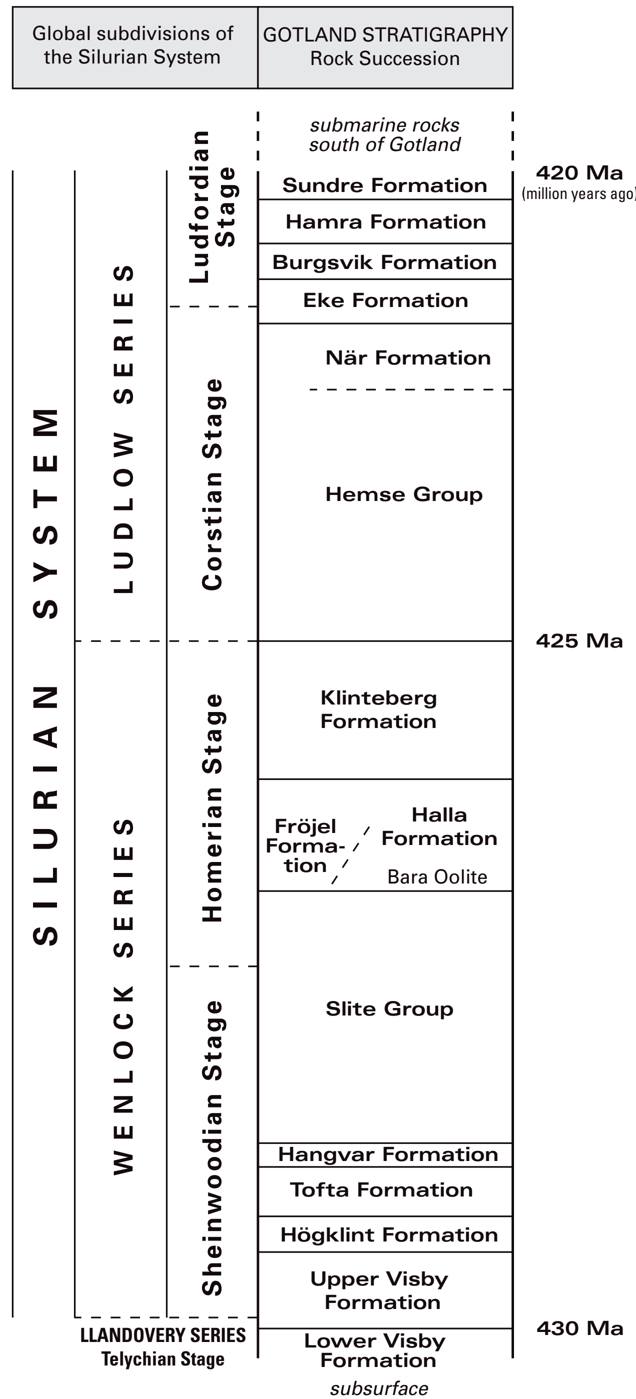
Tofta Formation

The next unit is the Tofta Formation. It is only 8 metres thick and has a limited distribution in northern Gotland. They also indicate a very shallow deposition environment, since they largely consist of algal limestone, a limestone comprising large calcareous nodules, a couple of centimetres in diameter, made up of a series of coatings around shelly fragments. The Tofta Formation might well be partly contemporaneous with the Högklint Formation.

Slite Group

The Slite Group reaches a maximum thickness of 100 metres, and is thus widespread in northern and central Gotland. It consists of a complex of several different types of limestone, formed in varying conditions; hence it is referred to as a group rather than formation. The stone industry in the north of Gotland quarries most of its stone from layers of thick-bedded, largely unfossiliferous limestone. These strata and the pure limestone of the Högklint Formation together form the areas of flat, rocky ground and the barren pine forest areas in northern Gotland and Fårö. The cement industry prefers marl-rich limestones. The marl-rich, often highly fossiliferous units of the Slite Group can be found in the southern and eastern parts

Succession and ages of major rock units on Gotland



of the area, and form the basis of the arable soil of the plains of Roma. The Slite Group is considered to have been largely deposited on a steadily-rising carbonate platform by periodic storms. In the Slite vicinity and along the coast to the north runs a stretch of hard reef limestones that has produced an undulating terrain, and the only archipelago Gotland has to offer.

Halla Formation

Overlying the southeastern parts of the Slite Group is a 15 metre thick sequence deposited in shallow water. The lowermost part is called the 'Bara oolite' and is a white so-called oolitic limestone with very small reef knolls enclosed. Above are brownish argillaceous limestones with reefs, and at the top there are grey argillaceous limestones and marl. Towards the southwest the Halla Formation thins out, disappearing completely in the Klinte area to return to view in the form of reef limestone and stratified limestone on the Karlsö islands.

At the top of the Halla Formation lies the 25 metre thick Mulde Brickclay Member, called the Mulde Beds or Mulde Marl in the older literature, since this homogeneous strata unit consists of bluish-grey layers of soft marlstones, alternating with thick layers of grey to blue-grey, argillaceous, compact limestones. The marl is rich in well-preserved fossils, mainly brachiopods and tabulate corals. Small trilobites, rolled into a ball, are not unusual, although the location that was by far the best for trilobites on Gotland, where the Mulde brickyard once lay, has now been filled in. The Mulde Brickclay Member is best viewed in the cuttings along the coasts of Fröjel and Eksta. The strata thin out and become more limestone-dominated towards the north east. At Klinte parish church they are less than 1 m thick and overlie the rest of the Halla Formation; they disappear completely about 5 km north east of the church. The Mulde Brickclay Member was probably formed in a similar deposition environment to that of the Visby formations. Earlier interpretations based on the depth of water will most likely be revised in favour of explanations based on variation in supply of sedimentation in connection with large-scale changes in the climate.

Klinteberg Formation

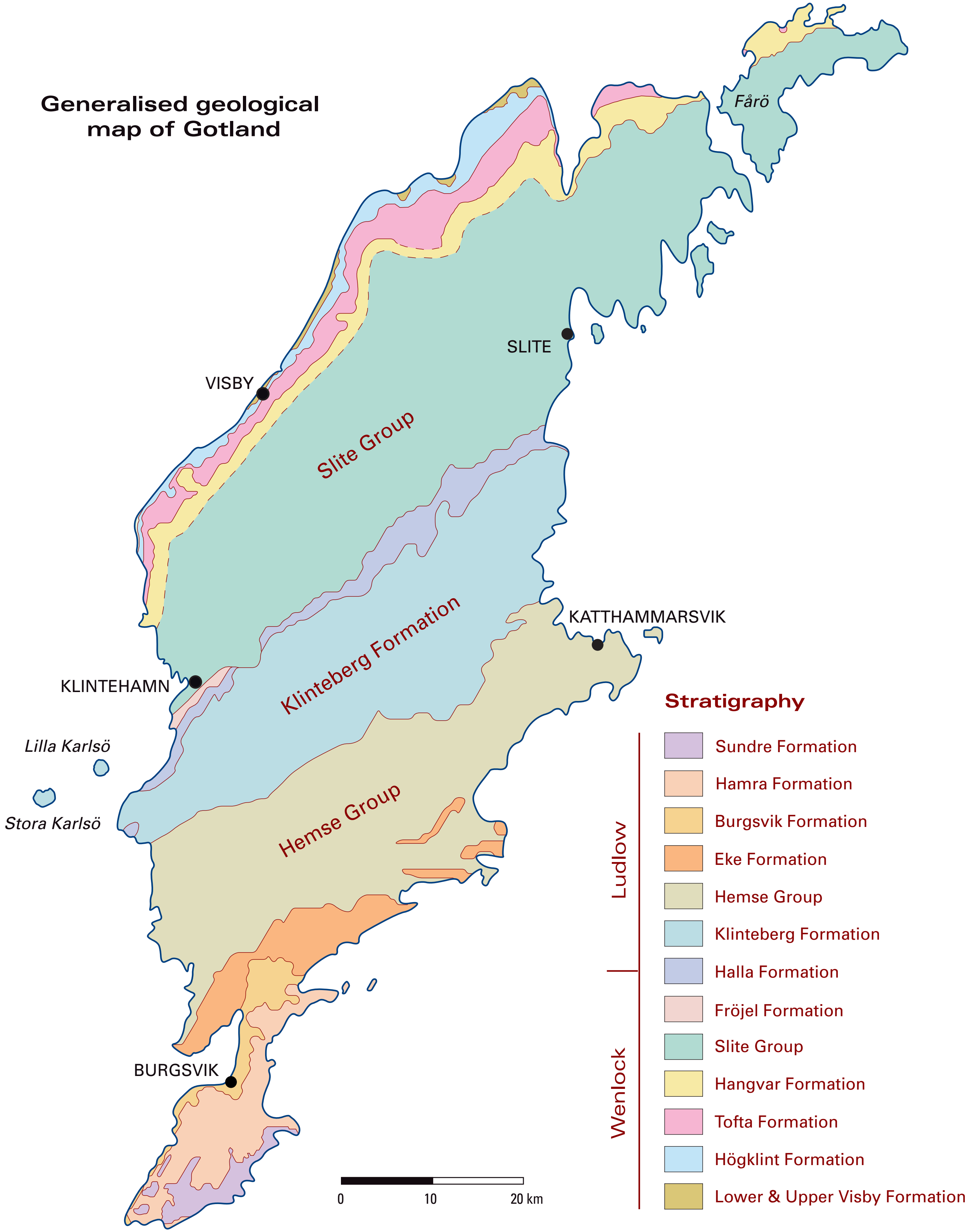
In the southwestern part of its range zone, the Klinteberg Formation is developed as reef limestone consisting mainly of stromatoporoids and tabulate corals. Thick layers of coarsely fragmented crinoidal limestone intercalate the reefs. Towards the north east the reef-predominant limestone transfers to a sequence consisting of different stratified limestones, rich in calcareous algae, and with a large number of the brachiopod *Conchidium biloculare*. The Klinteberg Formation is 70 metres thick, and the highest elevations of central Gotland can be found in this unit.

Hemse Group

The 100-metre thick Hemse Group, like the Slite Group, consist of limestones towards the north, and soft marlstone towards the south. The limestone sequence comprises different types of stratified limestone and reef limestone. The Östergarn area is composed of enormous reefs, mainly consisting of stromatoporoids.

Crinoids are abundant in the limestone area, just as bivalves, including *Ilionia prisca* and the large

Stratigraphic map of Gotland (adapted from Eriksson & Calner 2005 and Erlström et al 2009).


Generalised geological map of Gotland
Fårö
SLITE
VISBY
Slite Group
KATTHAMMARSVIK
Klinteberg Formation
KLINTEHAMN
Lilla Karlsö
Stora Karlsö
Hemse Group
BURGSVIK
0
10
20 km
Stratigraphy
Ludlow
Wenlock
Sundre Formation
Hamra Formation
Burgsvik Formation
Eke Formation
Hemse Group
Klinteberg Formation
Halla Formation
Fröjel Formation
Slite Group
Hangvar Formation
Tofta Formation
Högklint Formation
Lower & Upper Visby Formation

Megalomus gotlandicus, can be found in abundance in some other areas, as in the shell deposit at Katthammarsvik harbour. In the south, the limestone is replaced by reefs and a fairly homogeneous marlstone sequence of thin layers, nodules and lenses of limestone. Graptolites, otherwise rare on Gotland, can be found in the marl.

Eke Formation

The Eke Formation is characterized by an abundance of calcareous algae, indicating a shallow depositional environment. The strata, no more that 15 metres thick, consist of bluish-grey argillaceous limestones and micaceous marls. Crinoidal limestone, marlstone and argillaceous limestones with small reef knolls, the so-called *Rhizophyllum*-limestone, can be found on the isolated elevations of the Eke Formation in the north east, as at Lau backar.

Burgsvik Formation

The Burgsvik Formation, reaching a maximum thickness of 50 metres, is exposed along a narrow strip, mainly in the southernmost part of the west coast of Gotland. It stretches up to Grötlingbo, with a couple of isolated areas, known as outliers, at Närsholmen and at Burgen in Burs. The Burgsvik Formation mainly consists of fine-grained calcareous sandstone, often intercalated with thin beds of bluish clay. In many places, the sandstone is overlain by oolitic lime-

View to the north from top of Hoburg cliff.

stone or alternating layers of sandstone and oolites. In the northeasterly outliers, which are no more than 8 metres thick at most, the strata mainly consist of oolitic, arenaceous, partly conglomeratic limestones, (containing large pieces of rounded fossils), as well as reef and crinoidal limestones. The sandstone is poorly fossiliferous but shell deposits, mainly of the bivalve *Pteronitella retroflexa*, can be found here and there. Sedimentary structures, such as cross bedding, (inclined at steep angles to the dip of the strata), and ripple marks are usual, as well as trace fossils of burrowing animals. In the sandstone, some extremely interesting finds have been made of fin-spines, armour plates, teeth and scales from the rare spiny dogfish (acanthodians) and ostracoderms that lived here during the Silurian. The oolitic limestone, as opposed to the sandstone, is highly fossiliferous, including brachiopods, bryozoans, bivalves and fragments of the large trilobite *Homalonotus*.

When the Burgsvik Formation was deposited, the continental collision between the North American and North European plates was reaching its end and the Caledonides, the mountain range resulting from the collision, were being pushed up in the north. Erosive powers were already at work, and eroded products from the mountain range were washed out into the sea, some of them to form these sandy deposits in the area of Gotland. The sediments were deposited in shallow water close to land, partly as beach sediment. Subsidence structures bear witness to how movements in the earth's crust caused the collapse of

the sediment before it had lithified. In the Burgsvik sandstone and oolite, spores of terrestrial plants have been found, representing some of the oldest evidence of the plant conquest of land.

Hamra Formation

The basal part of the 40 metre thick Hamra Formation contains algal limestone, succeeded by argillaceous limestones and capped by reef and crinoidal limestone. Thinner layers of Hamra limestone can be found in the outliers at Burgen and Närsholmen, where they have developed into reef limestone.

Sundre Formation The Sundre Formation forms the youngest parts of the bedrock of Gotland. The strata, no more than 10 metres thick, consist of stromatoporoid and algae-predominant reef, surrounded by crinoidal limestone. The beautiful, red, glittering sea lily limestone has been quarried under the name of Hoburg marble and used for sculptures and decorative purposes in buildings such as the churches on Gotland. Only small quantities of the stone thus remain, although beautiful specimens can still be found amongst the rubble that has been discarded in the marble quarry at Hoburgen, for example. The sea stacks along the south and southeast coasts, as at Hoburgen and Holmhällar, are of sculpted Sundre reef limestone, which was deposited during early Ludlow. Sedimentation must, however, have continued in the area, since contemporaneous cracks in the sediment have been filled with calcareous sediment that has proved to be younger than the rest of the Sundre Formation. However, most of these younger beds were worn away by erosion at a later date.

Beneath the Silurian deposits there are older beds of limestone and sandstone, formed during the Ordovician and Cambrian. This entire block of sediment dips to the south-east, causing the edge of the Ordovician beds to rise up and form the island of Öland, while the Cambrian beds are exposed along the coast of Kalmar and at certain places along the west coast of Öland.

Gotland Fossils

More than 2000 fossil species have been described from Gotland, but because the only preserved organisms are mostly those that had mineralised shells or skeletons, this figure does not reflect the probable original diversity of life during the Silurian Period. We have very little knowledge of the probably large numbers of soft bodied animals, and plants such as algae, that lived here in the shallow marine environments of that time; soft tissues generally decay rapidly and are very rarely preserved in the fossil record. Trace fossils from the activities of soft bodied organisms, such as burrows and digging tracks in the sediment, are mostly the only proof of their existence. Algae were certainly very common, but only those that produced lime in their tissues – the calcareous algae – were preserved commonly, for example as substantial components within reef bodies where they performed an important function in binding sediments together. However, microscopic spores from algae and even from primitive land plants have been found on Gotland.

Typical fossils found in the bedrock of Gotland: A – Stromatoporoid, B – *Halysites* coral, C – Rugose coral, D – *Orthoceras* cephalopod, E – Rugose coral, F – Gastropod, G – *Heliolites* coral, H – Bivalve *Pteronitella retroflexa*, I – Gastropod *Loxonema*, J – Gastropod, K – Brachiopod *Leptaena*, L – Rugose coral, M – Trilobite *Calymene*, N – Brachiopod *Janius*, O – Brachiopod *Visbyella*, P – Ostracod *Hermannina*, Q – Broken crinoid stems, R – Broken crinoid stem, S – *Coenites* coral, T – *Palaeocyclus* rugose coral. Photo: R. Hejdström.


A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T

So, what kinds of fossils are most common? Of course this varies between different places and in different kinds of rock that reflect different original environments. Reef limestones are built mostly from robust, skeletal animals such as colonial corals and stromatoporoids, while the marlstones represent a relatively soft bottom, low energy marine environment in which brachiopods, trilobites and other bottom-living organisms were generally more abundant. Some fossils can be so common in certain sediments that their fragmental remains alone build up whole beds of limestone. For example, the sea lilies (crinoids) lived crowded in some beds and on reef slopes in such huge numbers that their skeletal remains now form coarse fragmental limestones that are sometimes referred to as marble, such as Hoburgsmarmor and Karlsömarmor – used especially as decorative and building stone.

The most common fossils in the reef limestones are stromatoporoids. These compact, conical, sub-spherical or sub-laminar skeletons were built up in concentric calcareous layers by a sponge-like tissue; they are also widespread in bedded limestones. Stromatoporoids have a particular place in Gotland folk history. In the burning of lime the inner hard parts of the fossils were commonly left unaffected by the burning, and the spherical remains resembled the skulls of cats, from which the stromatoporoids derived their popular name as 'kattskallar'.

The sea-lilies, or crinoids, were very common in Silurian tropical seas. These echinoderms were also associated primarily with reefs, anchored to the reef slopes or sea floor by a long, segmented flexible stalk, which supported a cup shaped body (theca). Five flexible feather-like 'arms' diverged from the theca as the food gathering apparatus. After death the soft tissue decayed and the many components of the skeleton disintegrated, to be incorporated as common components of limestone sediments.

Corals are naturally associated today with tropical reefs, but in the Silurian different types of corals were equally common in the off-reef, soft bottom environments. There were two main groups of Palaeozoic corals. Rugose corals were mostly solitary forms, generally with conical skeletons (theca) whose distinctive shape has given them the popular name 'tomteluvor' (Santa caps). One particular species however is quite different and distinctive, occurring only in the oldest beds along the northwest coast; this is *Palaeocyclus*, a small button shaped coral that has the popular name of 'knappkorall', and it is an important indicator of late Lower Silurian age in rock successions across much of the present North Atlantic region.

Tabulate corals were colonial forms, living in reef environments and on the soft seabed and whose skeletons vary in size from a few centimetres to tens of metres. Best known examples are the chain coral *Halysites* together with *Favosites* and *Heliolites*, all with distinctive shapes of the skeletal openings.

Brachiopods (often referred to as Lampshells) are bivalved shells, of which about 200 species are known today, but over 30 000 fossil species are known from Palaeozoic rocks and they are very common on Gotland. The two valves are of unequal size, with the larger, or pedicle valve having a distinctive aperture in the beak through which a soft fleshy stalk emerged (the pedicle) to anchor the animal to the sea bed.

The Bryozoa ('moss animals') are small colonial organisms that commonly live attached to other animals, plants or other objects. Some of the colonial skeletons have a superficial resemblance to tabulate corals, but the individual chambers are much smaller.

The Bryozoa are possibly related to the brachiopods. They are very common in limestone and marlstone sediments on Gotland, although generally fragmented.

Molluscs are well represented among the Gotland fossil faunas. The most common group is the Gastropoda (as marine 'snails'), found preferentially in marlstones. They are fairly easily recognised by their spiral shells, some as slender vertical spirals and others as more robust, horizontally coiled and generally larger forms as in the genus *Euomphalopterus*. Bivalvia ('lamellibranchs') are less common, but can be found occasionally in mussel beds at some horizons. Cephalopoda – essentially as fossil 'squids' belonging to the genus *Orthoceratites* – are not uncommon in the Gotland rocks, although mostly as a few chambers of the originally longer, straight tubular shells; many specimens retain detail of the concave chamber walls (septa) that were secreted as the animal grew.

Trilobites are an extinct group of arthropods, common in the Palaeozoic seas but which became extinct at the end of the Permian Period. They are seldom found as complete specimens, but they are fairly common throughout the Gotland sequence. Moulted segments of the body are not uncommon at many levels, and heads and tails are easy to recognise. The furrows that divide the body into three longitudinal segments are equally well defined in most specimens.

Apart from the main groups of fossils outlined above, there are various other groups known but which are rare or require specialist techniques to extract them as microfossils. For example, primitive fishes are known from fish scales, conodonts are part of the tooth apparatus of fishes, there are sea scorpions (Eurypterida), mussel shrimps (Ostracoda), early plant spores, and primitive molluscs known as Monoplacophora. It is remarkable to realise that when the rocks and environments of Gotland were being formed over 400 million years ago, all known major groups of organisms (phyla) that exist today were already in existence. Gotland provides abundant fossil evidence in support of this understanding of the development of life on earth.

Later Geological Periods and the Ice Age

Once Scandinavia and north-western parts of the Baltic basin had risen above sea level to form a large area of land at the end of the Caledonian orogeny, a long time passed during which Gotland has no sediments and thus no historical geological record of the area and its life. It was not until the very recent Quarternary period from 2.6 million years up to the present day, that more sediments were deposited on Gotland; dominated by the inland ice ages as is typical for northern latitudes in this period. These glaciations took place on probably six occasions, each lasting about 100 000 years. During the ice ages, shorter periods of warmer climate did occur – known as interstadial periods, when even vegetation colonised the areas from which the ice had temporarily retreated. Each time the glaciers crushed, ground, and transported the bedrock, traces of previous glaciation were largely wiped out, meaning that we are most knowledgeable about the latest glaciation.

The latest glaciation took place during the Weichsel Ice Age, that lasted until 10 000 years ago. At its greatest extent, glaciation stretched right down to Berlin with an ice-mass several kilometres thick. The enormous weight depressed the earth's crust by about 800 metres, and when the glacier began to thaw, it started to rise back to its normal position. This isostatic rise is still in progress in large parts of Scandinavia, albeit at a significantly slower rate.

Since an enormous bulk of water was locked up in the inland ice, the sea water level was over 100 metres lower than today, and Öresund and Stora Bält were still dry land, when the ice retreated from the south of the Baltic Sea area. Glacier water from the retreating ice mass filled the Baltic basin, and was dammed by the ice-front in the north and the newly-formed dry land areas in the south. Since there was no outlet to the oceans, the surface of the Baltic Glacial Lake rose at a higher rate than the sea level, until the thawed ice-front passed the northern tip of the Swedish mount Billingen 11 500 years ago. The glacial lake was then drained into the newly formed connection with the sea, whereupon the water level sank by 25 metres.

The ice first started melting in fluctuating climatic conditions. Temporary ice sheet thrusts sometimes interrupted the melting process, making the process more complicated than described here.

The saline sea stage that succeeded the Baltic Glacial Lake is called the Yoldia Sea, after the glacial sea bivalve *Yoldia arctica* (now known as *Portlandia arctica*) that can be found in the sediment from this time. Land elevation in the ice-free areas was now swift, soon equalling the rise in sea level. The Baltic Sea basin was again cut off from the ocean owing to land elevation in central Scandinavia about 10 700 years ago. This stage has been called the Ancylus Lake, after the freshwater gastropod *Ancylus fluviatilis*. Contact with the sea was again established 10 000 years ago via the Danish Sound, forming a sea called Littorina Sea after the littoral shell *Littorina littorea* that can be found in its sediments. The post-glacial warm period occurred at this time, and people living as hunter-fisher-gatherers became increasingly widespread in Scandinavia, as well as on Gotland. As the gradual elevation of the land diminished the size of Öresund and Stora Bält, salinity slowly decreased until we eventually reached the brackish water stage that prevails in the Baltic Sea today.

Quarternary Deposits

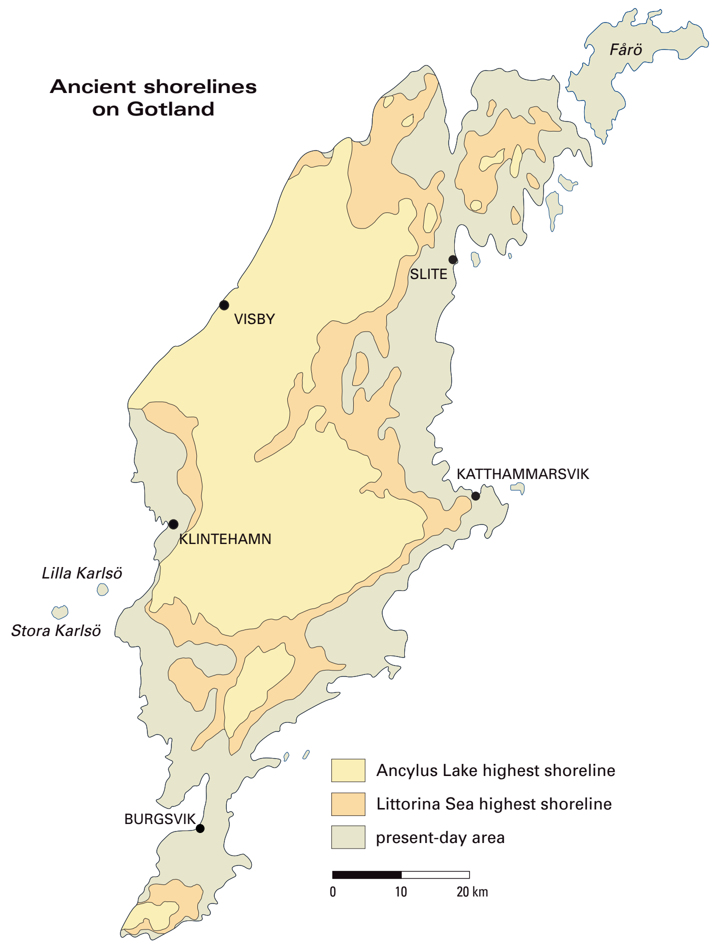
The inland ice deposited the loose soil cover of the Scandinavian and Baltic countries. The cold climate at the beginning of the Ice Age meant that the snow in the north did not thaw away, but accumulated in glaciers that increased in size and spread out further and further away from the mountain areas. The ice sheet was in constant motion and its enormous weight provided forces that ground and smashed the bedrock in its southward path. With increased pressure, the ice at the very bottom melted, helping the ice mass to slide more easily on its base. The unevenness of the bedrock with elevations and depressions caused constant changes in pressure. When pressure was eased on the leeward side of a hillock, the basal ice froze again, and the material shattered by the ice and mixed with the icy slush then became embedded in the ice and followed the movement of the ice mass. In this way the ice could transport large boulders, stones and gravel for hundreds of kilometres. The embedded material could act as abrasive particles, scouring the rocks beneath as the ice surged forward, producing the grooves that indicate the direction of movement of the ice. When the climate gradually became warmer, the ice melted at the edges at a quicker rate than it expanded in the north, leading to the deposition of the embedded material. This unsorted sediment of boulders, stones, gravel, sand and clay is called till.

On the sunlit surfaces of the shrinking ice mass, a flow of melt water was formed. This plunged down cracks in the ice where it collected to form glacial streams that flowed out to the snout of the glacier. The sediment in the ice followed the strong currents of the streams, to be deposited at the bottom of the cracks as the current velocity decreased, thus sorting the material according to grain size. When the glacial stream finally reached the snout of the glacier and the flow abated, sand was deposited in a delta outside the snout of the glacier. Clay particles, the finest material, were kept in suspension until all movement ceased, when they were deposited as a clay sediment on the bed of a glacial lake. The results can be seen today as glacial stream deposits, such as eskers and outwash plains, as well as varved (finely layered) clay deposited by the glacial lake.

LANDSCAPES OF GOTLAND TODAY

The landscape of Gotland has been formed through different processes during several phases. The large scale forms of today's landscape were created already during the time when the bedrock was a soft bottom sediment in a tropical near shore sea 420–430 million years ago. The marlstone rocks tend to be easily eroded and form flat-lying areas, while the pure bedded limestones and reefal units are much more resistant. Owing to the alternation of these rock types described above, the topography of Gotland is thus broadly divided into five regions: the hard limestones form elevated areas in the north, middle and far south of the island, separated by two large low-lying areas that lie either side of the central elevated region.

Over millions of years following the sedimentation on the seabed the sediments were lithified, and subjected to the erosive force of water and wind over millions of years. Movements in the crust also affected the Baltic region in other ways. Earthquakes created faults and cracks formed in the bedrock. In the bedrock west of Gotland there are traces of several faults. These have formed gorges in which rivers flowed at certain times, which then continued to erode the bedrock. Gotland's north-west cliffs are a result of these events. The entire island is also traversed by cracks and many deep bays are formed by erosion of weaker fracture zones in the bedrock.



Showing distribution of beach ridges that can be used to reconstruct former coastlines through time (adapted from Eliason 1999).

Coastal cliffs at Sigsarvestrand, NW Gotland.

THE BALTIC SEA AND THE SEA COAST

Gotland is, like all other islands, heavily influenced by the surrounding sea water. The climate is controlled in part by water temperature. Spring is delayed by the cold water mass, which on the other hand, once it has been heated, prolongs the mild autumn. The surrounding sea is also a barrier to migrating species. This has given Gotland a rather poor but interesting fauna developed in isolation from other populations.

The Baltic Sea is a young sea. When the ice began to retreat about 15 000 years ago, the Baltic basin was filled with water from the melting ice. The Baltic Ice Lake was established. This first stage in the development of the Baltic Sea was replaced by alternating salt water and freshwater stages until today's brackish water stage. Characteristic of this young sea with low salinity is low diversity, with very few brackish water species. Instead, freshwater species and marine species coexist, but under physiological stress, while they are not really adapted to the low salinity. Therefore, the marine species in the Baltic Sea are generally smaller in body size than they would have become if they lived in saline water. On the other hand, marine animals living in this environment are often very successful in terms of number of individuals, since they have little competition from many other species.

The Coast

Gotland is for many tourists equated with beautiful, often dramatic coastal sceneries. The 550 km long coastline (770 km long if you include Fårö, Stora and Lilla Karlsö and other fairly large islands around Gotland) varies depending on the bedrock, soils and landforms. It consists of alternating barren shingle beaches, steep cliffs, soft inviting sandy beaches and flat bird-rich beach meadows.

The broad outline of the coast is primarily formed by large-scale fault movements and river erosion in Palaeogene and Neogene time, long before the Ice Age. The shape of the coast is also determined largely by the nature of the rock. Where bedrock is composed of hard bedded limestone and reef limestone the coast is rocky, often with sharp cliffs. Where bedrock is composed of softer marlstone the coast is flat.

Coastal Cliffs

The western and north-west coast, from Gnisvärd in the south to Hallshuk in the north is about 50 kilometres long and is dominated by up to 40 metres high sharp cliffs. The uppermost part of the protruding cliffs consists of resistant reef limestone. In between them, the upper part of the cliff consists of thick bedded limestone. Underneath, there is the softer fine layered marlstone. The marlstone is constantly exposed to the erosion of the sea waves, ice and rain water. When enough material has been hollowed out from the cliff, the overlying limestone collapses and falls down on the beach, forming piles of rocks. Huge boulders of reef limestone are particularly common underneath overhanging cliffs. Weathered material from the marlstone forms screes at the foot of the cliff. The beach is covered by shingle, often forming beach ridges.

Outside the shoreline the water often covers a flat rock surface. This bedrock shelf, an underwater cliff, extends, at a depth of more than half a metre, from 20 to 200 metres out from the coast. At this point the edge of the underwater cliff steepens into a drop of several dozen metres. At certain wind conditions, when there are strong onshore breezes, dangerous underwater currents can form outside the cliff edge that can trap people bathing.

A wedding ceremony taking place in the Folhammar rauk area, eastern Gotland.

Colossal, ring-shaped depressions, so-called ‘Philip structures’, that are visible on the top surface of the underwater cliff all along the northwest coast, indicate the former existence of reefs. These structures, most clearly visible from the air, are actually parts of limestone beds, which once were pressed down by the weight of overlying large reefs, which have now been eroded away.

Coastal cliffs, albeit modest in height, can also be found along other parts of the coastline. In Eksta for example, the Mulde Brickclay Member forms a low cliff along the coast. Wherever the coastal bedrock consists of pure limestone with reefs, as it does at the northeastern, eastern and southernmost Gotland coastline is rocky, sometimes with sharp cliffs.

Sea Stacks

In many places along the coast, where the limestone cliffs meet the sea, the water has not been able to wear down the cliff in its whole. The resilient reef limestone remains as stone statues – sea stacks or ‘raukar’. These often occur in groups to form sea-stack fields. One can often see that all stacks within a group reach the same height, which shows the original cliff top level before the water erosion. The largest sea stack field is found along Digerhuvud on the north-west coast of Fårö. Langhammarshammar, also on Fårö, is the most famous and photographed sea stack field. Other scenic sea stacks along the coast can be found in Lickershamn, Lergrav, Kyllaj, Folhammar, Holmhällar and Hoburgen.

Shingle Beaches

Shingle beaches are the most common type of beaches on Gotland. These are found beneath the coastal cliff and along other stretches of the coast of Gotland, where the bedrock consists of hard limestone. Rubbles of limestone from the bedrock are mixed with igneous rocks and sandstones transported to the island by the inland ice. They form beautiful sea walls that may extend far up on land. The ridges far-away from the coastline were thrown up by storms during earlier stages of the Baltic Sea, when the water level was higher. As the water retreated, new beach ridges washed up below and parallel to the elderly. Such systems of beach ridges can be found in many parts of the island, sometimes they are completely covered with forest.

Since all soil is washed away from the gravel, very few plants can live in the arid and nutrient-poor environment of a shingle beach. Seaweed ridges washed up on the beach, however, have a nutrient demanding flora including nettle, curled dock and various oraches. In the past seaweed, called *släke*, was used as fertilizer on fields. Despite the barren environment, many birds breed here.

Sand Beaches

Sandy beaches are found in bays along the Gotland coast and the whole coast of northeastern Fårö. The sand, which largely consists of quartz grains, originates from eroded rocks on the Scandinavian mainland, and was initially transported to the island by the

Sea shore meadow at Falluden, eastern Gotland.

inland ice. The sand was deposited in the bays as the energy of the water transporting it decreased. Sand deposited by the large glacial rivers during the ice melting period forms widespread sandy areas, such as the northern Fårö, Salvorev and Gotska Sandön.

Sandy beach environments are harsh. The waves keep the sand in constant motion and it is difficult for land plants and algae to find 'foothold'. Further up the beach, where waves do not reach, some herbs such as sea sandwort and sea rocket, grow. Both are adapted to the dry sandy environment by having fleshy leaves with a relatively small area to prevent evaporation. On top of the dune the grasses lyme-grass and marram are growing. Their deep root system makes them resistant to sand drifts. If they are buried by sand, they quickly shoot up new shoots to the surface.

Sea Shore Meadows

Sea shore meadows are found along the flat coastal areas of Gotland, particularly in the southeast and southwest of the island. Here the bedrock consists of softer marlstone, eroded by former glaciers, and now covered with a clayey soil. The beach meadows used to be important pasture and hayfields. Haymaking and pasture kept them open, thus favouring the flora and fauna. Now EU-subsidies helps the farmers to keep these valuable coast areas open. Sea shore meadows are self-fertilizing by floods washing up nutritious seaweed on the flat beaches.

The flora of the sea shore meadows is very diverse. Many plants are adapted to withstand grazing, others are capable of tolerating high salt concentrations.

Hejnum hällar alvar in June.

After repeated floods, salt concentration can be very high in the hollows, where trapped seawater evaporates and leaves behind salt.

The beach meadow is a coastal biotope where a lot of birds thrive. In the fine-grained and nutrient-rich soil on the shallow bottoms many bugs live that attract waders and ducks.

The sea shore meadows on Gotland represent a fifth of the total area of sea shore meadows in Sweden.

THE INLAND

Forests

Nearly half of Gotland's surface is covered by forests. Coniferous forests, with pine as the dominant tree species, are most common, while areas with deciduous forests are relatively modest. If you compare a map of forest distribution with a geological map you will see that large coniferous forests grow on areas of harder limestone. This bedrock is covered with lime-rich till, which favours pine ahead of spruce that are not comfortable with a high pH, but require more acidic soils.

Limestone Pavements/Alvars

In the higher lying areas of Gotland the bedrock consists of hard, resistant limestone. The soil cover is very thin or absent. Trees and shrubs have difficulties in establishing themselves on the rocky ground, which therefore remains more or less open. Grazing animals, especially sheep that live outside all year around and even eat woody plants, have helped to

keep the landscape open for centuries, and a special habitat – alvar – has been developed. *Alv* is an ancient word describing land that is useless for cultivating. In Sundre parish on southernmost Gotland, in File hajdar, Hejnum hällar on northern Gotland, and on Östergarnslandet in the easternmost region there are large continuous areas of alvars. Large parts of Fårö also have examples of how a long tradition of grazing shaped the landscape, with groves of pines and cropped juniper bushes in meagre grassland.

The absence of shading trees and the thin, sometimes completely non-existent soil layer makes the rocky grounds/alvars extremely dry in summer. Many of the plants have become adapted to survive the heat and aridity of the summer. A number of plants are annuals, and blossom in spring before the arrival of the drought. Stonecrops have thick, succulent leaves which store water in rainy periods. Other plants, like *Vincetoxicum* have leathery leaves, which minimise transpiration.

In winter, when temperatures fluctuate around zero, alternating freezing and thawing cause movements in the ground, which can sever roots. Some plants on the limestone plateaux have adapted to this feature and have developed strong roots; these include the common rock rose, wild thyme and *Globularia*.

Rock outcrops are traversed by cracks primarily caused by structural movements in the bedrock. The cracks become expanded secondarily through chemical dissolution by carbonic acid in the seeping rainwater. This is the same process that formed karst caves such as Lummelunda cave. The cracks are often filled with weathering soil on which many plants can establish. They also preserve moisture and provide a shady habitat for plants such as the hepatica.

The limestone plateaux in the north of Gotland are covered with sparse pine forests growing in clusters wherever there are accessible cracks or a superficial soil cover, enabling the trees to take root. These areas thus display a mosaic of clusters of trees, juniper bushes and treeless areas with exposed tabular limestone slabs. The limestone plateaux of southern Gotland are more open, often coated with thin layers of stony soils.

In former times, fields, meadows and pasturelands close to the farms were fenced off. Ground further afield was declared commonland, and used jointly by several farms for grazing. This outlying land often comprised meagre pastureland, forest and tabular limestone rock. The long-term grazing of larger areas of the limestone plateaux led to the development of a rich flora and fauna adapted to grazing. When grazing diminished in intensity, the land gradually became overgrown, mainly with juniper and blackthorn, and the grazing-adapted plants died out, thus grossly reducing the number of species. Grazing is necessary for the preservation of the variety of flora and fauna on the limestone plateaux.

Changes in land use on Gotland have dramatically altered its original character. Most decidous forests are overgrown meadows, for example. The water bodies of Gotland have also been significantly altered. Many of the once common wetlands have been drained to make way for farmland; and rivers and streams have had their original courses deepened and straightened. Of the remaining wetlands, the largest are the Bäste and Tingstäde lakes, both in the north of the island.

HISTORY AND CULTURAL HERITAGE OF GOTLAND

Stone Age (About 7400–1800 BC)

Gotland was populated early in human history. Some of the oldest traces of humans in Sweden are 9400 year-old skeletal remains from the Stora Förvar cave on Stora Karlsö. The first people to inhabit Gotland lived on hunting, fishing and gathering. There were many seals, fish, poultry and edible plants. Stone Age Gotland was smaller than the island today, because sea level was significantly higher. The climate was slightly warmer than today and the landscape consisted of open moorland and forests of pine and deciduous trees. There were many lakes and streams. About 2000 years BC, agriculture became the main source of living and income. Around the coast of Gotland there are several large settlements from the Neolithic era.

Bronze Age (About 1800–500 BC)

Bronze, an alloy of copper and tin, was introduced to Gotland from Central Europe in the form of manufactured articles, mostly weapons. Animal husbandry and agriculture developed, but hunting and fishing continued to play an important part in the supply of food. More and more land was cleared and cultivated in the inland.

A society based on animal husbandry and agriculture, and with a more stable residence of population, required more organisation, as well as trade and craftsmanship of the precious metal. Even the large and impressive tombs, large cairns, and ship settings, suggest that society was divided more socially than before. Together with Scania, Gotland is the region in Sweden where most finds of objects from the Bronze Age have been made.

The Gannarve stone ship, 29 metres long and up to 5 metres wide, dates back to Late Bronze Age. Photo: T. Bauert.

Iron Age (About 500 BC–1050 AD)

The Gotlanders learned to use iron from about 500 BC, and became skilled blacksmiths. Iron was cheaper and more readily available than bronze. Arable and livestock farming were still the most important economies.

The climate deteriorated in the early Iron Age, which meant that farmers had to keep animals indoors and feed them during winter. Meadows were cleared to provide hay and leaf fodder. A landscape developed that was dominated by fenced meadows, pastures and small croplands near the farm. The animals grazed in the woods and on the limestone pavements. The cultural landscape that began to emerge during the Iron Age remained until the 19th century, and many remnants are still preserved. Large longhouses with heavy stone foundations were built on the farms. In many places today one can still see the remains of house foundations from the early Iron Age. They are found usually in the meadows. Together with the foundations there are often remnants of fences and burial grounds, which had eventually been built adjacent to the farms.

During the latter part of the Iron Age, in the Viking era (750-1050 AD), trading was an increasingly important source of revenue for the island. Trade and crafts were concentrated in the island's many harbours. Gotland's strategic position in the Baltic Sea made it easy for the islanders to transport the goods, and many of the most important trade routes at this time through the Baltic Sea passed Gotland. Inscriptions on picture stones and other objects tell of some of the islanders who made long journeys to distant countries. The travels resulted in huge profits, as evidenced by the many silver treasures found on the island. The increasingly extensive agriculture resulted in a slight surplus of produce. Barley, rye, oats, flax and hemp were cultivated. Sheep and goats, pigs, cattle, horses and chickens were reared.

Middle Ages (About 1050–1500 AD)

During the first centuries of the Middle Ages the importance of Gotland in the Baltic Sea trade continued to grow. At first, the rural population accounted for the majority of the trade, but during the 12th century the Viking Age harbour of Visby became the island's commercial metropolis. A large influx of foreign merchants contributed to the growth of the city as it grew in size and importance in international trade. It focused on trade between Novgorod in Russia and Western Europe. The trade was organized in the so-called Hanseatic League, which extended over the Baltic region, Norway, England, Netherlands and Belgium. Trading brought great prosperity both to Gotland's 'travelling peasants' and to the merchants in Visby.

The products that made Gotland so successful in the trade were not all produced on the island but were brought largely from the eastern side of the Baltic Sea. In Novgorod, islanders from Gotland had already built a trading site in the 12th century – Gutagård, where Russian hunters supplied furs, and from the Baltic area was bought beeswax, a coveted article for church people in the whole Christian world, where it was used for producing wax candles. In the Middle Ages, skilled stone-cutters on Gotland produced quantities of highly artistic baptismal fonts. Over a thousand fonts were exported to churches through the entire Baltic Sea region. The revenue from trade led to the construction of magnificent stone buildings

Excerpt from the map *Livonia vulgo Lyefland*, 1648.


FINLANDIÆ
ALANDIA
Stockholm
Sinus
Livonicus
Daghö
Ösel
GOTTLANDIA

both in Visby and in rural areas, and especially in the building of over one hundred beautiful churches on the island.

From its original organisation of merchants, the Hanseatic League became an international association of cities in the late 13th century. Farmers outside the city were no longer welcome to participate in international trade. The most important symbol for the break between urban and rural areas was the wall that the people of Visby built around their town. The controversy led to a civil war in Gotland in 1288. Visby residents won the battle, but already in the 14th century the city began to lose its importance. The Gotlanders met increasing competition in the trade with Eastern goods, and the plague struck the Baltic Sea region in 1350. In 1361 the Danish king, Valdemar Atterdag, conquered Gotland after clashing with the peasants in several battles.

1500 – 1900 AD

Gotland was affected by further deterioration in the early 15th century, not least because of large tax increases. Over many years, the island was ruled by different Danish castle lords, often with the imposition of very harsh conditions.

When the Brömsebro peace accord was signed in 1645, Gotland was returned to Sweden, a country whose territory had expanded greatly since the Middle Ages. The Swedish government now wanted to develop Gotland in military, administrative and commercial activities.

It was not until the second half of the18th century that trading was boosted, and prosperity then really returned to the island. During this time, timber, tar, stone and lime were sold to ports around the Baltic Sea coast and ruins from the 13th century building boom were demolished to provide building stone for the magnificent houses on rural farms and in Visby.

Agriculture expanded considerably during the 19th century. The growing population demanded more grain, and the opportunity to cultivate more arable land increased when chemical fertilizers were introduced. Meadow land was cut and cropped, wetlands were drained and converted to farmland. The landscape, dominated by meadows, pastures and small fields, which had prevailed since the Iron Age, was now changed radically.

Industrialisation reached Gotland in about 1900. Communications developed and the island was linked closer to the mainland. Meanwhile, the effects of previous visits of artists, poets and writers began to bear fruit. These groups had made pilgrimages to the 'fairy tale island' during the Romantic era in the late 18th and early 19th centuries. In books and paintings they had removed the image of an isolated landscape. Now the clear air, the clean health-giving water, the romantic ruins and the exciting history made Gotland one of Sweden's main centres for healthy and cultural tourism.

INDUSTRIAL HISTORY OF GOTLAND

There is a long history of quarrying for limestone and sandstone on Gotland. Stone has been used for various purposes since Prehistoric times. Initially, rocks and boulders were used from blocks that lay scattered on the landscape. The large Bronze Age cairns were built from such stone, and within them constructions of stacked limestone and cists of limestone blocks are quite common. Many of the ancient hill forts are constructed of limestone dry walling.

Smaller Iron Age cairns and dwellings – the so-called *kämpgravar* ('giants graves') – also included considerable quantities of stone, together with the stone walls built for boundary fencing. Limestone is considerably softer and therefore easier to carve than igneous rocks such as granite. It is no coincidence therefore that the unique picture stones were produced on Gotland. Limestone was also more easily accessible, often quarried in the immediate vicinity.

In the Middle Ages, both limestone and sandstone were important construction materials for the approximately one hundred churches that were built on Gotland. The Visby town walls, warehouses in Visby, and residential and farm buildings in rural areas were also built of easily quarried limestones, which were then produced as blocks for construction. However, limestone was not exported as building blocks, because outside Gotland cheaper brick was preferred. But for facades and decoration, Gotland limestone and sandstone became major products for export.

Sandstone was exported in the form of grinding stones and brows from as early as the Viking Era. Baptisimal fonts made of sandstone and limestone were exported widely through Europe in the Middle Ages. In the 1500s, when Danes held a monopoly on quarrying, sandstone was exported to Denmark, including construction for castles. After Gotland became a Swedish territory in 1645, exports of stone for facades and decorative buildings received a notable boost. For example, considerable amounts of sandstone from Gotland were incorporated in the construction of the Royal Palace in Stockholm.

Lime burning for construction materials purposes has been undertaken since the early Middle Ages. Initially, this was the work of peasants, but in the 1660s the burghers of Visby took over the business; they were known as lime barons and burned lime became an important export. Quarries and lime kilns were close to a port, and in the 17th and 18th centuries small cargo boats carrying burnt lime transported the products to Swedish, Danish and German ports. Northern and easternmost Gotland were the main areas for lime burning. Intense production of burnt lime led eventually to widespread deforestation, especially in northern Gotland; the wood used as fuel was replaced later by coal.

Industrialisation in Sweden in the late 19th century brought with it an increased demand for limestone. The cellulose industry in particular required lime for production, but it was necessary also for iron works and sugar refineries. Increased need for limestone led to the opening of many new quarries in northern Gotland. Stone blocks from several quarries on Gotland were shipped to Germany, and used for example in construction of the Autobahn road network.

Cement was the next product to be developed, using limestone, clay and marlstone as raw material. The Visby cement plant was built in 1884, and in the 20th century the Valleviken and Slite factories were established. The cement factory/quarrying complex in Slite is now the largest in Scandinavia.

In the early 20th century, 1.6 million tonnes of limestone per year were quarried on Gotland, and in the mid 1930's some 600 people worked in the quarries. Today, some 6.2 million tonnes are quarried, and about 350 people are employed in the lime industry on Gotland.

VISBY SURROUNDINGS

Högklint and Rövar Liljas Håla

An impressive section of the coast extends from Högklint, 5 km south of Visby, southwards to Nyrevsudde. Högklint itself is 48 m above sea level, one of the highest coastal cliffs on Gotland. The area is also a much visited and well organised nature reserve. From the top of the cliff there is a wonderful view over the sea northwards to Visby and Fridhem. The bedrock consists of reef limestone, part of the Högklint Formation.

A steep staircase leads down to a ledge in the cliff, called *Getsvältan* ('Starving goats'). This name comes from the fact that at one time goats went down to the ledge to graze, but could not climb back up the cliff again and met a miserable death. From here the reef structure is very clear, as large irregularly shaped rock bodies with no bedding planes. High up in the cliff, two very large sea caves have been hollowed out by waves when the sea level of Lake Ancyclus reached up to this height.

The lowermost 15 metres of the cliff section below the reef are composed mainly of marlstone, followed by about a metre of crinoidal limestone on which the massive reef complex sits. The reefs were so large and heavy that during Silurian time they sank down into the underlying softer sediments. The result can be seen as down-warped limestone beds in the lower part of the cliff face. More reefs extended previously beyond the present shore line, but have long been eroded away. An underwater rock shelf stretches away from the beach, then plunging into a steep submarine drop in the sea floor. From the top surface of Högklint this underwater cliff margin is clearly visible, barely one metre below the water surface. Here and there large scale circular patterns are visible in the sea-bed; these are known as Philip structures, indicating where previ-

View at Högklint from south. Photo: T. Bauert.

ous reef bodies were once present and depressed the underlying sediments, but which have long since been eroded away. Essentially, these structures form part an 'underwater map' of the former extent of Silurian reefs in this part of the Baltic.

Högklint lends its name to a stratigraphical unit of the bedrock sequence – the Högklint Formation, which sits on top of the Lower and Upper Visby formations – the oldest exposed rock units on Gotland.

A signposted path on the tree-covered southern part of the cliff plateau leads south to the fishing base of Ygne. After about 800 metres the feature known as Rövar Liljas håla ('Robber Lilja's Cave') is on the sea-ward slope below the path. It is a cleft inside a part of the cliff that has long been falling away, and now stands as a 'pseudo-sea-stack' on the beach. The cleft was named after an escaped villain, Jonas Nilsson Lilja, who in the mid 18th century carried out a series of robberies on Gotland and was probably hiding here when he was arrested in 1753. In the early Spring of 2010, however, most of the stack collapsed and the area close to the remaining structure is now closed off because of the risk of further landslide and collapse.

Rövar Liljas håla is also accessible directly from Ygne, northwards along the beach. This is a popular place for a day's outing from Visby, as can be seen from the number of barbecue areas. Högklint forms a fine view to the north. Note the signs that point out that the whole area is a nature reserve. This means that, for example, it is forbidden to deface the rock with hammers, chisels or other tools. However, it is allowed to pick up fossils and pebbles that lie freely on the ground. Here, as along the entire coast of Gotland, please be aware of the overhang below the cliffs because the soft, loose marlstone is weathering away rapidly, so that the rocks are undermined and there is a high risk of rock falls.

The cliffs themselves at this point are up to 15 metres high, consisting of bluish-grey soft marlstone at the base, with embedded calcareous nodules and thin, grey, finely crystalline limestone beds. The lowest 3 to 3.5 metres of marlstone belong to the Lower Visby Formation, which are the oldest strata exposed on Gotland. They are succeeded by the Upper Visby Formation, which contains more limestone units than the beds below, and which is more irregularly bedded. The abundance of benthic fossils (animals that lived on the sea-bed) also increases. Small reef mounds are present in the upper levels, marking the first appearance of reefs in the Gotland sequence. The mounds consist mostly of tabulate corals and stromatoporoids, with subordinate rugose corals. The marly sediments were deposited under fairly quiet water, low energy conditions below the wave base in well oxygenated waters. Upward changes involve less mud units and more limestones, with more diversified faunas, generally formed in slightly shallower water. Above the easily eroded marly sediments are the more resistant beds of the Högklint Formation, forming the cliff tops and comprising crinoidal, stratified and reef limestones.

This stretch of coast is one of the classic fossil localities on Gotland, partly because of the rich faunas from the Lower Visby Formation. Large numbers of 'petrifactions' were collected from here at the end of the 19th century by the schoolmaster Mathias Klintberg (and presumably his pupils), and they are now preserved in the Natural History Museum in Stockholm and the County Museum of Gotland in Visby. 'Masse' Klintberg was a remarkably versatile and talented man, best known as a linguistic researcher and documentary photographer, as well as being an avid fossil collector.

The eroded sediments now piled up on the beach are studded with many different types of fossils. Small stromatoporoids, tabulate and rugose corals are encrusted

The pseudo sea stack at Rövar Liljas håla. Photo: T. Bauert.

on rock surfaces, and there are many other specimens of groups that include brachiopods and gastropods. Of particular interest are the distinctive coral *Goniophyllum* with its square-shaped form and opening, which in life had an operculum or 'lid'. Also common is the beautiful, small 'button coral' *Palaeocyclus porpita*, which is a precise indicator of rocks of this age across wide areas of the Atlantic Region as well as Baltoscandia. Among the brachiopods, *Eoplectodonta transversalis* is common and readily recognised with its concavo-convex shell, generally preserved in a brownish colour. 'Index fossils' such as these are important tools for correlating beds from different localities.

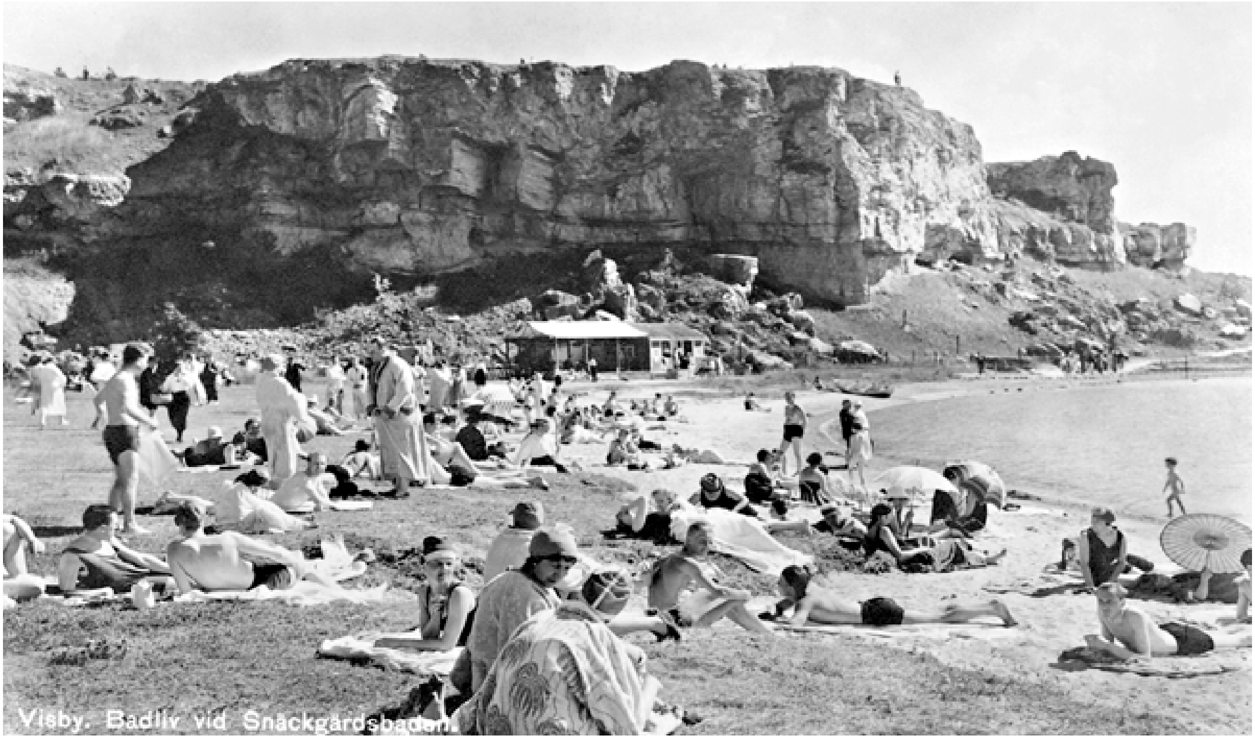
Small, loose fossils here are found most easily in the wave-washed pebbles, and the best rewards come from sitting calmly in one spot to sift through the material – which is far more comfortable than walking along with a bent back and peering at the ground!

Snäckgärdsbaden and Korpklint

Many of the most interesting geological localities on Gotland are within walking or cycling distance of Visby. One example is at Korpklint by the beach at Snäckgärdsbaden, just north of the town. Also, the nearby road cutting on the hill slope leading up from the Snäck building complex.

Korpklint is a vertical cliff with a large scree slope on which large boulders have tumbled down towards the road and beach. Over 20 metres high, the cliff is a beautifully preserved section through the Upper Visby and Högklint formations. The lower beds, about 5 metres thick through the Upper Visby Formation, com-

Swimming by Snäckgärdsbaden, Visby in the early 1900 (top photo on right page). Photo G. Heurlin.
View towards the north showing the Upper Visby Formation (lower part) and Högklint Formation (topmost). Photo S. Willman.


Visby. Badliv vid Snäckgärdsbadan.

prise bluish-grey marlstones with irregular calcareous nodules and thin beds of brownish grey, fine crystalline limestones. The sequence is highly fossiliferous. Högklint rocks at the top of the section are difficult to access, but there are many boulders on the slopes below the cliffs.

The Högklint rocks in the cliff are thick-bedded, light grey, fine to medium grained crinoidal limestones. Common fossils are stromatoporoids, corals, bryozoans and brachiopods. Many of the fossils are fragmentary and worn, indicating transportation in the high energy reef environments.

Beds of the Upper Visby Formation are best exposed and accessible in the road cutting ascending the hill from the beach, immediately south-west of the hotel complex. This section is extremely fossiliferous. There are three small reef knolls in the section, which are easily recognised and accessible for close study; fossils are very common around the reef margins. The most common fossils are tabulate and rugose corals, stromatoporoids, gastropods and brachiopods.

Lummelundsbruk and Lummelunda Cave

Energy from the rapidly flowing water of the river Lummelundaån was once the basis for industrial activity at Lummelunda, including a textile mill, paper mills and sawmills. From the late 17th century until 1712, five water wheels provided the power for an ironworks, using iron ore from Utö in the Stockholm archipelago. One of these waterwheels, Överstekvarn, is preserved today. Around the river there are still traces of the industries in the form of slag heaps, ruins of buildings, remains of roads, and bridges. In the late 19th century the digging of drainage ditches around Martebo mire, from where the water came, made it impossible to continue the industrial activities when the water flow in the river decreased dramatically.

Martebo mire was formerly one of Gotland's larger bog areas, most of which are now drained and converted to croplands. Water ran from the bog through

Dripstones at the Lummelunda cave. Photo H. Reintz.

underground cracks to form the rapidly flowing stream, which then carried on downslope before emerging through a beach cave at the foot of the cliff. Although no longer a source of industrial power, the river is still important in many ways, including a breeding location for sea trout.

In 1948, three curious teenage boys managed to creep inside the beach cave along the outlet stream, and discovered the passage into a very large cave with stalactite formations. This cave was formed probably before the last Ice Age, eroded and hollowed out by the carbonate-rich water that flowed through the cracks in the bedrock, and which dissolved the calcium minerals in the rocks. When the water, saturated with lime, dripped down from the roof of the cavern, the calcium carbonate built up as beautiful stalactites and stalagmites.

Parts of the cave were opened to tourists in 1959 after a new entrance was blasted open. Since then, speleologists have penetrated further and further into the cave system, and as of now approximately 4 kilometres have been mapped. A small current of water still flows through the active part of the cave, and after the spring snowmelt it can sometimes reach former flow volumes, making it impossible to visit. However, throughout the summer the cave is open to tourists, and in one of the outside barns there is an exhibition with information on the geology of Gotland in general and karst caves in particular.

A nature trail starting from the mouth of the tourist cave leads upwards to the cliff top. Here the ground is uneven because of the shape of the reef bodies in the underlying rock, but also because there are many sinkholes in the area. Sinkholes, or dolins, are funnel shaped pits in the ground, resulting from collapse of the bedrock because of undermining by chemical dissolution of the underlying limestone. The path then leads further along the beach ridges formed during Ancylus times. The largest and highest ridge, the 'Ancylus wall' marks the level of the highest water surface of Lake Ancyclus, where it stood for an extensive time before the lake waters regressed. The main road 149 from Visby runs along the level of this beach ridge.

From the lookout point on the cliff edge, with its marvellous views, a staircase then leads back downhill. In the cliff walls there are several beach caves, carved out by waves in former times when the sea reached to this level. At the base of the cliff there is a lush deciduous wood. The rich vegetation is a result of the fine nutritional sediment, now as soil, that was deposited on the sea-bed in earlier stages of development of the Baltic Sea, and which is kept moist constantly by the water flowing through cracks into the springs and stream of Lummelundaån. Here and there are eroded gutters, which drain off waters from the springs and shallow wells during periods of high flow rates.

NORTHWESTERN COAST

Lickershamn

Lickershamnsviken is one of the bays of the northwest cliff coast that was formed originally as an erosion valley. Rivers and glaciers eroded weak parts of the cracked cliff bedrock. Thus, the coastal cliff turns inward toward the land here and appears in the bay as an inland cliff. Sediments have accumulated in the bay and now fill a large part of the ravine.

Naturally, post-glacial erosion has also affected the area. The inland cliff on the west side of Lickershamn valley is highly eroded by forces of the sea and there

Jungfrun at Lickershamn is the largest sea stack on Gotland.

are a large number of sea stacks, either in smaller groups or in large sea-stack fields. The sea stack field, which lies just to the left of the road down to Lickershamn, is worth visiting. The stacks here look very strange where they protrude from the surrounding green vegetation.

Further out on the coast to the west of the harbour the steep coastal cliff is again present. The cliff exposure displays the same bedding sequence as in Ireviken, and it also contains essentially the same fossil fauna. At the base there are thin-bedded marlstones of the Lower Visby Formation, followed by the slightly more calcareous marlstones of the Upper Visby Formation and limestones of the Högklint Formation at the top. The sharply protruding cliffs of Jungfruklint and Stuklint are Högklint reefs. The reef limestone is more resistant to erosion by the sea and ice than the bedded limestone in between.

The cliff reaches its maximum height, 27 metres above sea level, at Stuklint. The only remains of the reef in Jungfruklint is a very large, high sea stack, known as Jungfrun (the Maiden). It is the largest sea stack on Gotland, 26 metres above sea level and 11.5 metres above the ground. The name derives from the tragic tale of the virgin Öllegård and her beloved, a story you can read more about on the information board. The sea stack has been sculptured by the waves of the Littorina Sea, 6 500 years ago. The north side of Jungfrun is almost flat as it comprises one wall of an old vertical crack; the opposite wall has collapsed down onto the beach. On its landward side is a shallow beach cave. Below the cliffs there is a great accumulation of collapsed rocks, many of which are unusually large.

Southeast of Jungfruklint the cliff is divided into an outer, lower coastal cliff, consisting of marlstone, and an inner limestone cliff on the higher 25-metre level. On the sloping shelf between these cliffs there is a series of well developed sea walls. A creek that drains Sågvätar, a wetland area a few hundred metres inland, cuts deeply through the rock before it runs out at the beach. The stream dries out in summer, but the water flows rapidly during winter and spring.

At several places on and below the cliff, calcareous tuffs are deposited. These are related to groundwater seeping from the cliff at specific levels. The levels coincide with bentonite beds within the layer sequence. Bentonite is volcanic ash that has been deposited as a clay. The clay swells up when it is wet, forming dense layers. As a result, water flows within the cliff onto the top of the bentonite layers and down to the beach on the cliff wall. Flush fen plants like bird's-eye primrose and the lily *Tofieldia calyculata* often grow where the water seeps out.

The area around Jungfruklint and Stuklint is a nature reserve.

Ireviken

Ireviken is one of the deep bays on the north-west coast, interrupting a long stretch of high cliffs and with a long, sandy beach. The coastal cliff here turns inland, forming a ravine filled with sediments. Through the valley runs the Ireån stream, which drains Tingstäde lake and Elinghems bog. It cuts deep into the valley sediments that were deposited originally as beach sediments and drifted sand. The sand, gravel and shingle were deposited during Littorina time. The inner parts of the bay are lined by cliffs with beautiful abrasion formations such as sea stacks, beach caves and niches, all formed by waves during the maximum level of the Littorina Sea.

From the fishing hamlet on the south-west side of the bay, follow the coastal cliff southwards. There are four high, protruding and overhanging cliffs, Tretrivsklint, Millingsklint, Gaituklint and Snipklint, each comprising enormous reefs. There are also many large boulders that have fallen onto the beach. These reefs represent contemporaneous reef structures that largely ran parallel with the coastline.

The lower part of the cliff, mostly between the reef masses, is 24 metres high and consists of soft, highly fossiliferous bluish-grey marlstone. It is thin-bedded with irregular nodules and beds of fine-grained limestone. These beds are part of the oldest exposed rocks on Gotland. The lower 9 metres belong to the Lower Visby Formation. The boundary to the Upper Visby Formation, which is about 15 metres thick, is in the middle of the section, 13.5 metres above sea level. The boundary is difficult to identify without detailed study of the fossil fauna, but it is roughly at the level where the scree slope is succeeded by the vertical cliff, because the Lower Visby Formation are more argillaceous, making them softer than the Upper Visby Formation, whose higher content of limestone has produced a vertical profile.

Especially after recent rainfall, a sharp horizontal boundary is visible between the dry upper part of the cliff, and the damp lower part of the marlstone. This is because of the presence of a bentonite bed. A bentonite is a thin layer of clay that was deposited originally as volcanic ash on the sea floor. Bentonite clay swells on contact with water, making the horizon impervious, so that groundwater cannot percolate through it, but flows out at the bentonite bed and then runs down the cliff face. At least three such bentonite horizons are present in the lower part of the section. The bentonite beds are easily traced, because their upper surfaces are aquifers and the percolating water gives rise to a border of herbaceous plants.

At one point along the lower part of the section, there is a colony of the tabulate coral *Halysites*, about 100 metres long, although much of it is often covered by beach shingle. On this reef there are also specimens of the rugose coral *Cystiphyllum* in their original growth position. Note the root-like appendages on these corals. They can also be found in the form of small, loose 'twigs' in the fossil material eroded from the marlstone. It is very important that this reef should not be destroyed by chipping off fossils and hammering the cliff. The erosive forces of the waves, ice and rain are beyond our control, but if you wish to collect fossils, take advantage of this erosion and only take loose-lying corals.

The Lower Visby Formation is comparatively fossiliferous. The small 'button coral' *Palaeocyclus*, and the brachiopod *Eoplectodonta transversalis* occur only in these beds, and are used as index fossils to correlate contemporaneous sediments throughout the world.

The Upper Visby Formation has an extraordinarily rich fossil fauna, dominated by corals, brachiopods and bryozoans, although stromatoporoids, gastropods, ostracodes and trilobites are abundant, whereas crinoids, bivalves and cephalopods are sparse. Limestone beds are more common higher up in the Upper Visby Formation, where there are also small reef knolls.

The Högklint Formation rocks at the top of the cliff are dominated by limestone with isolated, massive, dense reefs at intervals of several hundred metres. The reefs consist mainly of stromatoporoids and tabulate corals, but also of bryozoans, crinoids and calcareous algae. Coarse fragmental limestones, made up of crinoidal fragments, occur on the sides of the reefs. These are succeeded gradually by fine-grained stratified limestones further away from the reefs. Reef, frag-

The Snipklint at Ireviken, NW Gotland.

mental and fine-grained limestone can all be studied more closely in the scree on the beach.

Because of the steepness of the cliff, the reefs are difficult to access, but there are many large boulders of reef material on the beach. The reefs are surrounded by a well-bedded limestone-marl alternation.

Ireviken is one of the most fossiliferous localities on Gotland. Because the cliff erodes at an annual rate of about 1.5 cm, new material is exposed constantly. In addition to fossils, the glittering, golden, cubic crystals of the mineral pyrite (iron sulphide) are common here. In some cases the calcite in the fossils has been replaced by pyrite, which unfortunately corrodes easily, partly due to its iron content.

At some places along the cliff, where the water slowly trickles out, calcareous tufa is being formed. The calcite-saturated water deposits calcite on the moss that grows on the ledges. The greyish calcareous covering feels hard and crisp, and gradually, when the actual moss has decomposed, it will leave an impression – a type of modern fossil-formation.

The marlstone in Ireviken has been the subject of many extensive studies of the evolution and extinction of different animals. These studies have provided data for theories on global cyclic changes in the oceans, and their impact on sedimentation. The 'Ireviken Event' is the established name for a minor extinction event that occurred all over the world during this time.

The area around Ireviken bay has a number of hillforts in beautiful surroundings, an old mill setting, and a pleasant bathing beach. The old mill once belonged to Ire farm, dating back to the 16th century. Red helleborine blooms around the bay in summertime.

In autumn sea trout migrate up Ireån, and fishing is therefore prohibited between 1st October and 31st December. Birds also thrive by this river, and dippers live off the insects at Ireån.

Bläse Limeworks Museum

The lime industry has left its mark on northern Gotland. Old quarries, lime kilns, lime warehouses and heaps of waste products are spread along the entire coast. Quarrying and lime burning have been undertaken since the Medieval Period, and on an industrial scale from the 17th century, when the farmers no longer were allowed to burn lime and the businesses were taken over by the burghers of Visby. The large wooden-fired lime kilns demanded huge amounts of fuel, and as early as in the 18th century, the surrounding woods were almost all cut down, leaving a barren landscape. During his trip to Gotland in 1741, Linnaeus noted that in Kappelshamn:

There is enough fuel here, but the wood is uneven in quality; if the lime-burners are allowed to do as they please with the woods, this part of Gotland will soon be cleared of forest, since for every 2 days' burning, 20 fathoms of firewood are used.

Bläse Limeworks is situated on the east side of Kappelshamn bay. Lime has been burnt here since the late 19th century, with production continuing until 1945. The works, together with the harbour, two coal-burning lime kilns with huge chimneys, and the lime warehouses now form a museum of the stone industry. During its days of glory in the 1920s and 1930s, about 140 men worked at Bläse. An entire community grew up around the works. The quarry from which the limestone was taken is situated 2 km north-east of the works. The railway line to the quarry has been restored and tours with the 'Stonetrain' are popular among visitors. The museum also offers demonstrations of the lime-burning process, and there is an exhibition portraying the life of the former workers.

The coal kilns at Bläse were shaft furnaces for continuous burning. Limestone and coal were packed in at the top and the burnt lime taken out at the bottom. The burnt, unslaked lime, was put in storehouses where it was then slaked; i.e. water was added, reducing it to white, powdery slaked lime. In modern times the lime is slaked in the big silo.

The older, wooden fired kilns were stoked at the base, and limestone was stacked on top. The kiln was closed and the lime then burned for three to four days. When firing was complete and the fire was extinguished, the lime was removed to the warehouses where it was slaked. A kiln of this kind, built in the mid 18th century, is preserved near the old limestone quarry.

Fårö

Digerhuvud

The largest continuous sea stack area of Gotland, and of the whole of Sweden, is along the north-western coast of Fårö. It is called Digerhuvud; there are parking spaces and explanatory sign-boards on the roadside above the localities. From a cliff composed of reefs belonging to the Hangvar Formation, waves and water currents have carved out several hundred stacks. The area of the sea stacks extends from Slähällar in the south-west to Helgumannen fishing base in the north-west. It is 3.5 km long and on average 50 metres wide. The sea stacks were formed during the post-glacial regression, when elevation of the land gradually exposed the rock surface. The stacks stand-

'Stonetrain' at Bläse Limeworks Museum. Photo: T. Bauert.

ing in the water are still influenced by the erosive forces of the waves. The limestone plateau from which the lowest sea stacks are carved forms an underwater cliff, dropping vertically down to 50-60 metres under water. Outside the cliff edge, strong underwater currents can be formed during certain wind conditions. Please beware that these can be extremely dangerous for swimmers.

The sea stacks consist of reef limestone, dominated by stromatoporoids which are the most resistant fossils, although there are also corals that include colony-forming rugose and tabulate forms. Remains of sea lilies (crinoids) that accumulated along the flanks of the reefs are also present at places in the limestone. The closely standing sea stacks vary in size up to 8 metres high. The ground is otherwise covered by beach ridges of shingle, which also covers part of the remaining cliff along the landward side of the sea stacks.

Avanäset

Travelling towards Avanäset on north-eastern Fårö, there is a noticeable and quite abrupt change in landscape vegetation. Whereas limestone bedrock and sea walls of shingle dominate the rest of the island, this region has a deep sandy soil, with hardly any limestone bedrock exposed. Only at the beach to the south-south-east of Holmudden lighthouse are there some low sea stacks. Sand dunes form smooth landforms and a sand pine forest covers the inner parts of the area. The ground is covered with mosses, lichens

Sea stacks at Digerhuvud consist of hard, weather-resistant reef rubble limestone (above). M. G. Bassett pointing at cross-bedded fossiliferous limestone which represents high-energy channel deposits between reefs.

Langhammarshammar

The contemporary reefs forming the sea stack area at Digerhuvud are also preserved at Langhammarshammar on the northernmost peninsula of Fårö. A narrow road that meanders through a bleak, barren landscape of shingle banks with low-growing windswept junipers, leads to a beautiful sea stack area on the beach. From the landward cliff edge the ground slopes out into sea. Here there are 70–80 sea stacks, with heights up to 10 metres. Many are pillar shaped and stand majestically and closely grouped on the beach. They are among the most impressive and spectacular rauks on Gotland, and Langhammarshammar is without doubt one of Gotland's biggest attractions.

and vascular plants such as heather, blueberry and lingonberry, uncommon in the rest of Fårö, typical of lime-poor soils. In depressions between the dunes, small bogs have been formed bordered by alder, a rare species elsewhere on Gotland. The bogs are affected by acidic water, which has resulted in the formation of a wetland environment which is unique for Gotland. Here, there are peat mosses (sphagnum), crowberries and common bog-sedge, which are typical species in such acidic bogs.

The nature reserve at Skalahauar is a large sand-drift field located on the south-eastern area of Avanäset. The dunes are high and make the landscape hilly and undulating. The drifted sand area probably accumulated in the 18th and 19th centuries, when land clearance from logging and intensive pasture development allowed the wind to push the sand freely across the area. Now forests again cover most of Avanäset.

Another reserve, at Ulla Hau, located further west in the middle of the narrowest part of the tongue, consists of a giant horseshoe-shaped sand dune. The opening of the horseshoe faces to the north. From the inside of the horseshoe, forming a deflation surface some 1.3 km wide, the sand is blown by the wind, transported to the south and deposited on the dune which is up to 15 metres high. This dune probably formed already in 18th and 19th centuries as a result of high-intensity land use. In order to prevent the dune wandering migrating southwards, pine and sand-binding grass were planted during the early 20th century. Now the sand dune is covered largely with pine forest. In this environment, with open sandy areas, an ancient pine forest and a particular local climate, there is an interesting insect fauna in which many rare species thrive. Ripple-marks (small ridges formed by wind) are common on the open sand surfaces.


Sand dunes at Ulla Hau, Fårö. Photo: T. Bauert.

The sand deposits of Avanäset were deposited by the glacial rivers that flowed through cracks and tunnels in the glacier during the deglaciation phase of the Weichselan ice. They are part of the same glaciofluvial deposits that form Gotska Sandön, and are exposed parts of a 120 km long ridge of sand, gravel and till that stretches from Klints Bank to the east of Gotland north, over Salvorev north-east of Fårö, and to the shallows of Kopparstenarna 20 km northwest of Sandön.

NORTHEASTERN COAST

On the north-eastern coast of the island is the only archipelago displayed on Gotland. From the coast of Bungenäs to Slite there are a dozen small islands. The coastline is lobate, with many deep bays and protruding headlands. Land topography is often hilly because of the reef limestone in the bedrock. Stratigraphically, this bedrock is part of the Slite Group, which apart from reef limestone, includes bedded, pure limestone and occasionally marlstone. Limestone has been quarried in the area for centuries, and lime industries, primarily the burning of limestone, have been intense. Traces of these activities, in the form of the many quarries and lime kilns, are a distinctive feature of the coast here.

LERGRAV

The nature reserve and fishing base of Lergrav lies between the bays Lergravsviken and Valleviken. In the 800 metres long sea stack field below the eastern cliff of Lergravsberget, one of Gotland´s most remarkable sea stacks, Lergravsporten, is preserved. It is an arch-shaped sea stack through which many visitors enjoy running. Madonnan med barnet (the Madonna with child) is another popular high sea stack, named in relation to ancient folklore.

From the coast there is a spectacular view of Bungenäs in the furthest distance, and of the isles of Skenholmen and Furillen. The landscape at Lergrav is barren, but the environment is favourable to spiked speedwell, common rock rose, *Vincetoxicum* and moon carrot.

South-east of Lergrav is the island Furillen, where limestone was quarried and shipped out from the beginning of the 20th century until the 1970s. The abandoned lime factory has now been transformed into a fashionable hotel and restaurant. A large part of the island is a bird protection area during the breeding season. The island is so close to the coast that it can be reached by car via a road running along a spit.

KYLLAJ

Kyllaj is a village and an old harbour built around the former lime industry on the eastern coast of the parish of Hellvi. From the edge of the hillside there is an astonishing view over sea stacks, limestone ruins, harbours, the sea, and the archipelago with its isles of Klasen, Fjaugen and Lörgeholm.

The stone and lime industry developed during the 17th century. Limestone was quarried in the surrounding region, then taken to the kilns on the hillside and burnt. The burnt lime was stored in warehouses by the harbour, where it was slaked with water and then packed into barrels. The lime was shipped on small cargo boats to harbours along the Baltic Sea coast.

Limekilns close to the cliff comprise remains of the earliest kilns, together with well-preserved 19th and early 20th century kilns.

On the hillside at Kyllaj, facing the sea and surrounded by grassland, there are many beautiful sea stacks. These were sculpted by the waves of the Littorina Sea, about 6500 years ago. When Linnaeus

Lergrav rauk field overlooking Lergravs-
viken bay in northeastern Gotland.

was here in 1741, he made a completely accurate description of the sea stacks and the formation of them, although he had no knowledge of inland ice and isostatic land elevation. In his travelog he wrote:

We called the 'Stone Giants', as had the learned bishop G. Wallin, that which we saw by the sea near to Kyllaj: between the customs officer's house and the lime kiln of Kyllaj there was a slope towards the sea where stood many high and thick limestone rocks 4-6 fathoms (8-12 m) high, arranged in a row like the ruins of churches or castles, of which those standing at a lower level of the slope were taller than those higher up, so that the heads were all at the same level. From a distance they looked like statues, horses, torsos and I do not know what kind of ghosts. Evidently, this had been formerly a limestone mountain, the roots of which had been ground, cut and formed by the heaving waves of the sea, till it finally left these stones in their present form; there is no doubt that the water that has cut into the sides of these cliffs and made them narrow at the base has also been able to cut away and erode the earth between them. Stone giants of the same size were seen all the way along the road to Slite.

Lime kiln remains at Kyllaj, northeastern Gotland.

The old house Strandridargården was built in the 18th century by the customs officer Johan Ahlbom, a former warrior in King Karl XII's army. Strandridaren (the Beach Rider), was a customs officer who had the task of guarding the coast and the harbour. Strandridargården is now owned by the Bunge Museum and is open for visits during summer.

From the beach, probably sitting on a pier, Linnaeus was able to see all the sea stacks and the house. A woodcut, made after his artwork, is included in the published travel log from 1745.

St. Olofsholm scenery.

Some of the raw material from this industry is from the nearby limestone outcrop, Kyllaj hajdar – a flat, treeless landscape. Scattered around are small, shallow limestone quarries.

St Olofsholm

The southernmost headland in Hellvi parish is named St Olofsholm, which is a hill of reef limestone; in prehistoric times and in the Middle Ages this was an island, called Akergarn. The area south of the old harbour on the eastern coast is a nature reserve. Here the limestone slabs are partly visible and descend in wide steps towards the sea. The slopes of the hill are covered by sea walls, and a low cliff runs along the eastern shore. Along the beach in the north-east there are 15 sea stacks, many of which are high out of the water on the washed rocks. The largest sea stacks are 5-6 metres high. On the southern slope, in the central area are single small stacks. In the western area there are several large old limestone quarries. Grazing animals have long shaped the landscape and today the area is open moorland with grass and low junipers. Here and there spruce, pine and white beam are growing.

According to the legend of Olaf the Holy, the Norwegian King Olaf Haraldsson came ashore at Akergarn (St Olofsholm) during a trip to Russia in 1029, and then converted the Gotlanders to Christianity. Up on the hill are the remains of a chapel, St. Olaf's church, built in medieval times in memory of this alleged landing. According to legend, Gotlanders were baptised in 'St. Olaf's vaskefat' (St Olaf's wash-bowl), a depression in one of the sea stacks just south-west of the chapel.

Gotland's first lime kiln was erected on St Olofsholm in the early 17th century. Gotland belonged to Denmark at the time and it was the Danish King and a company called Gullandska Compagnie, that were behind the enterprise, with the intention of producing lime for export. The activity was continued until 1860. In 1901-1953, blocks of stone were quarried on a large scale. A harbour with a quay made it possible to export the limestone further. Wagons on rails were loaded with limestone, and the loads were transported to the quay and tipped directly into the holds of the boats. In 1953 the limestone quarrying was moved to Storugns in Kappelshamnviken on north-western Gotland. Traces of the limestone quarrying can still be seen in the surroundings of St Olofsholm.

NORTHERN INLAND

Tingstäde – Hejnum area

Tingstädeåsen is a ridge situated 10 km west of Slite. It is one of very few and the largest esker on Gotland. An esker is a glaciofluvial deposit, formed by a melt-water stream inside a tunnel or crack in the glacier. It consists of sorted sand, gravel and stones. Tingstädeåsen reaches a maximum height of 12m and a length of 12 km. It extends from south-west to north-east on the northern side of the lake Tingstäde träsk. The lake, which is the second largest on the island, is dammed by the esker, making its water level higher compared with the ground level north of the ridge. Some people have interpreted Tingstädeåsen as a terminal moraine, formed parallel to the ice margin during a period with little or no melting. However, eskers are always extended along the ice movement direction.

St. Olofsholm: view at adjacent Ytterholmen island.

Southwards from the lake runs the valley of Hejnum parish. From the parish church towards the northwest there is a dirt road across some hilly fields. The elongated hills are parallel land forms interpreted as drumlins, which are types of moraines formed during the expansion of the glacier. They extend in the same direction as the ice movement. Part of the agricultural lands in the valley, were former wetlands that have been drained. The valley is lined with prehistoric settlements and burial grounds. East of the valley, Hejnum hällar and File hajdar, is the largest continuous stretch of flat limestone outcrop/alvar area on Gotland. If you turn eastwards towards the nature reserve Kallgateburg, from the road between Tingstäde and Hejnum, you will pass part of the area before you reach the reserve itself.

The bedrock of the rocky ground consists of pure, hard limestone which belongs to the Slite Group. It is covered partly with thin layers of till or weathering soil. Open pine forest alternates with treeless areas, where only dry-hardy vascular plants, mosses and lichens grow, together with scattered juniper bushes. Sheep and cattle have grazed here for long periods of time, keeping the woods and rocky ground open.

The white stonecrop, with its red, bulb-shaped leaves, which store water, brings colour to large areas of the rocky ground. In June it blooms with white and pink flowers. Another creeping plant growing on the shallow soil cover is the Gotlandic variety of rockrose, which in Sweden is present only on Öland and Gotland, and here rather rarely. It has needle-shaped leathery leaves, also adapted to the dry climate. Its yellow flowers shine brightly in the June and July morning sun. File hajdar also hosts the largest population of Easter pasque flower in Scandinavia. Its large, light purple flowers bloom in April-May.


Hejnum hällar alvar.

Pine and juniper are prevalent in the forest, although spruce, oak, yew and white birch also occur.

The eastern edge of the rocky area is intersected by ravines that were eroded by glacial rivers in the melting inland glacier. Here is a border between areas of different bedrock. To the north and west are File hajdar and Hejnum hällar, the higher extensive areas of pure limestone, while the lower, muddy areas on marlstone ground at Hejnum Kallgate are to the east and south-east.

On the slope, there are several springs and brooks, created by emerging subsoil water, which has infiltrated through cracks in the limestone. The water flows over the muddy, slightly sloping area and a special wetland, a flush fen/spring mere, is formed. This fen is called Rövätar. The calcareous, cold and constantly moving water has given rise to a very distinctive flora, with species such as brown bog-rush, broad-leaved cottongrass, blunt-flowered rush, birdseye primrose, butterwort, alpine butterwort, great sundew and Pugsley´s marsh orchid.

Rövätar is damned to the east by a major shingle beach ridge, Kallgateburg, which was formed during the Ancylus lakes highest water level 8000 years ago. On top of the ridge runs the former main road from Fårösund to Visby – Kallgate (Charles' road), now visible as a broad path. Here grows one of the largest yew populations in the country. East of the ridge is Hejnum Kallgate. This area is particularly popular among day visitors in early June, when the lady´s slipper orchid is in bloom.

EASTERN COAST

Gothemhammar

The headland of Gothemhammar to the north of Botvaldevik in Gothem, eastern Gotland, is reached via a poor gravel road that runs along the coastline from Åminne to Botaldevik. From Åminne, turn off towards the road marked to Gothemhammar and drive through the cottage area past the small fishing base of Bryggan. Park by the information board. After a short walk along the beach to the east you will come to some low cliff sections. The beach itself is made up of shingle banks, which change from year to year because of wave action. This also means that the exposure of the rocks also varies from one year to another.

The strata exposed in the upper part of the beach and in the low cliff belong to the upper Klinteberg and Halla formations. They are mostly thin-bedded, commonly penetrated by trace fossils. The rocks consist mainly of nodular and laminated argillaceous limestones, interbedded with softer, bluish-grey marlstones. Fossils are very common at some levels, including numerous brachiopods, trilobites, bivalves, gastropods, tentaculites, bryozoans and ostracodes. Calcareous algae, up to several centimetres across, are abundant. One bed is covered completely with the bivalve *Modiolopsis*.

The boundary between the Klinteberg and Halla formations is clearly visible in parts of the section, as a geological discontinuity between the two rock units.

Shallow coastal cliff at Gothemhammar. Photo: T. Bauert.

A discontinuity indicates that the sequence of rock layers is not complete, but that a layer representing a certain period of time is either missing or not fully represented, because of a gap/long interruption in sedimentation. The original surface may have been just above, or just below, sea level and subjected to erosion by currents and waves – so that there is a gap in the record of sediment deposition. During this interval, sediments on the sea-floor may have become lithified as 'hardgrounds' on which various burrowing and boring organisms were active.

Strata immediately overlying the discontinuity surface are developed as thin marlstones with common and well preserved brachiopods and trilobites. These beds indicate a reintroduction of marine sedimentation.

Above the beach, alpine blackberries carpet the ridges, succeeded at higher levels by coniferous forest and where the landscape rises as a cliff. Higher up, at about 12 – 15 metres there are remains of a hillfort. Such forts may have served as fortified settlements in times of unrest, but could have also been used as trade centres, for rituals, and as courts (Tings) in peacetime. What remains today is a 500 metre long rampart, running completely across the highest point of the promontory.

Grogarnshuvud

By contrast to most of the east coast of Gotland, which is quite flat, the area known as Östergarnslandet is quite different in having limestone hills. The easternmost headland on the hill Grogarnsberget is named Grogarnshuvud. From Katthammarsvik there is a signposted gravel road towards Grogarnsberget; follow the road for about 2 kilometres. At a fork with a sign to the right uphill to Grogarnsberget itself, take the left fork instead which leads to the beach at the locality of Grogarnshuvud.

The cliff here is about 20 metres high, comprising reef limestones with abundant stromatoporoids and crinoidal beds. Between the foot of the cliff and the sea there are huge fallen boulders, in which stromatoporoids are preserved in their position of growth. All the rocks here belong to the Hemse Group. The stratified limestones, which are also clearly visible at the water's edge and under the sea itself, are about 15 metres thick, bluish grey in colour with argillaceous beds and are quite thinly bedded. Many fossils from these beds can be found in the shingle and gravel on the beach.

Probably nowhere else on Gotland is there such an abundance of fossil molluscs, with regard to both the number of individuals and the number of species. Of particular note is the profusion of the bivalve *Illiona prisca*, whose characteristic features include its smooth, brownish shell surface. The numerous straight orthoceratid cephalopod shells preserved in rocks near the water's edge are almost all pointing in the same direction. This indicates that sometime during the Silurian Period, the floating empty shells from dead animals were aligned by waves/current action and then embedded in the sediment in that position. Other fossils such as brachiopods, ostracodes and tabulate corals are also very common.

Among the pebbles on the upper of the two beach ridges are some fossils preserved in a different texture, and which are also notably different to the touch. These are mostly tabulate corals, especially *Syringopora* and *Favosites*, and they come from a bed of silicified rock. The original calcite skeleton in these fossils has been replaced after the animal died by the harder silica mineral quartz, which was introduced into the sediment in the form of volcanic ash and dust from nearby volcanic eruptions.


Cliff at Grogranshuvud.

At the harbour in Katthammarsvik is an exposure on the rock surface by the beach, just to the right of the jetty at the far end of the car park. Here there is a deposit formed almost entirely of accumulated shells of the large bivalve mollusc *Megalomus gotlandicus*, and which gives its name to the bed of rock itself. This bed lies immediately below the exposed beds at Grogarnshuvud, and forms the base of the Hemse Group in the north-eastern area of its outcrop.

Kuppen and Snabben

The Östergarn peninsula is characterized by several low, undulating hillocks composed of stacked stromatoporoid flat reefs and interbedded coarse-grained limestones. Stratigraphically, they belong to the Hemse Group. From the fishing hamlet at Herrvik there is a small road running uphill and then towards Kuppen, the easternmost part of the peninsula. Where the road reaches the shore it forks, and the northern fork leads to an old restored navigation beacon where there is room to turn and park.

From Kuppen northwards the beautiful coastal cliffs are very well exposed. The cliffs extend for several hundred metres back towards Herrvik. They are formed of spectacular stromatoporoid reefs consisting of large, non-framebuilding stromatoporoids. The reefs grew on a broad, shallow-water carbonate platform. A high-energy environment is indicated by abundant coarse-grained fragmental limestones, eroded surfaces, and abraded boulders. On the shore immediately opposite the car park, the low cliff Snabben preserves spectacular exposures of the laterally extensive bedded stromatoporoid reefs, with evi-

Coastal cliff at Kuppen.

dence that karst surfaces and sea stacks were developed during Silurian times.

The sea has undermined the cliff all along this coast, dislodging enormous boulders which have then slid down to the water. The shores southeast of Kuppen consist of shingle beach ridges alternating with sandy areas. From this part of the coast there are fine views across to the small island of Östergarnsholm, which is also made up of Hemse stromatoporoid reef limestones.

SOUTHEASTERN AND SOUTHERN COAST

Uggarderojr

The south-eastern coast area of Gotland, with its bedrock of soft marlstone, is a very flat lowland, sloping gently towards the seashore. At Uggarderojr, a few kilometres from the coast to the south-west of Ronehamn, there is an example of a special landscape, which was influenced very early by man. A cattle path, lined with dry-stone walls, leads from the parking place to an open, flat and desolate moor where there are eight scattered giant Bronze Age cairns. Uggarderojr is the name of the largest cairn. With its 45 metre diameter and almost 8 metre height, it is the largest cairn on Gotland.

Bronze Age cairns are graves, built in prominent places along the coasts and fairways, probably forming landmarks, and demarking territory. Today, the surrounding land area is about 7 metres above sea level, and since the land has risen by about 2 metres per thousand years, the shoreline must have been 6 metres higher in the mid-Bronze Age, three thousand years ago. This means that the cairns here must have been built immediately adjacent to what was then the shore.

The surrounding area is now quite void of stones, but before the cairns were built, great quantities of boulders and rocks from the rocky moraine cover must have covered the ground. The rocks were then used as building material for the cairns. Further away from the cairns, for example on the coast north of Hus fishing base, there are examples of areas still rich in a cover of rocks and boulders.

Only a few Bronze Age cairns on Gotland have been excavated, but inside the cairns are found dry-stone walls, stacked towers, coffins of limestone slabs (cists), and other building structures. The cairns often contain burials of more than one person, and they were used over a long period of time. Later cairns, built during the Iron Age, are often smaller than the Bronze Age cairns, and are often gathered together into larger grave fields.

Holmhällar

Holmhällar is the furthest headland on the south-eastern coast of Gotland. From the car park at the boarding house it is a short walk to the beach via a long dirt track. On the beach there is a sea stack field with stacks that are somewhat different from others on the rest of Gotland. But as elsewhere, the stacks, or raukar, are limestone formations, that have remained standing after the sea eroded the weaker rock surrounding them. They often comprise original parts of reefs, since reefal limestones are the hardest parts of the limestone bedrock.

The sea stacks at Holmhällar expose a very special reef type. The characteristic form is that of an atoll-like semicircle open to the north-west and with distally dipping reef surfaces. By analogy with similar structures observed in the Maldive islands, this reef

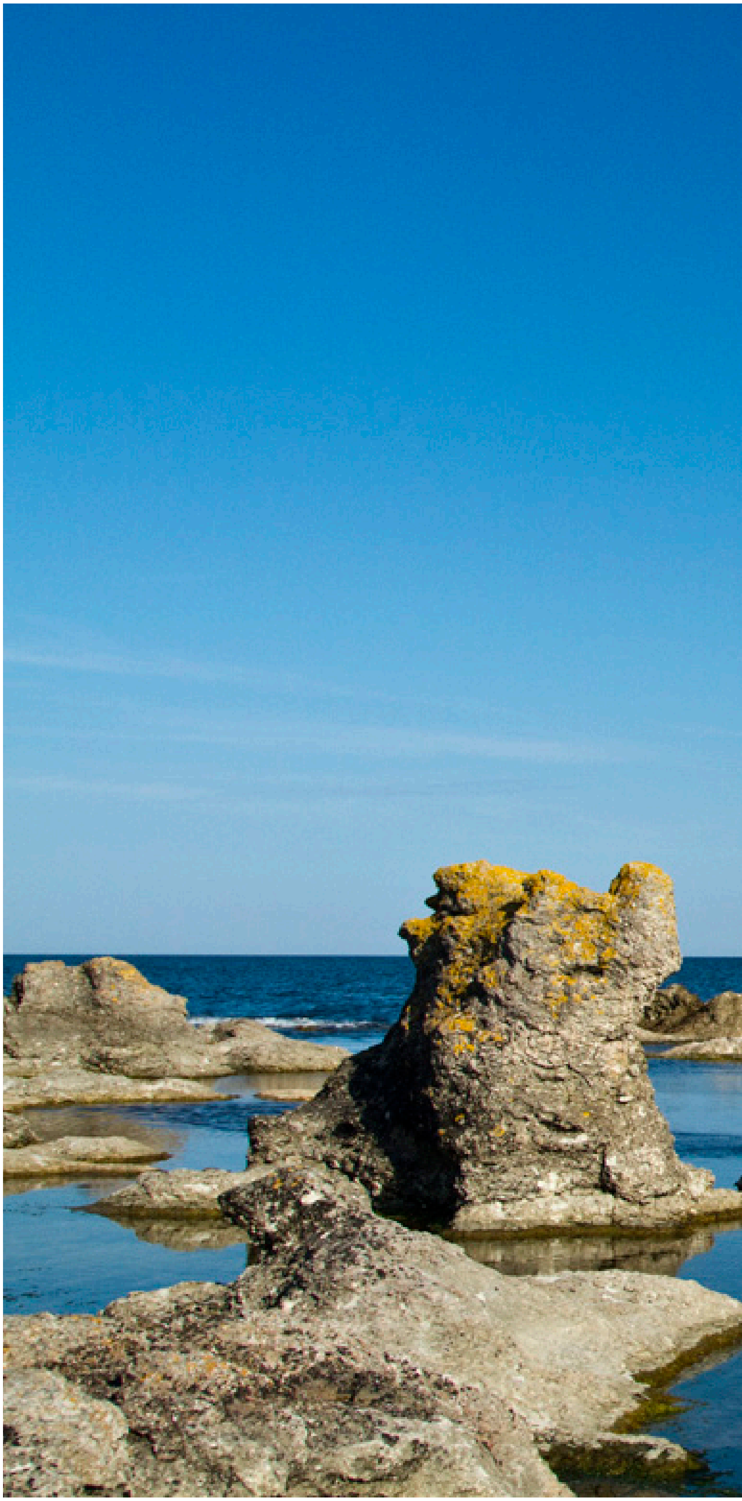
Bronze Age cairn at Uggarderojr.

type is called 'faro'. On Gotland, such structures are known only from the uppermost Sundre Formation. The reefs are composed of dense stromatoporoid and crinoidal limestones, normally with a fine-grained infill (matrix). Occasionally, solenoporaceen algae are present. The reef rocks alternate with crinoidal limestones, and coarse, partly conglomeratic limestones. Interior areas of the faros formed lagoons, which were presumably filled with soft sediments. Conspicuous vertical fissures, up to 0.5 m wide, cut radially and concentrically through these reef rings. These so called neptunian dykes have been repeatedly opened and refilled with sediment. The faros were situated on the south-eastern margin of an extended stromatoporoid reef platform. During rising sea level, they grew predominantly in a south-easterly direction, and because of their increasing size and weight fissures were opened, and then filled repeatedly with sedimentary material.

Along the gravel road leading to the north, there is a bay named Skvalpvik, which has a fine sandy beach. And slightly further on is another sea stack area; Hammarshagehällar.

South of the sea stack area at Holmhällar there is an old fishing base, where the stone huts have sandstone-slab roofing, typical of southern Gotland buildings. Fishing was an important supplement to the diet of farmers in the coastal parishes, where the soil is thin and poor. Most farmers owned a hut at a coastal fishing base. Baltic herring was the main catch.

There are also sea stacks and caves on the islet of Heligholmen, a bird sanctuary just off Holmhällar, where gulls and terns breed in spring and early summer. Access is prohibited between 15th March and 30th June.



Holmhällar rauks. Photo: T. Bauert.

Husrygg and Hoburgen

The best known scenic route with some of the finest views on Gotland is along the road that winds between the sea in the west and the ridge-like limestone hill of Hysrygg in the east, far down in the south of the island at Storsudret. Husrygg is gently rounded by the waves of the Ancylus Lake and Littorina Sea. The thin soil cover and grazing over a long time have created an alvar with low vegetation. Here breckland thyme, *Vincetoxicum*, *Euphrasia* and salad burnet grow in profusion. If you have chosen to visit Gotland in the second half of April or in the beginning of May, you should climb up the slopes to admire the blooming pheasant's eye (*Adonis vernalis*), a relict from the Warm Period. In all the Nordic countries, it occurs only here, on Stora Karlsö, and on Öland. Otherwise it grows on the steppelands of south-eastern Europe.

The road leads south to Hoburgen, an area consisting of five hills of reef limestone on the south-westernmost peninsular of the island. Tourists flock to this spot, mainly to see the remarkable sea stacks, such as the famous Hoburgsgubben (Old Man of Hoburgen) and the deep caves, the most famous of which is Hoburgsgubbens sängkammare (the Old Man's chamber). According to folklore, a giant lived in this cave. He had moved to Gotland with all his treasures and with the stolen church bell from Kisa church in Östergötland on the Swedish mainland, because he disapproved of the building of a church in his neighbourhood.

The sea stacks and caves were sculpted by waves of the Ancylus Lake 8000 years ago. The undulating raised beaches along the shingle shores were thrown up by storms, and the characteristic wave pattern has been formed as the land rose slowly from the sea.

Hoburgen exhibits interesting bedrock geology, with a large variety of rock types, sedimentation structures, and a good number of fossils. However, Hoburgen is not predominantly a fossil locality, but is mainly worth a visit to see its sedimentary rocks and the information that the area provides of the most recent history of the Silurian on Gotland.

The cliffs reach a height of 30 metres. They are built up from the three youngest stratigraphical units of Gotland: Burgsvik, Hamra and Sundre formations. The second hill from the south descends abruptly to the beach, with quite a steep section. On the beach, at the water's edge, especially at low tide, the upper part of the Burgsvik Formation is clearly visible, consisting of sandstone and oolite. Oolite means 'fish roe stone', and the name refers to the similarity between the small round spherical calcareous particles that make up the rock, and fish roe. Calcareous particles, ooids, are of sand-grain size, 0.06 – 2 mm, and have been formed by the deposition of coatings of calcium carbonate around tiny fragments that were rolled around in very shallow, warm water. Ooliths made up of larger fragments are called pisoliths, meaning 'pea stones'.

In the cliff section, the sequence of layers is easy to follow. At the bottom is the Burgsvik Sandstone. This is then succeeded gradually by the fossiliferous Burgsvik Oolite, in which cross-bedding can be seen. The oolite becomes increasingly pisolithic (the grains become coarser) higher up. The Burgsvik Formation, no more than 1.5 metres at this point, is overlain by a marly and highly fossiliferous limestone belonging to the Hamra Formation. Some of the sediment is made up of conglomeratic calcareous algae, derived from the calcareous algae *Rothpletzella*. Both the oolites and the calcareous algae indicate a very shallow depositional environment. The rest of the limestone is

Husrygg scenery at sunset (top). Hoburgsgubben – the Old Man of Hoburgen. Photos: T. Bauert.

mainly fragmental. The Hamra Formation at this point is about 20 metres thick.

The upper part of the cliff consists of stratified and reef limestones belonging to the very youngest formation on Gotland, the Sundre Formation, with a thickness at this point of about 8 metres. Most of the rocks are reddish limestones consisting almost entirely of crinoidal remains that have fallen down from the nearby reef and now form a coarse fragmental limestone. This has been quarried under the name of Hoburg Marble, and used for decoration and sculptures, predominantly in churches in the south of Gotland. A gaping hole in the southernmost and largest hill is a heritage from a long period of quarrying of Hoburg Marble. In large boulders of stone debris, you can study the beautiful red limestone whose fractures glisten in the sun. The quarrying, which was carried out since the Medieval Period, was abandoned long ago, when the quarry had been depleted of its best stones. The name 'marble' is of course erroneous, but it has been used commercially both for this and for other crinoidal limestones, such as Karlsö Marble.

By you ascending the scree slope and walking up the hill path, you will see the large reefs at close range. These have been subjected to detailed scientific study, and give their name to a 'Hoburgen reef type', which is characterized firstly by its size of about 100 m^2, secondly by its content of many different species, and thirdly by the predominance of stromatoporoids, corals and calcareous algae.

Kettelvik

Along Storsudret – the western coast of southernmost Gotland – there are low cliffs formed mainly of sandstone. Because the sandstone was quarried in the past, most exposures are in abandoned quarries between the road and the sea, often with large piles of waste stone lying on the coastal side of the quarries. However, in Kettelviken bay there is an easy accessible natural coastal section cutting through the sediments, which belong to the Burgsvik Formation, one of the younger formations on the island. The sediments are thinly and thickly bedded, light grey, fine-grained sandstones, partly interbedded with bands of argillaceous rock. In the uppermost part of the sequence there are oolitic and oncolitic (calcareous algae) limestones.

Sandstones on Gotland occur essentially only along a small belt running from Grötlingbo in a south-easterly direction along the west coast of Storsudret down to Hoburgen. The sandstones are made of quartz grains cemented by calcium carbonate; that is, the pore spaces between the sand grains have been filled with calcite precipitated from water trickling through the sediment. Since calcite is easily soluble and the stone becomes porous, the sandstone rock crumbles rather easily. This also makes it easy to work for building and sculptures. Furthermore, it occurs in easily-quarried, homogenous layers. In air-polluted towns, such sandstone buildings and sculptures are unfortunately decomposing at an alarming rate.

The sandstone was deposited as a near-shore sediment. Ripples are common, as well as other sedimentary structures indicating a shallow environment. Finer bedding, sitting at a low angle across the horizontal beds, is also preserved in the section. This is known as cross-bedding, which indicates a rapid deposition of sand, either in a tidal environment or during a storm. Other, somewhat larger structures include concave beds, indicating partial collapse of the sediments before they became lithified, possibly due to minor earthquakes. Towards the end of the Silurian Period, when these sediments were formed, the collision between 'our' continent and Laurentia was drawing to a close. The resulting high mountain range, of which the Norwegian-Swedish mountain chain is a remaining part, immediately began to erode, and provided enormous volumes of sediment in the form of clay, sand and gravel. Volcanic eruptions and movements in the crust of the earth were also associated with these events. The boundary between the sandstones and the overlying limestones represents a time when sea level began to rise again.

Oolite means 'fish roe stone', and the name alludes to the similarity between the small round spherical calcareous particles that make up the rock, and fish roe. Calcareous particles (ooids) are of sand-grain size, formed by the deposition of coatings of calcium carbonate around tiny fragments that rolled around in very shallow, warm water.

Oncolitic, or algal limestones consist mainly of irregular calcareous nodules, a few centimetres in size. In cross-section each nodule can be seen to be made up of thin, spherical layers of calcium carbonate coating a core of shelly fragments. These calcareous nodules were formed by calcite-precipitating algae in shallow water.

Fossils are relatively scarce in the sandstone. On horizons in the oolitic upper part of the section, however, there are accumulations of shells from the bivalve *Pteronitella*, together with numerous other fragmental fossils. Parts of the large trilobite *Homalonotus* occur in the sandstone, and with a certain degree of stubbornness, time and a stroke of luck, it might be possible to find parts of fishes such as acanthodians and ostracoderms. Otherwise, in the Burgsvik Sandstone, the richest finds of spores from the oldest terrestrial plants can be made. Trace fossils in the form of infilled tunnels of burrowing organisms, probably bristle worms, are common in the sandstone. It is also possible to find various kinds of traces, grazing tracks and imprints of resting animals, all documenting the activities of a bottom-living fauna in this environment.

Kettelviken Sandstone Museum

Along the beautiful western coastal road down to Hoburgen, there is a series of small stone quarries, between the road and the sea. Here, sandstone has been quarried since the 11th century. The stone was used for baptismal fonts, and for building and ornamental stones, which were exported to the mainland and the continent. Even grinding stones and whetstones have been, and still are, an important product of sandstone.

A museum exhibiting the history of stone quarrying and Limeworks industry has been set up in one of the old abandoned quarries just south of the bay of Kettelvik. The last stonemason worked here until the 1980s. Grinding stones were produced. In the museum there are displays that show how the quarrying was done, and how the stone was processed. Tools, grinders and a wind-power-driven water pump are still preserved. Grinding stone history and stone workers life is portrayed in the indoor exhibition. You can also try to cut sandstone using traditional tools.

The sandstone was mined in opencast workings located alongside the beach. The natural low coastal cliffs, where sandstone layers were accessible from the side, were used initially, and then the stone was gradually quarried towards the inland. Waste stone was thrown in heaps on the seaward side. The sandstone was thickly bedded, with thin clay layers in between and with vertical cracks cutting the stone. These cracks and clay layers were a precondition for breaking the stone easily, with the methods that were available at that time.

Kettelviken Sandstone Museum.

Stora Karlsö and Lilla Karlsö

The small islands of Lilla Karlsö and Stora Karlsö, off the south-western coast of Gotland, are clearly visible from the coast of Eksta. The islands are south-westerly extensions of the reef complex that runs from north-eastern Gotland, across the Klinte area and out into the sea.

Stora Karlsö is the largest and furthermost island, 6 km from the coast of Gotland. It has an area of less than 2.5 km^2. The bedrock comprises mainly hard reef limestone and bedded limestone belonging stratigraphically to the Slite Group. Along the west coast there is a fossiliferous marlstone unit.

A horseshoe-shaped plateau dominates the island, forming a slightly arched and somewhat hilly surface because of the reefs in the bed rock. The highest point, Roisu Haid, is 52 metres above sea level, located on the eastern side, while Marmorberget on the plateau's western section is 45 metres above sea level. Between these points, in the shallow hollow of the plateau, is the plain of Norderslätt, bounded by the steep cliff of Norderhamnsberget to the west and Austerberget in the east. A beach plain, Suderslätt, covered with sea ridges of shingle, spreads to the south.

In the west, north and north-east, the plateau is bounded by steep, 10-30 metres high coastal cliffs. Rocks and boulders form large scree areas on the foreshore below. The plateau is criss-crossed with cracks in the bedrock caused by movements in the crust. On the cliff slopes, these are often developed as caves and gorges. At the south-western part of Marmorberget the cracks have been subjected to chemical weathering and a distinctly flat karst landscape is formed.

Like the rest of Gotland, Stora Karlsö was completely below the water surface at the time when the inland glacier left the area. Subsequent uplift then led to the origin of the island. On higher areas, such as Raisu Haid and Marmorberget, loose weathered rock deposits are almost completely washed away. Intense wave action has also carved out a number of caves in the cliff walls. The 25 metre deep Stora Förvar, together with Jungfruhålet and Korphålet at a depth of 12 metres, are caves formed by waves of the Ancylus Lake. Well-formed sea stacks are preserved at the beach called Svarthällar on the south-eastern coast. The waves have also thrown up shingle in unusually well-developed beach ridges.

Until the late 17th century sheep grazed the entire island all year around and the original forest had long since given way to a grazing-resistant vegetation. After 1884, when grazing was stopped, deciduous trees and other lush vegetation began to regain ground. Today, a part of the island is again pastureland.

Stora Karlsö is known for its rich flora. In late April and into mid-May pheasant's eye (*Adonis vernalis*), a heat-loving steppe plant, blooms commonly. Otherwise in Scandinavia it is found only along Husrygg at Hoburgen and on Öland. The elder-flowered and early purple orchids show displays of colours a few weeks earlier. *Globularia vulgaris*, *Anemone sylvestris*, goldilocks aster, *Mulgedium quercinum* and *Artemisia rupestris* are other heat-loving plants that previously had a wider distribution. Stora and Lilla Karlsö have Sweden's only bird cliffs, on which guillemots and razorbills nest.

Lilla Karlsö is just over 3 km off the coast of Gotland and 4.5 km from Stora Karlsö. It is 1.6 km^2 in area, dominated by an almost circular plateau whose highest point is 66 metres above sea level. The plateau is bounded on the north and south by beach plains, but in the west and east are steep cliffs that drop almost straight down to the sea. At various levels in the cliffs the sea has hollowed out some 25 caves, of which a few are 30 metres deep. Some sea stacks are present along parts of the coast.

The vegetation of Lilla Karlsö is affected by intensive sheep grazing, which has been maintained on the island for hundreds, perhaps thousands of years, and most of the island is barren of trees and shrubs. Only in the scree above Suderslätt is there a sparse grove of several hundred year old ashes, oaks and elms. Lilla Karlsö is now grazed by Gutefår, an ancient Gotland breed of sheep in which both rams and ewes have horns.

The flora of Lilla Karsö is dominated by pasture-dwelling species, such as sheep's fescue, meadow oat grass, soft-brome, common rock-rose, *Vincetoxicum*, breckland thyme, lady's bedstraw, rock wormwood, wild marjoram and spiked speedwell.

Like Stora Karlsö, Lilla Karlsö is however, best known for its bird life. Large numbers of guillemots and razorbills breed on the steep cliffs. Other typical birds are herring gull, lesser black-backed gull, great black-backed gull, eider, velvet scoter, northern wheatear and rock pipit. A newcomer to the island's fauna is the great cormorant, which began nesting here in 1992, since when numbers have risen sharply.

Both islands are nature reserves and have large bird sanctuaries. It is also strictly forbidden to collect fossils. Day visitors during the nesting season may not walk freely around the islands, but must be in the company of the knowledgeable guides. There is accommodation on both islands. Between May and August there is daily boat transport from Klintehamn to Stora Karlsö. From Djupvik fishing village, about 15 km south of Klintehamn, there are daily ferries to Lilla Karlsö.

Stora Karlsö. Photo: T. Bauert.

Stora Karlsö scenery.
Photo: T. Bauert.


Langhammarshammar
Avanäset
Digerhuvud
Tunguhuvud
Gamlahamn
FÅRÖ
Bläse
Fårö-
sund
Bungenäs
Sigsarve
Ireviken
Lickershamn
Lärbro
Lergrav
Furillen
Kyllaj
Lummelunda
Slite
Tingstäde
Kallgateburgs
St. Olofsholm
Hejnum hällar
Korpklint
VISBY
Högklint
Rövar Liljas håla
Gothemhammar
Roma
Grogarnshuvud
GOTLAND
Kuppen
Klintehamn
Gannarve
Folhammar
Ljugarn
Lilla Karlsö
Stånga
Stora Karlsö
Hemse
Havdhem
Uggarderojr
Burgsvik
Faludden
Kettelvik
Husrygg
Holmhällar
Hoburgen
geotourism sites described in the text
geotourism sites mentioned in the text
0
5
10 km

ISBN 978-9985-9973-4-5