1 Coastal dynamics

> Coasts – the areas where land and sea meet and merge – have always been vital habitats for the human race. Their shape and appearance is in constant flux, changing quite naturally over periods of millions or even just hundreds of years. In some places coastal areas are lost, while in others new ones are formed. The categories applied to differentiate coasts depend on the perspective from which we regard them.

On the origin and demise of coasts

> Coasts are dynamic habitats. The shape of a coast is influenced by natural forces, and in many places it responds strongly to changing environmental conditions. Humans also intervene in coastal areas. They settle and farm coastal zones and extract resources. The interplay between such interventions and geological and biological processes can result in a wide array of variations. The developmental history of humankind is in fact linked closely to coastal dynamics.

Special allure

Coasts are a special habitat. They are the transition area between land and sea and are influenced by both realms. Rivers carry nutrients from the land to the coastal waters and thus represent the basis of the marine food chain. The seas transport sediments – washing them ashore, reworking them or carrying them away, all of which change the shape of the coast.

No other marine environment is more productive. Coasts provide nourishment in the form of fish and other seafood. But they are also important transportation routes for shipping and are intensively exploited for the production of natural gas and oil. At the same time, the coasts are highly desirable recreation areas for millions of vacationers. Numerous cities have been built on the coasts, and industries and power plants take advantage of their often well developed infrastructures.

1.1 > Many cities developed in coastal areas. The Beyoğlu district of Istanbul, for example, is thousands of years old. It lies on the Golden Horn, a fjord-like inlet that divides the European part of the city into southern and northern areas.

In general, the coastal zones of the Earth are extremely variable in shape and form. They are of great importance for humans, animals and plants, as well as for the atmosphere and climate because:

- they comprise around 20 per cent of the Earth's surface;
- they represent important transportation routes and sites for industry;
- they are attractive recreation and tourist areas;
- they are sources for mineral and fossil raw materials;
- they encompass key ecosystems with great species diversity;
- they act as important sediment traps that consolidate river sediments;
- in their role as a buffer between the land and sea, they affect many global parameters;
- 75 per cent of all megacities (populations greater than ten million) are located in coastal zones;
- 90 per cent of global fisheries operate in coastal waters.

The attraction of coasts for people is very strong today. Globally, coastal populations are growing at a rapid pace. According to estimates by the United Nations, around 2.8 billion people presently live within 100 kilometres of a coast. Of the 20 megacities in the world with populations of more than ten million, 13 are situated near a coast. These cities or areas of high population density include Mumbai (18.2 million), Dhaka (14.4 million), Istanbul (14.4 million), Calcutta (14.3 million) and Beijing (14.3 million). Many experts believe that the urbanization of coastal regions will continue to increase in the coming years.

The coast – where does it start, where does it end?

As a rule, maps depict coasts as lines that separate the mainland from the water. The coast, however, is not a sharp line, but a zone of variable width between land and water. It is difficult to distinctly define the boundaries of this transition zone. In the 1950s, scientists suggested using a definition of coast as the area that is influenced by the surf. Landward, this includes the extent to which the airborne saltwater spray can reach, thus encompassing some vegetation on the land. Seaward, this would extend to the area where the surf makes itself noticeable, for example, where it contributes to shaping the sea floor.

Although efforts are being made to establish a theoretical and universally accepted definition for the term "coast", in practice disparate conceptions come into play. Different aspects predominate in science, depending on the particular sub-discipline being applied. Biologists, for example, concentrate primarily on life in the sea or in wetland areas along the coasts or in estuaries. Coastal protection specialists, on the other hand, who make plans for dikes and other protective infrastructures, are also interested in the hinterland to the extent that it could be impacted by storm floods. Economists have an especially broad definition of the term "coast". As a rule they consider not only harbours and industrial areas near the coast, but also the flow of goods over the sea or to inland regions.

Over the past several decades, geologists and oceanographers have also attempted to systematically delineate and catalogue the world's coasts. Here there are also different approaches depending on the focus of the effort. Coastal types are differentiated based on whether they are characterized by "high-energy" formations such as rocky or sandy coasts that are directly bathed by the surf or, like the Wadden Sea, are characterized by relatively calm, "low-energy" areas that are protected by sand banks or offshore islands.

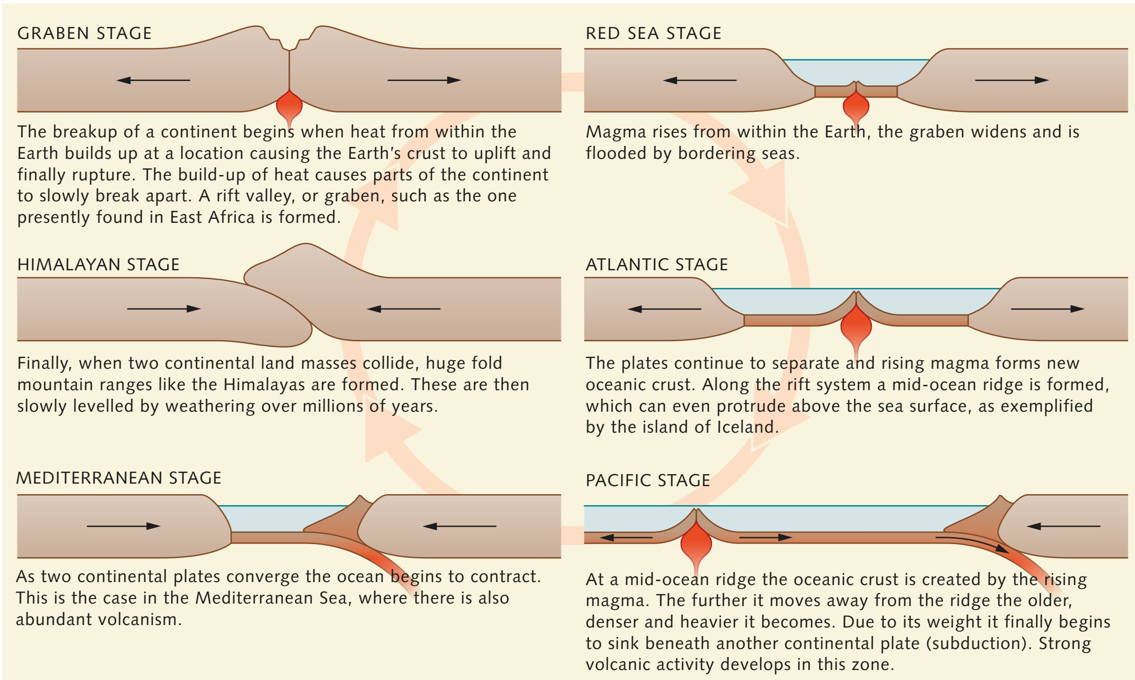
In spite of their differences, many coasts have one thing in common: their great importance for humans. Coasts have been the starting points for explorers and the targets for conquerors. Archaeologists and ethnologists believe that the coasts have played a great role in the settlement of new continents or islands for millennia. Before people penetrated deep into the inland areas they travelled along the coasts searching for suitable locations for settlements. The oldest known evidence of this kind of settlement history is found today in northern Australia, where the ancestors of the aborigines settled about 50,000 to 40,000 years ago, presumably arriving on boats from islands that today are part of Indonesia.

Dynamic habitat

Coastal contours are often viewed as fixed and immovable. People try to maintain a fixed line, not least of all to protect cities and systems that have developed and are concentrated at the coasts. But generally there is hardly any other area that is so dynamic and undergoes so much constant change as do the coasts. Experts call it a transient habitat.

Depending on the time span being considered, different kinds of change can be observed. The slowest, but at the same time most drastic changes that coastlines undergo are caused by the motions of the continents. Movement of the continents was first postulated by the German researcher Alfred Wegener, who published his theory of continental drift in 1912. In the subsequent decades this theory was constantly expanded and improved. Today it is

1.2 > Alfred Wegener (1880–1930) was a German meteorologist, polar researcher and geoscientist. He proposed the scientific principle of continental drift. His theory, however, was long considered a foolish idea. It was not generally accepted until the 1970s.



1.3 > Crustal material is created and destroyed at time scales of millions of years. In a continuous cycle, the individual continental plates collide, drift, and change their position relative to one another. It is possible to break the cycle down into individual stages, some of which are named after a present-day region that represents that stage. John Tuzo Wilson, a Canadian geoscientist, was the first to describe these cycles.

called plate tectonics. It states that the Earth is comprised of multiple layers, the uppermost of which, the lithosphere, is slowly moving. The lithosphere is made up of numerous large plates that lie side by side and move relative to each other by as much as 10 centimetres per year. The lithosphere includes the continents, but carry also the large ocean basins. It has an average thickness of around 100 kilometres and glides along atop a second Earth layer called the asthenosphere.

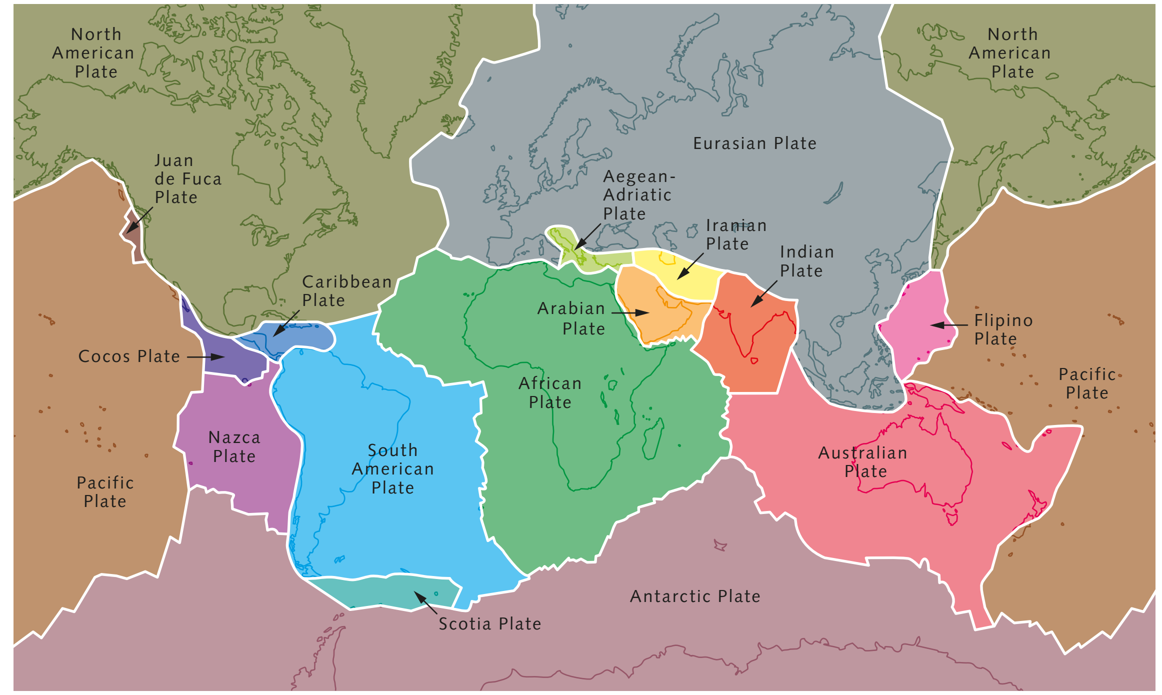
In some places one lithospheric plate is thrust over another, causing upward folding of the rocks over millions of years and forming high mountains like the Himalayas. In other regions the plates slide along beside each other or drift apart. Coastal regions and the shallow marine areas called shelves are especially affected by these movements because they are situated on the margins of the continental parts of the plates, and are thus strongly deformed by the drifting of the continents.

Today, the vestiges of coastal seas such as fossilized bivalves, snails and other organisms of the shallow coastal waters can be found in many mountain ranges worldwide, including the Alps.

Continental drift also changes the shape of coasts by another mechanism. When a mountain range is created on land by uplift and folding, that is, when part of a continental plate is thrust over another and rises out of the water, one result is a drop in sea level. However, sea level can also rise to the extent that magma gushes in at the mid-ocean ridges, displacing large volumes of water.

Breakup of the supercontinent

Throughout the **Earth's history** many alternating tectonic phases have occurred. There have been times when the continents were connected to form a single supercontinent or a few large continents. These were followed by phases when the giant and large continents drifted apart again. These repeating sequences are named the Wilson cycle, after the Canadian geologist John Tuzo Wilson who first described this principle in a journal article in the 1960s. The most recent cycle began about 300 million years ago when the continental plates collided to form the supercontinent Pangaea. Around 230 million years ago



1.4 > Continental plates carry both the land masses and the oceans. They move at speeds of up to several centimetres per year. At some places the continental plates move away from each other, for example, at mid-ocean ridges. At other places plates are thrust over or under one another. The Indian plate is being subducted below the Eurasian Plate, causing continued growth of the Himalayas.

1.5 > Millions of years ago the continental plates formed a largely contiguous land mass, the supercontinent Pangaea. At that time the Atlantic Ocean did not exist.

Pangaea began to break apart again, separating first into a northern (Laurasia) and a southern part (Gondwana). In the second phase, beginning about 140 million years ago, Gondwana split into the land masses that eventually developed into present-day Africa, South America, India and Australia. The breakup of Laurasia began around 65 million years ago with the separation of the North American and Eurasian land masses. This opened the North Atlantic, and India drifted more than 6000 kilometres to the northeast to collide with the Eurasian Plate about 40 million years ago. Over time the Himalayas were thrust and folded upward. India is still drifting northward today, causing the Himalayas to grow about one centimetre higher each year.

Evolutionary biologists believe that the early phase of the breakup of Pangaea, associated with the formation of new coasts, favoured the origin of new species.

Life goes ashore

As a result of the drifting of continents, coasts were not only created and destroyed, but also moved laterally. Entire coastal regions drifted into different climate zones, resulting in adaptation by existing organisms and the emergence of new life forms. An interesting aspect of these developments is assessing the role of coasts in the transition of life from the sea onto land. Today it is generally accepted that the first life forms developed in the sea and expansion to the land occurred at multiple locations at different times and at different rates. This took place within different groups of organisms completely indepen-

1.6 > Evidence for movement of the continental plates can be seen in Iceland. The island lies partly on the Eurasian and partly on the North American Plate. These two plates are drifting apart by a few centimetres every year. The fissure that cuts across the island is called the Silfra rift.

Evolution of the eel – a matter of continental drift

Many new animal species have originated when the population of an existing species was divided. Through the course of evolution these separated populations then developed along different paths, so that new species with different traits emerged. The major causes of separation included ice-age glaciers, which cut off entire regions from one another, and continental drift, which pulled land masses apart.

In many instances populations of marine organisms were also separated by continental drift. Such processes are exemplified by the eels. Today there are around 15 species of eels, including the American eel *(Anguilla rostrata)*, which lives on the east coast of the USA, the European eel *(Anguilla anguilla)* and the Japanese eel *(Anguilla japonica)*. It is assumed that all eel species in fact descend from a common ancestor. The home territory of that ancestor lay to the east of the supercontinent Pangaea, in the Tethys Ocean in the general vicinity of present-day Indonesia. The ancestral eel, like the modern eels, must also have made regular long migrations between its spawning region in the ocean and its nursery areas in the rivers.

As the northern part of Pangaea (Laurasia) separated from the southern part (Gondwana), an east-west waterway opened for the first time, connecting the Tethys Ocean in the east with the sea in the west. The ancestral eel was thus able to spread into the western sea. But continental drift continued. Around 140 million years ago Gondwana began to split into the land masses that became Africa, South America, India and Australia. Africa and the land mass of the Arabian Peninsula moved northward and eventually collided with the Eurasian Plate. This effectively closed the connection between the western and eastern oceans again. The two eel populations were isolated from one another and continued to evolve separately. This theory is known as the Tethys corridor hypothesis. Other hypotheses have been suggested for the genesis of eel species, but experts consider this to be the most probable.

The splitting of the Atlantic population into two distinct species, the European and the American eel, can likewise be attributed to continental drift. Although these animals are outwardly very similar, there are differences in detail that allow a distinction of the two species. Both the European eel and the American eel live in coastal waters and rivers until they reach sexual maturity. They both migrate from their regions in America and Europe into the Sargasso Sea in the Western Atlantic to spawn. Here they release sperm and egg cells into the water. Still in the Sargasso Sea, larvae hatch from the fertilized eggs and then embark upon the return trip toward Europe or America.

During the migration phase back to Europe of one to three years, larvae grow from an initial size of three millimetres to a length of up to 70 millimetres. A second larval stage follows this. While still in the sea, the larvae take on the shape of a willow leaf: at this stage they are also called willow-leaf larvae. These then develop into transparent juveniles called glass eels. They continue to migrate into coastal waters and rivers where they develop into mature animals. Because their respective spawning grounds only overlap slightly, the two species rarely crossbreed. Thus hybrids are only sporadically observed.

It is thought that the Atlantic eel split into two species over time because the Atlantic has continued to widen. Two populations were formed, one in the east and one in the west. Even today the Atlantic is widening by several centimetres each year. This is because two continental plates are slowly moving apart in the middle of the Atlantic. Today the European eel has to swim a distance of 5000 to 6000 kilometres to reach its spawning grounds in the Sargasso Sea.

1.7 > Before Europe and Africa were connected by a land bridge the eels could disperse from the east to the opening Atlantic Ocean region.

1.8 > Whales evolved from land mammals. Their terrestrial provenance can be recognized by the fact that they move their tail fins vertically, using the same up-and-down motion that large predatory cats employ. By contrast, fish move their tail fins horizontally back and forth.

dently of one another. It is thought that the arthropods, a group with jointed appendages that includes crustaceans, insects and spiders, settled on land independently of vertebrates. Genetic analyses have shown that the ancestors of present-day insects made the transition from an aquatic to terrestrial life habit around 480 million years ago.

It is assumed that the move to land for vertebrates began around 415 million years ago and lasted until about 360 million years ago. The first land vertebrates presumably evolved from the bony fishes. The first **amphibian** creatures may have been animals of the genus *Kenichthys*. Remains of this small animal, whose skull is only a few centimetres long, were found in China and have been age-dated at about 395 million years. It is possible that they preyed on insects at first. They might also have settled in near-coastal wetlands, river estuaries, wet river banks and brackish water areas where river water mixed with sea water. Among amphibians today there is still an animal group that lives both in the water and on land. Toads need water to reproduce. The development of their larvae takes place in water. For the adult animals, on the other hand, land is the predominant habitat, where they mate and hunt for prey.

Coasts as a bridge between sea and land

Fish of the sturgeon family also exhibit an amphibious adaptation. Sturgeons live primarily in the sea, but seek out freshwater areas to spawn. Interestingly, in addition to the gills typical for fish, sturgeons also have lung-like organs, small cavities in the skull. With a gulping action they fill these with air and can extract oxygen from it – presumably as an adaptation to possible arid conditions. Thanks to the ability to breathe air a sturgeon can survive these dry periods, for example, when a stream or lake shore dries up or carries less water for a short time.

But coasts have also played a role in the opposite direction by facilitating the return of life forms from land back into the sea. Today there are numerous animals whose ancestors lived on the land that have now readapted to the marine habitat. Whales, for example, derive from four-legged land animals, but their two rear appendages have regressed to rudimentary stumps of bone. Their mode of swimming, however, is similar to the motion of some four-legged animals on land whose lower body moves up and down at a fast run. The fluke, or tail fin, of the whale moves in a similar way because the spine and skeleton are still much the same as those of the land mammals. By contrast, fish move their tail fins horizontally back and forth.

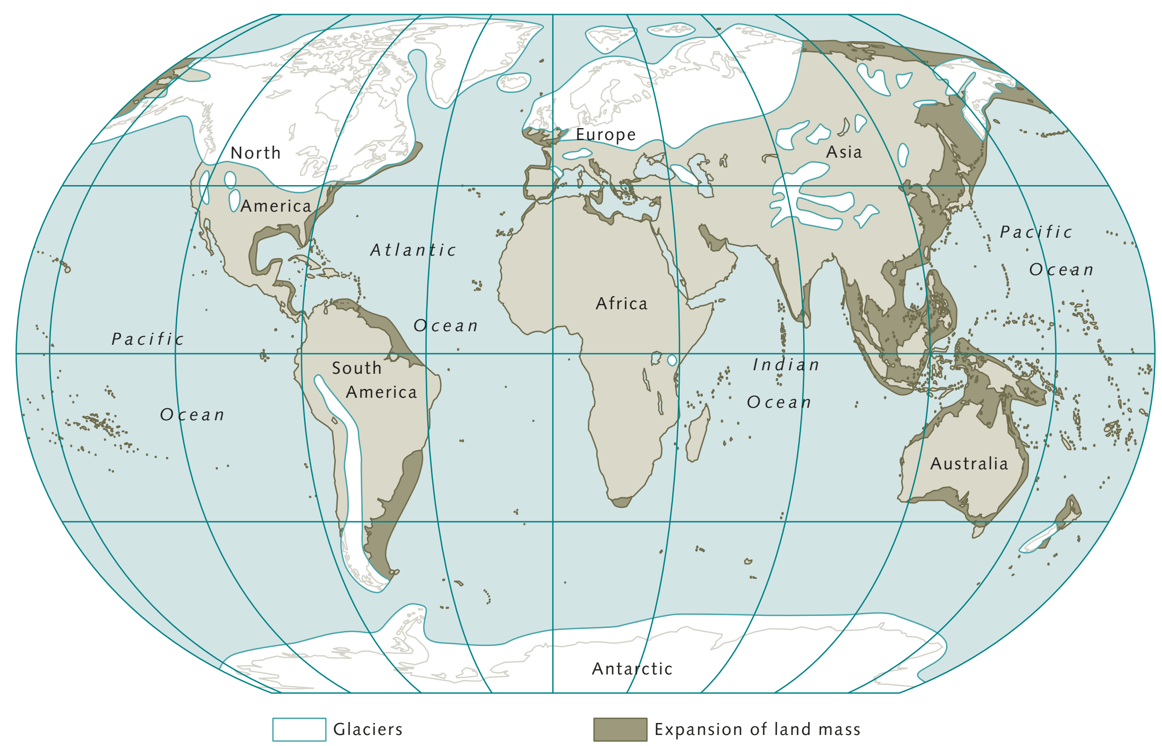
Some turtle species have also made the return from the coast back into the water, although they had originally evolved as four-legged land animals. Sea turtles have developed an amphibious habit, living between the land and sea. Many of these species search out a beach to lay their eggs at spring tide when the water reaches especially high levels. They can thus bury the eggs in the sand high up on the beach where they are protected from flooding. Later the hatchlings also break out during a spring tide, when the water is high again and the arduous and dangerous journey back across the beach into the sea is shortest.

Highs and lows through the millennia

Not only do coasts change their shape at a scale of millions of years, significant changes also occur over much shorter time periods. In cycles with magnitudes of several tens of thousands of years, alternating warm periods and ice ages, with the accompanying sea-level changes, play a significant role.

During the ice ages large areas of the land masses freeze. Precipitation in the form of snow forms glaciers thousands of metres thick. Because large volumes of water are bound up in ice on the land, and river flow into the sea is diminished, sea level falls gradually during an ice age. The most recent ice age ended around 12,000 years ago. The last period of heavy ice cover on the Earth was from 26,000 to 20,000 years ago. Sea level then was about 125 metres lower than today. Broad regions of the northern hemisphere were covered with glaciers, to as far as the Netherlands in central Europe. In warmer regions of the Earth the coastline looked completely different than today.

Around 15,000 years ago temperatures on the Earth began to rise rapidly again. This warm phase is still continuing today. The last warm phase before this one to see temperatures comparable with today's occurred between 130,000 and 118,000 years ago. Sea level at that time was about four to six metres higher than it is today.



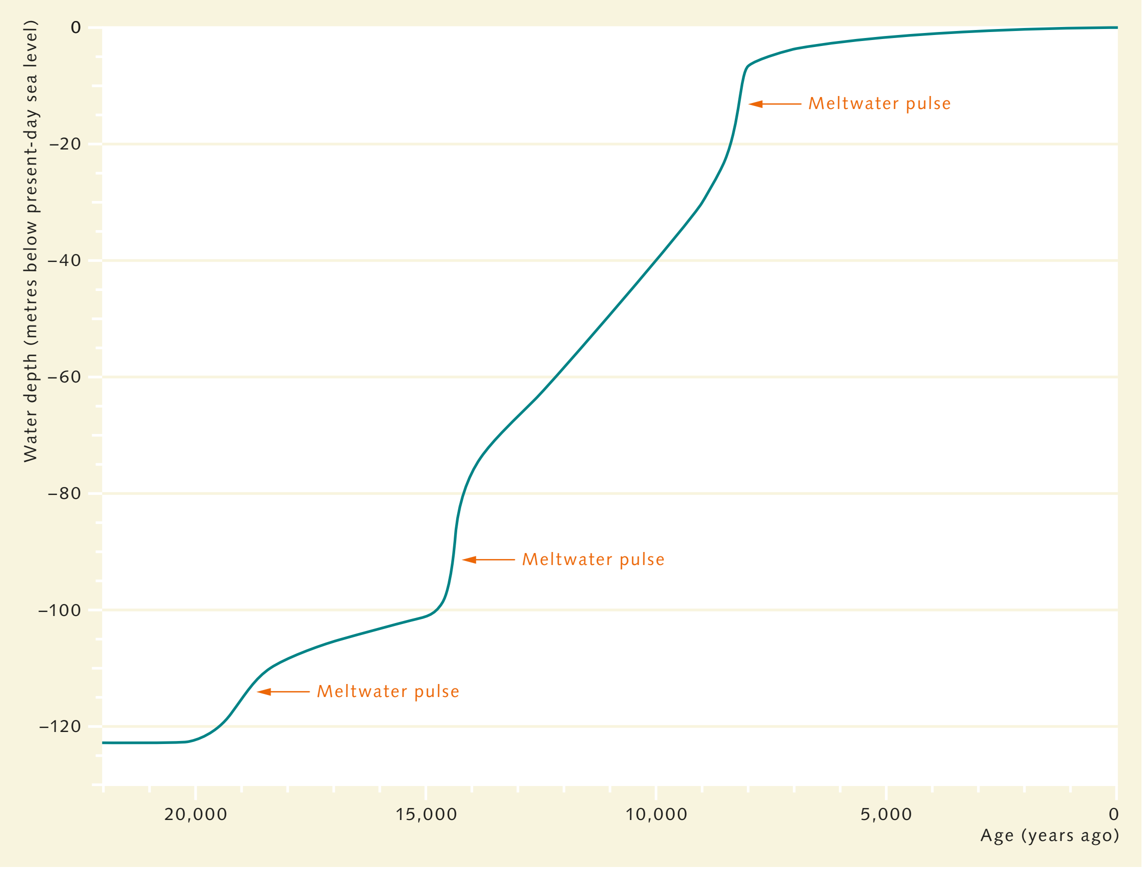
1.9 > At the peak of the last ice age sea level was around 125 metres lower than today. The total global land mass protruding out of the water was about 20 million square kilometres greater.

The big melt

Sea level rose again with the melting of glaciers after the last ice age. This rise generally proceeded steadily but there were occasional periods of accelerated rise triggered by events called meltwater pulses. These involved large amounts of meltwater that were released within a relatively short time. One significant event was a meltwater pulse that began about 14,700 years ago and lasted 500 years. The cause of this, presumably, was calving of the large glacial masses in the Antarctic, or in the Arctic between Greenland and Canada. With the melting of glaciers, sea level rose globally during this time by around 20 metres. Other large events included the runoff of immense dammed lakes that had formed from the meltwaters of retreating inland glaciers. According to scientific estimates, Lake Agassiz in North America had a maximum area of around 440,000 square kilometres, making it even larger than today's Great Lakes.

It broke through the surrounding glaciers multiple times, pouring large amounts of fresh water into the ocean, with one especially significant episode around 8200 years ago. This one meltwater pulse alone is believed to have raised sea level by several metres within just a few months.

The magnitude of sea-level change since the last ice age can be reconstructed based on various lines of evidence, for example, by studies of coral reefs or sediments on the sea floor. Tropical coral banks on the slopes of South Pacific islands have been growing slowly upward along with sea-level rise over recent years and decades. They can only grow in shallow water that is flooded by sufficient light. When sea level rises, the zone in which corals can thrive also shifts slowly upward. By drilling deep into the coral banks, older dead corals are encountered whose age



1.10 > Sea level has not risen at a constant rate over the years. It has been punctuated by surges resulting from events such as meltwater pulses.

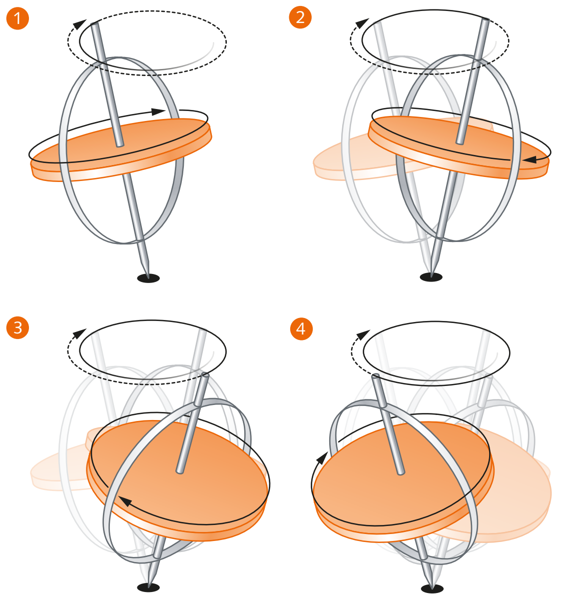
can be determined by special analytical methods. Sea-level elevation at different times can thus be estimated.

The second method involves detailed study of sediments on the sea floor. By examining microfossils found in the sea-floor sediments, including the remains of single-celled organisms or fossilized fish bones and teeth, it is possible to determine when the bottom was part of the exposed land area, whether it was covered by fresh water from the melting glaciers, and when it was finally flooded by salt water from rising sea level. Depending on environmental conditions, different organisms are present and their organic remains are concentrated there. A sediment layer that derived from land plants can thus be clearly distinguished from one in which the remains of marine algae are found.

The sun – a climate engine

The cause for alternating warm and cold phases, with the associated rise and fall of sea level, is related to natural climate fluctuations at regular intervals. Milankovich Cycles, postulated by the mathematician Milutin Milanković in the 1930s, could have had an influence on the warm and cold periods. His theory maintains that the position of the Earth relative to the sun changes regularly, causing variations in the amount of incoming solar radiation received by the Earth. These variations particularly affect the northern hemisphere. According to Milanković there are three primary causes:

- Change in the precession of the Earth's axis, which varies on a cycle of around 23,000 years. Precession can be best explained by a spinning top that has been disturbed by a gentle push. The top continues to rotate, but the axis direction defines a larger circle. The cyclical change in direction of the axis is called precession.
- Change in the tilt angle (inclination) of the Earth's axis, with a cycle duration of around 40,000 years.
- Change in the eccentricity of the path of the Earth around the sun. The shape of the elliptical orbit of the Earth varies. The change occurs in cycles of around 100,000 years and 400,000 years.



1.11 > The Earth changes its precession, the rotation motion, over a period of about 23,000 years. This is comparable to a gyroscope that gradually begins to wobble. It continues to rotate but the axis makes increasingly large circles.

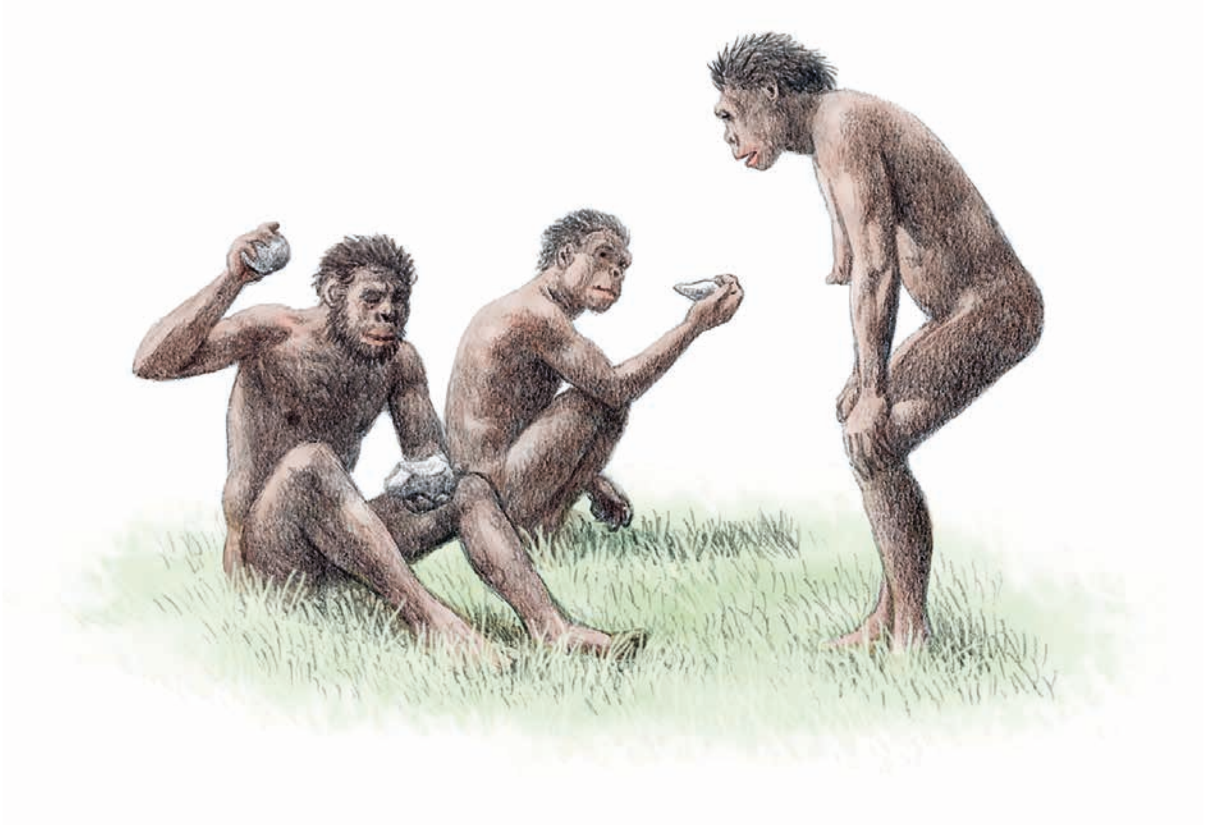
It is known today that the Milankovitch Cycles alone cannot explain the large temperature differences between warm phases and ice ages. But it is very probable that they contribute greatly to the change. There is also an amplifying effect that contributes to the origin of ice ages: the ice-albedo feedback. Ice and snow strongly reflect sunlight (the ratio of reflection is called albedo). The thermal radiation of the sun is thus also reflected, which results in further cooling. The growth of glaciers is thus enhanced.

Changing sea level – the pulse of human evolution

The rise and fall of sea level changed the available land area significantly with each cycle. Many areas that are flooded today were dry at the peak of the last ice age when sea level was about 125 metres lower. The land area in Europe was almost 40 per cent greater than it is today, and worldwide it was about 20 million square kilometres larger, which is approximately equal to the area of Russia. People thus had more extensive areas available that could be used for fishing, hunting and settlements. Experts believe that humans were already practising navigation then. At that time many land bridges between present-day islands and the mainland were still above sea level. Pathways that no longer exist today were available to people for exploiting new areas. These include the northern connection between America and Asia, which is cut off today by the Bering Strait. Another example is the 500-kilometre wide Arafura Sea, the marine region between Australia and the island of New Guinea to the north, which is an important fishing area today but was dry land at the peak of the last ice age.

Out of Africa

Today, it is widely accepted that humans originated in East Africa. The following important epochs of their dispersal are recognized. The first was around two million years ago. At this time the early man *Homo ergaster/Homo erectus* spread, presumably by land, to Europe, China and down to southern Africa. Whether *Homo ergaster* and *Homo erectus* are related, and to what extent, is an object of ongoing research. It is conclusive, however, that both became extinct and were not direct ancestors of modern humans, *Homo sapiens*. The second epoch involves *Homo sapiens*, who had a significantly wide range almost 200,000 years ago. Around 50,000 years ago they migrated to New Guinea from present-day Indonesia and finally to what would become the continent of Australia. New Guinea, which belongs half to Indonesia and half to Papua New Guinea, was separated from the rest of Indonesia by the sea, like today. But by that time, according to experts, the people already had simple boats and basic nautical skills. During this phase navigation on the water, from coast to coast over large distances, already played a role. America, however, was reached and colonized by crossing the land bridge in northern Asia about 15,000 years ago. Much of the evidence of these early human migrations is covered by water today, so there is often an absence of relics or prehistoric indicators of settlements. It is presumed, however, that people spread primarily along the coasts. Inland forests would have made migration difficult over the land, so the coastal pathways were simpler. In addition, fish and seafood were a reliable source of food. With the end of the last ice age, the conquest of new areas by *Homo sapiens* also received a boost. As the glaciers thawed they made room for modern humans, who were now able to spread northward as far as the arctic regions.



1.12 > The early man *Homo ergaster* had many of the skills of modern humans. He made tools. This could have helped in his migration two million years ago from Africa to the north and east.

Modern technology reveals old clues

To better reconstruct the spread of humans and to evaluate the importance of coasts, specialists from various disciplines have been collaborating intensively for several years. Teams comprising geologists, archaeologists and climatologists have joined forces to search for the traces of early settlements and, using modern submersible vehicles and high-resolution echo-sounder technology, to reveal structures in the sea floor in great detail. Underwater archaeology is important in this endeavour because areas on land have been continuously altered by people over thousands of years, while some evidence on the sea floor – including stone-age – has been covered and protected by sediment layers. Near the coasts, scientists now search systematically for underwater caves that were above sea level and dry during the ice age. These caves were used in the past as living areas and could hold interesting clues.

New knowledge is now being obtained from many areas of the world, for instance of the settlement pathways between Africa and Europe in the Mediterranean region. It was long believed that modern humans from Africa advanced to the north by land, along the eastern margin of the Mediterranean. But new finds indicate that migration over the sea from coast to coast must also be considered as a possibility. At present, there are ongoing intensive studies of the role that Malta, an island archipelago between Tunisia and the Italian island of Sicily, could have played. It may have been an important bridge between the two continents. At the peak of the last ice age Malta was significantly larger and was connected to present-day Sicily over a 90-kilometre long land bridge called the Malta-Ragusa Platform, so that the distance northward from Africa across the Mediterranean was much shorter than it is today.

The sea floor around Malta has been mapped in detail in recent years with the help of modern underwater technology. Bottom samples have also been taken. Ancient land structures on the sea floor that have hardly changed over thousands of years became visible: old river valleys, sand banks, stone-age shore lines and possibly even old lakes. In the past, the three present-day islands of the Malta archipelago were connected and there were evidently large fertile areas that would have been of great interest for settlers from Africa. According to the researchers, the trip would have been possible with simple boats. Efforts to find concrete evidence of early settlements are continuing.

Evidence of early settlements is also being sought on the sea floor 200 kilometres to the northwest. There lies the small island of Pantelleria, directly upon the shortest line between Tunisia and Sicily. It is known for its occurrences of obsidian, a black, glassy volcanic rock that was used by stone-age people. Scientists searched a small area for chipped obsidian and were successful. The flaked stones appear to be concentrated at an ancient shoreline that lies below 20 metres of water today. Closer investigation should be able to determine whether it is a stone age find. The scientists believe this is probable.

Sundaland – a melting pot for humanity

Efforts are also being made in Southeast Asia to locate flooded shorelines where evidence of prehistoric settlements may be found. The challenge here lies in the sheer immensity of the ocean region to be investigated. During the last ice age, the present-day marine area between the Asian mainland and the islands of Borneo, Java and Sumatra was a large contiguous land mass that is called Sundaland, and was at that time as large as Europe. Scientists believe that the climate and vegetation in parts of Sundaland changed repeatedly. During some periods there were dense rain forests and at others savannah landscapes predominated. These fluctuations led to periodic large-scale migrations. People migrated from the northern regions to Sundaland. At other times they moved in the opposite direction. Thus, according to genetic models and a few archaeological finds, different tribes intermingled repeatedly at certain times. The region was a genetic melting pot that probably played an important role in the development of modern humans. It is further assumed that during times when the savannahs were predominant, the people moved over particular corridors or plains, possibly also on elevated plains along the coasts.

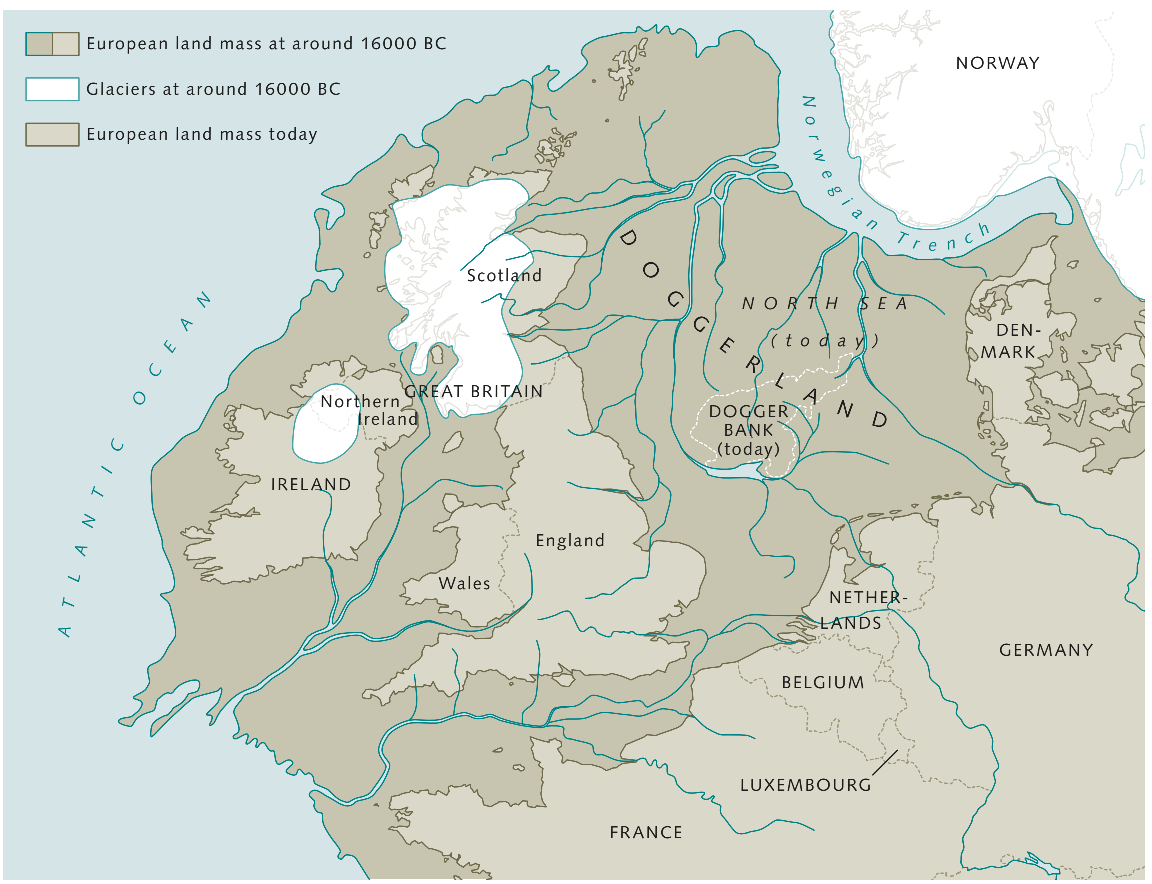
Much is still unknown about the settlement history of this region. This is regrettable because the region represents an important stepping stone in the colonization of New Guinea and Australia, which were a contiguous land mass called Sahul during the last ice age. A land connection between Sundaland and Sahul, however, can confidently be ruled out because the marine area between them, the Banda Sea, was up to 5800 metres deep even at that time.

The Baltic Sea – a young coastal sea

Different factors played a role in the settling of the northern hemisphere as compared to the southern hemisphere. In addition to changes in sea level, the ice masses of glaciers also had an enormous influence on the natural environment and on the history of human settlement. The Baltic Sea is a good example of the extreme changes in landscape. Its history can be fairly accurately reconstructed based on numerous sedimentological studies. It began around 12,000 years ago when the glaciers of the last ice age had retreated back to as far as Scandinavia. At that time sea level stood about 80 metres below its present level. A meltwater lake formed near the centre of the present Baltic Sea, initially with no connection to the open sea because the present-day Kattegat Strait between Denmark and Sweden was still situated above sea level, and was thus dry land. It would have been possible to walk on dry land along the shore of this lake from the present site of Rügen Island to the area of the Danish island of Bornholm.

With rising sea level, as a result of meltwater pulses, this land connection was flooded some 10,000 years ago. However, the connection to the open sea was cut off again about 9300 years ago due to the gradual uplift of the Scandinavian land mass. During the ice age the weight of glaciers caused the land to subside, but this decreased steadily with the thaw. Incidentally, the rebound of Scandinavia is continuing today at a rate of approximately nine millimetres per year.

As a result of the meltwater pulses and accelerating sea-level rise, however, the Kattegat Strait was irrevocably flooded around 8000 years ago.



1.13 > Around 18,000 years ago the North Sea was largely dry land. The area between present-day Great Britain, Denmark, Germany and the Netherlands is called Doggerland, although the exact locations of land masses, glaciers and rivers are uncertain. Doggerland shrunk with the rising sea level until it completely disappeared about 7000 years ago.

Disappearing land

At this time the North Sea was also formed. Until about 10,000 years ago the area between present-day Netherlands, Germany, Denmark and Great Britain was still a large contiguous land mass. It was crossed by large rivers that can be seen as precursors to the Rhine, Weser, Thames and Elbe Rivers. At that time they emptied into the sea several hundred kilometres further to the north than today. Archaeological evidence indicates that the landscape was characterized by moors and birch forests. This area is now called Doggerland, after the Dogger Bank, a shoal present in the North Sea today.

Discoveries of hunting weapons prove that people lived here during the Middle Stone Age or Mesolithic. Rising sea level also flooded Doggerland so that people living near the river mouths had to gradually retreat from the coasts. By around 7000 years ago it had probably completely disappeared. Sea level at that time was about 25 metres below the present level.

Today, the floors of the North Sea and the Wadden Sea on the Dutch, German and Danish North Sea coasts are largely covered with sand and soft sediments that the precursor rivers had carried far out into Doggerland. The cliffs of Heligoland probably projected as an imposing mesa above the vast plain. They are part of a red sandstone layer that actually lies 2000 metres underground but was pushed upward by an enormous salt dome that formed 100 million years ago and underlies the sandstone.

Meltwater disrupts the marine heat pump

With regard to life on the coasts, the most direct impact of the onset of warming 20,000 years ago was the rise in sea level and flooding of large regions. But the presence of Lake Agassiz in North America, which repeatedly released large meltwater pulses into the sea, again exemplifies the fact that these climate changes had other, much further-reaching consequences for people. At this time the northern hemisphere had already warmed significantly compared to conditions during the ice age. The massive release of fresh water interrupted this trend and led to renewed cooling of the northern hemisphere by up to 5 degrees Celsius. The reason is that the surge of fresh water into the Atlantic disrupted the oceanic heat pump, the global thermohaline circulation that moves water worldwide like a giant conveyor belt (*thermo* – driven by temperature differences; *haline* – driven by salinity differences). Through this phenomenon, which occurs in polar marine regions, cold, salty and comparatively heavy water sinks to great depths and flows toward the equator. As the surface water sinks, warm water flows in from the southern regions to replace it. The Gulf Stream, whose branches and extensions transport warm water from southern latitudes to the northeast, and which contributes to Western Europe's mild climate, also depends on this phenomenon.

Even at the time of Lake Agassiz this heat pump led to relatively warm climatic conditions in the northern hemisphere. Discussions continue among specialists regarding the extent to which the meltwater pulses reduced salinity, and whether the thermohaline circulation completely

1.14 > 12,000 years ago people used axes and daggers made of flint from Heligoland. At that time Heligoland, part of a colourful sandstone formation, protruded as a prominent mesa above Doggerland.

1.15 > The Sognefjord is one of the most popular travel destinations in Norway. It was formed during the ice ages by glaciers that slid into the sea here and gouged out the rock below. As the glaciers thawed and sea level rose, the glacial valley was slowly flooded.

stopped. It follows that a halt in the circulation would also interrupt the transport of warm water from southern ocean regions. The climate in Europe and the Near East became cooler and dryer. These changes could have had a decisive impact on **human history**, particularly on the Neolithic revolution, which began about 10,000 years ago. Many humans made a lifestyle transition from hunters and gatherers to sessile farmers and livestock breeders. There are various scientific theories for this transition. One explanation is the "oasis" hypothesis (also known as the "propinquity" or "desiccation" theory). This states that the hunters and gatherers could no longer find enough food, especially because certain prey animals became scarcer due to climate change, meltwater pulses and interruption of the thermohaline circulation. As a result people began to cultivate types of wild grain that grew well in the new prevailing climate.

With the thawing of glaciers the meltwater flow from Lake Agassiz gradually diminished, resulting in higher salinity in the Atlantic again. This gradually restarted the thermohaline circulation, causing temperatures in Europe and the Near East to rise again.

In summary, a comparatively strong rise in sea level began around 20,000 years ago and lasted until about 6000 years ago. Since then, sea level has only varied slightly, with fluctuations of a few centimetres per century. Now with the global warming caused by human activity, the rise has accelerated noticeably again in recent decades.

Glaciers shape coasts

Alternating warm periods and ice ages change coasts, but not only through the rising and falling of sea level caused by glacial melting and growth. They also influence the form of the coastal landscape. During the ice age, glacial ice packages several kilometres thick placed a heavy load on extensive areas of the northern hemisphere land masses. Glaciers typically move slowly across the underlying rocks. One way they move is by gliding on a film of meltwater that forms from ice at the base of the glacier under high pressure. They also move slowly as the ice undergoes internal plastic deformation under its own weight. The migrating glaciers act like giant planers that shape the coasts in different ways. The Stockholm coastal archipelago, for example, consists of 500-million-year old solid granite and gneiss that even a glacier could not strip away, but it abraded the rocks into smooth round hills. Geologists call this kind of region a glacial drumlin landscape. Rising sea level then transformed this region into an archipelago.

1.16 > The Stockholm coastal archipelago is composed of very hard granite and gneiss rocks that were abraded to gently rounded hills during the ice age.

On the steep coast of Norway, by contrast, the round glacier tongues dug deep into the rock and created typical valleys that are sometimes very deep and have a u-shaped cross section. The Sognefjord, for example, presently has a depth of 1000 metres.

The physical character of the land in North Germany, on the other hand, is different. Here the bottoms are relatively soft and very wide glacier tongues formed that pressed the coastal lands downward and at the same time abraded them horizontally. Examples of this include the wide openings of the Kieler Förde and the Eckernförde Bay.

The myriad faces of the coasts

> Our coasts are multi-faceted in appearance. For the most part, their character is determined by the materials that they incorporate and by the physical forces shaping those materials. Attempts to categorize coasts are marked by the diversity of distinguishing features, resulting in the creation of a number of different types of classification schemes.

A million kilometres of coasts

The coasts of the world are highly diverse. The northern coast of Brittany in France is characterized by granite cliffs interspersed with numerous bays. In Namibia the high dunes of the Namib Desert extend to the Atlantic shore, where the coast runs nearly parallel to the dunes. In Siberia, by contrast, the flat coastal region is dominated by permafrost, a metres-thick layer of frozen soil whose surface thaws out for a few weeks each year during the short Arctic summer, when it is especially susceptible to wave action. During storm-flood events, several metres of the saturated banks can break off, creating a constantly changing shore face.

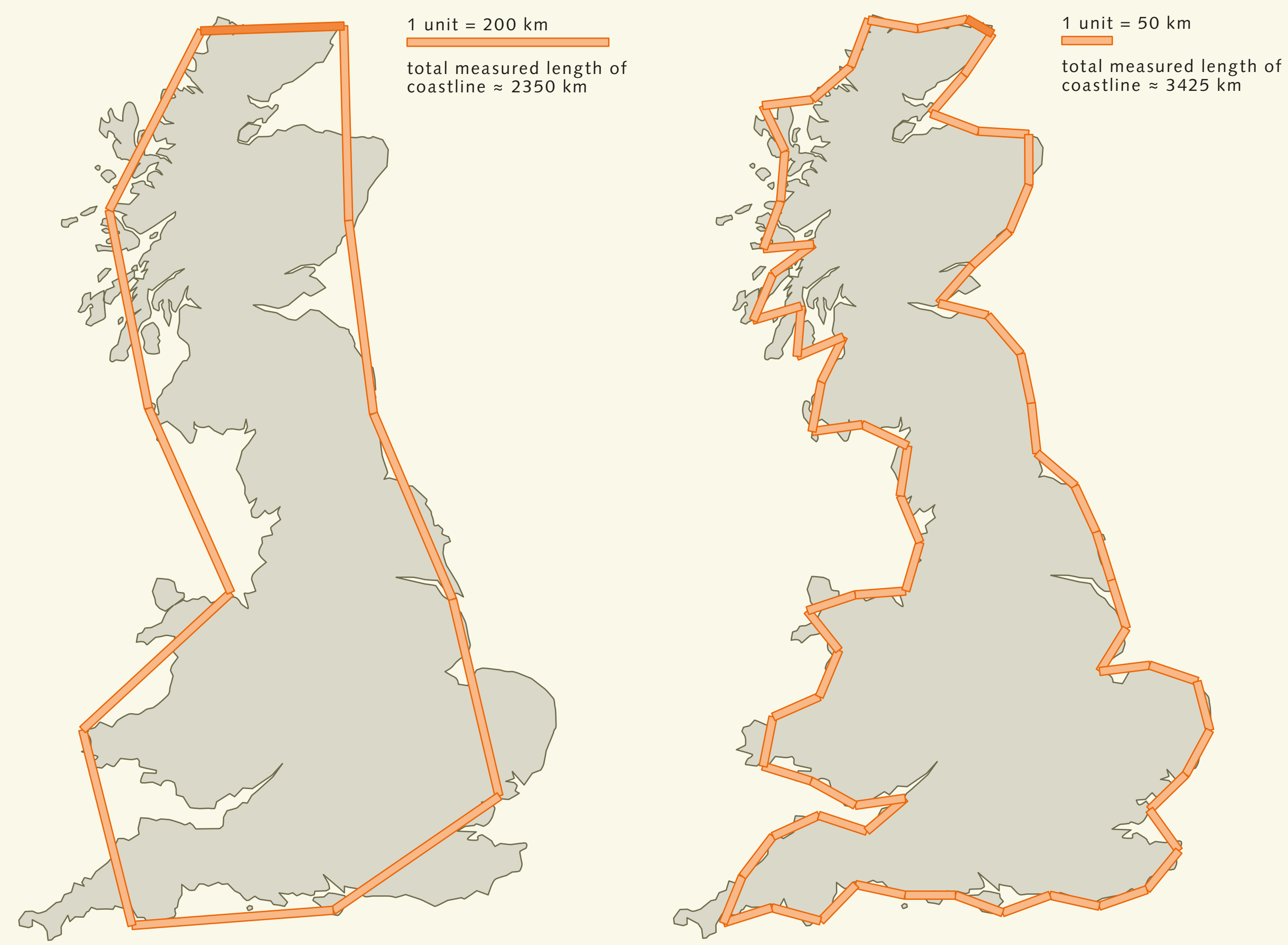
What all of these coasts have in common is that they are narrow strips of land exposed to the forces of the sea. Depending on the context they can be classified in different ways. Coasts can be distinguished based on whether they are strongly or weakly washed by the surf and currents. They can, alternatively, be classified according to the materials they comprise or by the rate that the material is eroded away by the sea. Coasts can furthermore be characterized by their ability to capture sediments that are delivered by rivers or currents. The ultimate form exhibited by a coast also depends significantly on the interplay between the materials that make up the substrate or that rivers transport to the coast, and the physical forces of wind and wave action that impact those materials.

1.17 > In Namibia the dunes of the Namib Desert run parallel to the Atlantic coast.

How long are the world's coasts?

The estimates for the global length of coastlines found in the literature vary widely. This is not surprising because the projected length of a coast depends upon the measurement scale applied. Reference to this fact was made in an article by the mathematician Benoît Mandelbrot published in 1967 in the journal *Science*. In his article, entitled "How long is the coast of Britain?", he also concluded that the answer to this question depended on the magnitude of the measurement scale selected. Using a coarser scale that does not take into account the length of shorelines in the bays, for example, results in a shorter total length. Applying a finer scale for measuring, taking into account smaller embayments, gives a longer coastline. Benoît Mandelbrot later linked his work to the mathematical concept of fractals, a term also coined by him.

A fractal is a mathematical object that is constructed from a repeating structural pattern down to the smallest dimension. In this sense, a coastline can also be resolved to an infinitely fine scale. It is thus theoretically possible when measuring a coastline to include the dimensions of every pebble or sand grain that makes up the coasts. There is a difference here with respect to mathematical fractals in that the structures do not repeat identically at all size scales.

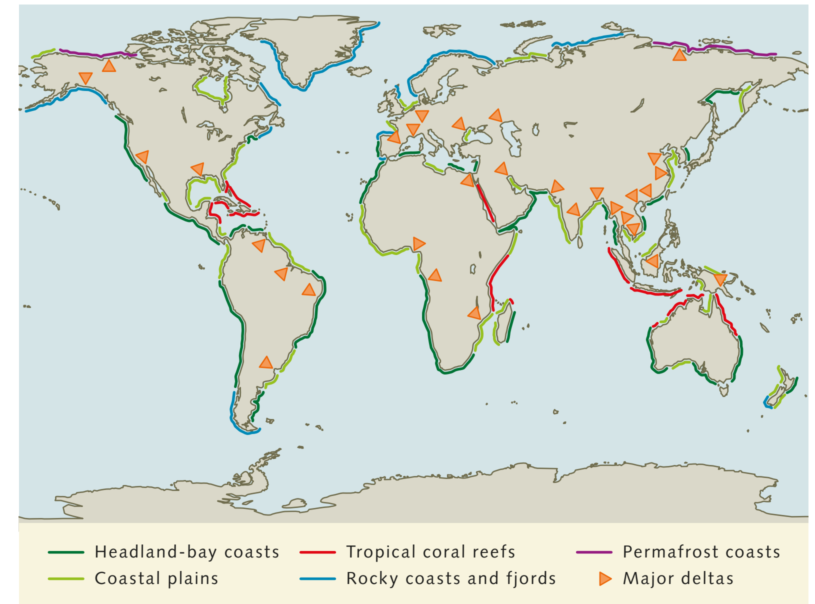


1.18 > The finer the scale used to measure a coastline, the greater the calculated length becomes.

1.19 > This satellite photo shows the Lena River delta in Siberia with all its fine structures, extending around 150 kilometres into the Laptev Sea. A large proportion of the sea ice that eventually drifts out into the Arctic Ocean originates in this marine region.

Geologists estimate the total global length of coastline to be around one million kilometres. This projection, of course, depends on how fine a scale is applied. When considering the entire globe, any differentiation of the coasts is only practical at a relatively coarse scale. For this categorization the continental margins can be traced in their present forms, which are in part a result of plate tectonics. Researchers created such a classification system in the 1970s, under which six different categories of coasts were distinguished.

- **Coastal plain:** an area where the land gently flattens toward the sea. An example is the coast of the West African country of Mauritania, where the land merges into the sea through a broad strip of coastal marshes and low dunes.
- **Major delta:** a large river mouth where sediments from the river are deposited because the ocean currents or tides are not strong enough to transport the material away. This is the case with the delta of the Lena River in Russia, which flows into the Laptev Sea in the Arctic Ocean.
- **Tropical coral reef:** a structure composed of carbonate produced by sessile corals (Cnidarians). It develops as a fringe along the coasts in near-surface waters penetrated by abundant light. Reef-building corals occur in tropical and subtropical waters at temperatures consistently greater than 20 degrees Celsius. A spectacular tropical coral reef is situated along the Central American Caribbean coast between Honduras and Belize. It is around 250 kilometres long and is among the most popular diving areas in the world.
- **Rocky coast and fjord:** a coast of solid rock. Fjords, like those found abundantly on the west coast of Norway, represent a special kind of rocky coast. They were formed during glacial periods, when the motion of the glaciers scoured deep valleys into the bedrock.
- **Permafrost coast:** a deeply frozen soil covering large areas of the Arctic land masses in the northern hemisphere since the last glacial period. Permafrost is found over many thousands of kilometres along the coasts of North America, Siberia and Scandinavia.



1.20 > The Earth's coasts can be roughly divided into six different categories.

- **Headland-bay coast:** a coast where rocky headlands extend into the sea. The headlands act as barriers to obstruct the surf and currents. Slow eddy currents form in the sheltered areas between headlands, gradually eroding the shore and forming bays. An example of this is Half Moon Bay on the Pacific Coast of the United States near San Francisco. There, over thousands of years, a half-moon shaped bay has formed behind a prominent headland.

Wind and waves shape the coasts

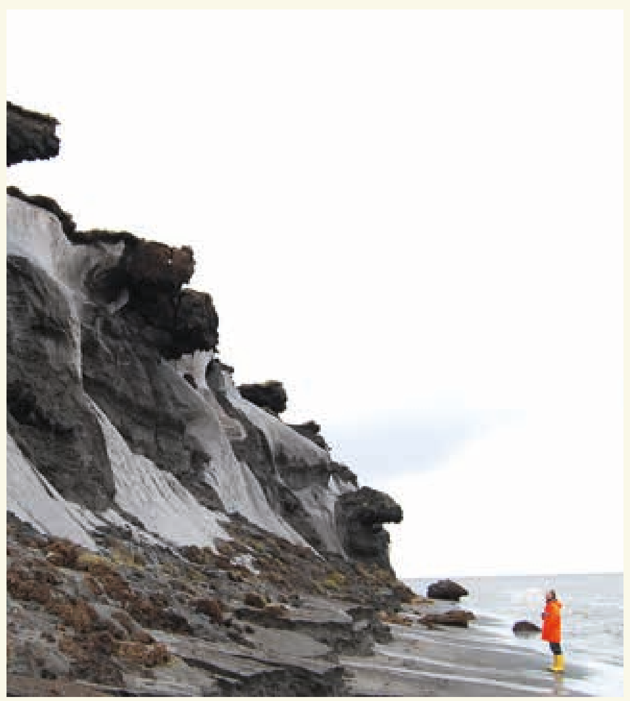
The physical forces of the sea – the waves, currents and winds – have a substantial effect on the shape of the coasts. The intensity of these forces is used to distinguish between low-energy and high-energy coasts.

The kind of material that makes up the substrate of a coastal area is also a key factor influencing the formation of the coasts. Tidal flats comprising relatively fine sediments can be reworked fairly quickly because these materials are easily transported by the currents. Fine sands can also be easily transported, as illustrated by the East Frisian Islands off the German North Sea coast. Because the prevailing winds there blow from

Deep-frozen coast – permafrost

Permafrost is the condition of a soil that has been permanently frozen to a depth of several metres since the last glacial period about 20,000 years ago. The largest permafrost regions are located in the Arctic areas of Alaska, Canada, Siberia and Scandinavia. In all, permafrost covers almost a quarter of the total land mass of the northern hemisphere. Although these areas are very remote and only sparsely settled, the permafrost is of global importance because, like a giant deep freeze, it conserves massive amounts of dead biomass, especially plant material.

A critical current problem is accelerated thawing of permafrost due to climate change. Previously conserved biomass is now being made available for degradation by microorganisms. The metabolism of the microorganisms, however, produces the greenhouse gases carbon dioxide and methane, whereby the amount produced depends upon various factors. One of these is the form in which the carbon is bound up within the biomass and another is the favourability of environmental conditions for the microorganisms.



1.21 > The Siberian island of Muostakh exhibits a permafrost coast that is increasingly susceptible to erosion due to global warming.

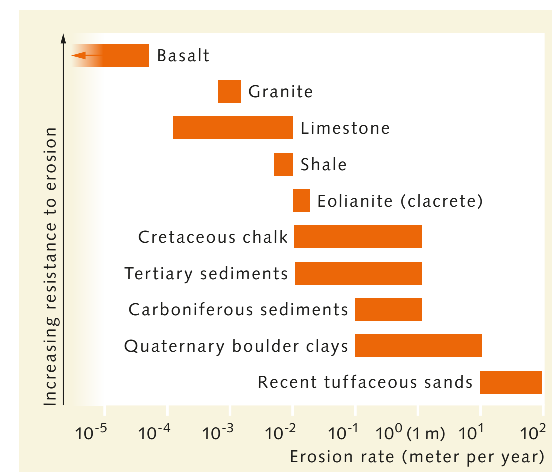
Carbon compounds bound up in the biomass are either stable or labile compounds. In wood pulp lignin, for example, the carbon bonds are very stable, so wood degrades very slowly microbiologically. This will remain the case in the future under cold Arctic conditions because at sub-freezing temperatures the microorganisms are very weakly or not at all active. Labile compounds like plant tissue that were frozen during the glacial period could virtually be degraded immediately. How rapidly biomass will be degraded in the coming years due to permafrost thawing has not yet been conclusively determined. The appearance of many thawed permafrost areas today is similar to moorlands, with standing water on the surface. Because of the low oxygen content of water in boggy soils, however, biomass is only weakly degraded. This is the reason that historical wooden objects or animal pelts remain well preserved in moors. Thus, the questions of whether and to what extent the thawing permafrost will release greenhouse gases are likewise still open. It is quite obvious today, however, that thawing is causing a reduction of permafrost on the coasts. This is releasing more biomass, which is becoming available to microorganisms. One factor is that summers in the Arctic are becoming longer as a result of global warming. The ground thaws earlier in the year and freezes later. The waves thus have a longer time window to erode the permafrost. Another factor is the shrinking ice cover in the Arctic Ocean, which promotes an increased intensity of the waves attacking the coasts. At some locations the permafrost grounds are breaking off at a rate of 20 metres per year.

Permafrost thawing is also a problem for local human populations. In Alaska many Inuit are losing their ancestral homes on the sea. According to reports by the U. S. Government Accountability Office (GAO) many villages are threatened by the accelerated melting of permafrost and loss of coastal land. Presumably, these villages will have to be abandoned in the future. At a meeting in August 2016, for instance, the community of Shishmaref decided to relocate to a safer site on the mainland that is yet to be determined. The village of 600 residents is located on an island in the Bering Strait off the coast of Alaska that has long been inhabited by the Inuit. Around 30 metres of shoreline have been lost over the past 20 years due to the thawing of permafrost. 13 houses have had to be dismantled and rebuilt. Although breakwaters were constructed to protect the island, they have not been able to stop the loss of land. Specialists estimate that relocation to the mainland will cost around 180 million US dollars. It has not yet been determined who will bear the cost.

1.22 > The village of Porthleven in the English county of Cornwall is located on an extremely high-energy rocky coast. Accordingly, the shoreline fortifications, including massive walls, are very substantial. Under conditions of very high seas, however, they are hardly noticeable.

the west, wave action carries sand away from the northwest side of the islands and redeposits it on the east side. In the past this has caused the islands to slowly migrate eastward. To impede this motion, rock jetties and breakwaters were built as early as the 19th century to fortify the islands. This greatly helped in preventing further migration.

While changes in the shape of sandy coasts are often visible with the naked eye, they can be more difficult to recognize when other material is involved. But even high-energy rocky coasts do change their appearance over time. The rate of change, however, depends largely on the properties of the rocks. Coasts composed of compacted but not yet lithified ash, generated over time by ash falls from volcanic eruptions, are especially easily eroded. Examples of this kind of coast are found in New Zealand. Up to ten metres of coast can be lost there within a single year at some locations. Chalk cliffs, like the White Cliffs of Dover in the extreme southeast of England are also relatively soft. When exposed to strong currents they can be eroded by several centimetres per year. By contrast, hard granitic rock is depleted at most by only a few millimetres in the same space of time. Harder still, black volcanic basalt is only destroyed by water each year by a maximum of a few hundred billionths of a metre.



1.23 > Depending on the material making up the coasts, they can be eroded slowly or more rapidly. Some can be depleted by several metres in a single year.

The intertidal zone
The intertidal zone is the area of the coast that is flooded and then exposed again by the rhythm of daily tidal cycles. The surface can be mudflats, sandy beaches or rocky cliffs. Rocky shores are exceptional because they occur on steep coastlines, while most other intertidal zones are found on flat coasts. Large-scale flat intertidal areas which include the salt marshes on the shore are called mudflats.

A question of particle size

Understanding the nature of the substrate in coastal areas is especially crucial for coastal protection, coastal management, and the planning of waterways and port installations. In particular, the size and density of the particles that make up the material play an important role. These can be factors, for example, in determining whether the shore of a populated island is in danger of erosion or whether shipping channels might shift their positions causing ships to run aground. With respect to the size of particles, the following coastal types are differentiated:

1.24 > The materials that make up the coasts are classified according to the size of the particles they are composed of. This scale extends from microscopically small clay particles to large boulders.

- muddy coasts,
- sandy coasts,
- pebble coasts,
- cobble coasts,
- rocky or boulder coasts.

The category that a coast belongs to is determined by the grain size of the particles present. Clay particles, transported from the mainland to the coastal waters by rivers, are the smallest. These are a maximum of 2 micrometres (1000 micrometres equal one millimetre) in size. The next size class incorporates silt particles with a maximum size of 62 micrometres. This is followed by the sand class, which is divided into additional subclasses. Fine sands, together with clay and silt particles, can form a mud substrate such as that found in the Wadden Sea. The subsequently larger size categories are pebbles, cobbles and boulders, which can likewise be divided into narrower subclasses.

The filtering function of the coasts

In many areas the character of the coasts is strongly shaped by rivers – through both their current strength and the material loads that they transport. They carry many minerals and nutrients that are incorporated to some extent into the sediments. Coasts that are rich in such sediments are also highly productive. A good example are the Sundarbans in Bangladesh and India, which, with a total area of around 10,000 square kilometres, comprise the largest block of mangrove forest in the world. The Sundarbans formed in the estuarine areas of the Ganges and Brahmaputra Rivers, which deliver immense amounts of material into the Gulf of Bengal. The Sundarbans are a vital unspoiled natural region. They are home to abundant birds, fish, crocodiles, pythons, deer and wild boar. Furthermore, rare animals such as the axis deer and Bengal tiger may also find refuge here.

Depending on the ability of a particular coast to filter and store the material transported by rivers, it can be designated as having an active or inactive filtering function.

A distinctive coastal form – tidal flats

On many low-energy coasts around the world tidal flats are formed when large amounts of clay, silt and fine sand particles are imported by rivers. These tidal flat areas, however, do not look the same everywhere. A distinction can be made between "closed" tidal flats, characterized by plant growth, and "open" tidal flat areas where the sediments are exposed. The largest tidal flat area in the world extends across broad stretches of the Dutch, German and Danish coasts of the North Sea and is an "open" tidal flat. It has been listed as a World Natural Heritage Site by UNESCO (United Nations Educational, Scientific and Cultural Organization) since 2009. The intertidal area here contains the typical mud consisting of 30 per cent clay, 30 per cent fine silt and more than 30 per cent sand as well as dead biomass. But technically this area cannot be referred to as a muddy coast because of the relatively high sand content in most areas. Thus, in the strict sense, this tidal flat is considered to be a sandy coast.

A true "open" muddy coast, on the other hand, is found in the South American country of Suriname, where the coastal Atlantic currents are very weak. Here, even the finest clay and silt particles can be deposited to form thick muddy sediment packages. The bulk of these are transported over a distance of around 600 kilometres from the mouth of the Orinoco in Venezuela, through the Atlantic and into the calm waters off Suriname.

On the east coast of the USA, however, the situation is quite different. Salt marshes have formed at many locations between Florida and the peninsula of Cape Cod in Massachusetts, which defines them as "closed" tidal flats. These form along low-energy segments of the coastline where rivers import large volumes of material that are primarily deposited in shallow areas near the shore. The tidal flats grow upward on the order of decimetres through time, and thus become less frequently inundated by water. Specialized salt-resistant plants can then colonize here. These salt marshes are important stopover and breeding sites for birds and thus represent a crucial habitat within the tidal flat environment.

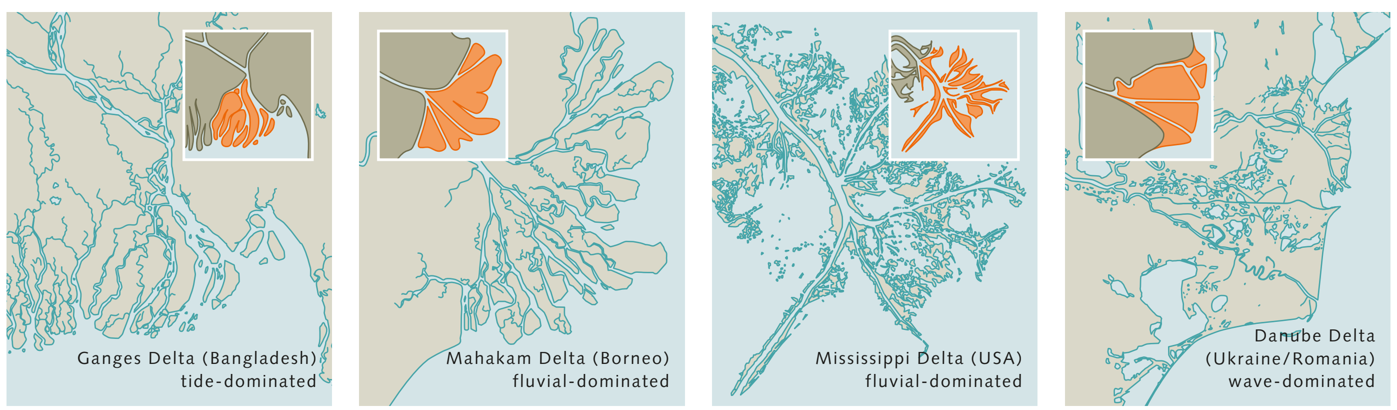
Tidal flats often form between the mainland and offshore islands. Because of the low-energy currents here, fine particles can be deposited on the sea floor. A prerequisite for the formation of these island or backshore tidal flats is a significantly large tidal range, the difference in the water level between low and high tide, so that the area is regularly flooded and exposed as in the western European Wadden Sea. As a rule, the tidal range here is between 3 and 3.5 metres. Island tidal flats are also found on the Pacific coast of Colombia, for example. These, however, are not "open" tidal flats, but covered by salt-resistant mangrove trees.

1.25 > The Wadden Sea on the margin of the North Sea is very popular with tourists. Many people are fascinated when they walk across the muddy sea floor at low tide for the first time.

Coasts with an active filtering function

- **Delta:** A river mouth that gradually grows outward into the sea due to the deposition of sediments is called a delta. The ocean currents or tides are not strong enough to carry the material away. Deltas can take on different forms. Ultimately they are shaped by the interacting forces of waves, river currents and tides. Depending on which of these forces is predominant, different types of deltas are created, which are then categorized as tide-dominated, fluvial-dominated and wave-dominated deltas.
  - Because of the constant cycle of advancing and receding tidal currents, sediments in a tide-dominated delta form long sand banks perpendicular to the coast. The surf here is comparatively weak. The combined mouth of the Ganges and Brahmaputra Rivers in India is an example of this kind of delta.
  - The influence of waves is also relatively minor in a fluvial-dominated delta. Furthermore, the tidal range, the vertical difference between low- and high-tide levels, is at most two metres, which produces a relatively weak tidal flow. A large amount of sediment can thus be deposited at the river mouth. Over time, this kind of river delta can become choked by sand. The river is then diverted to a new channel, creates new beds and bifurcates repeatedly to form a bird's foot delta.
  - Over time, in the wave-dominated form, the surf pushes the sediment into mouth bars, beaches and sand bodies orientated parallel to the shore. Neither the river nor the tides are strong enough to carry these mouth bars away. An example of this can be seen in the Danube Delta in the Black Sea.
- **Tide-dominated estuary:** In contrast to the delta, a tide-dominated estuary refers to a single large river estuary that is shaped by the tides. This usually has a funnel-shaped mouth that extends far inland, following old river valleys formed during the glacial period, as in northern Europe, for example. During high tide the river water is piled up into these funnels. At low tide the backed-up water then flows rapidly into the sea, washing a load of sediment out with it, so a delta cannot form within the estuary. Instead, large-scale tidal flats may be created on both sides of the funnel, such as those seen near the mouth of the Elbe River in Germany. The Elbe can thus be considered a typical tide-dominated estuary.
- **Lagoon:** Lagoons are characterized by relatively shallow coastal waters with a maximum depth of five metres. As a rule they are separated from the open ocean by barriers. These can be sandbanks, coral reefs, or offshore islands. Lagoons are usually elongate and orientated parallel to the coast. This is the case for those in the Baltic Sea, which are separated from the sea by elongated dunes, such as the Vistula Lagoon. In lagoons the interaction between the sediments and water is especially pronounced.

1.26 > River deltas can be formed in different ways. Their shapes are ultimately determined by the interplay of the forces of tides, waves and river currents.



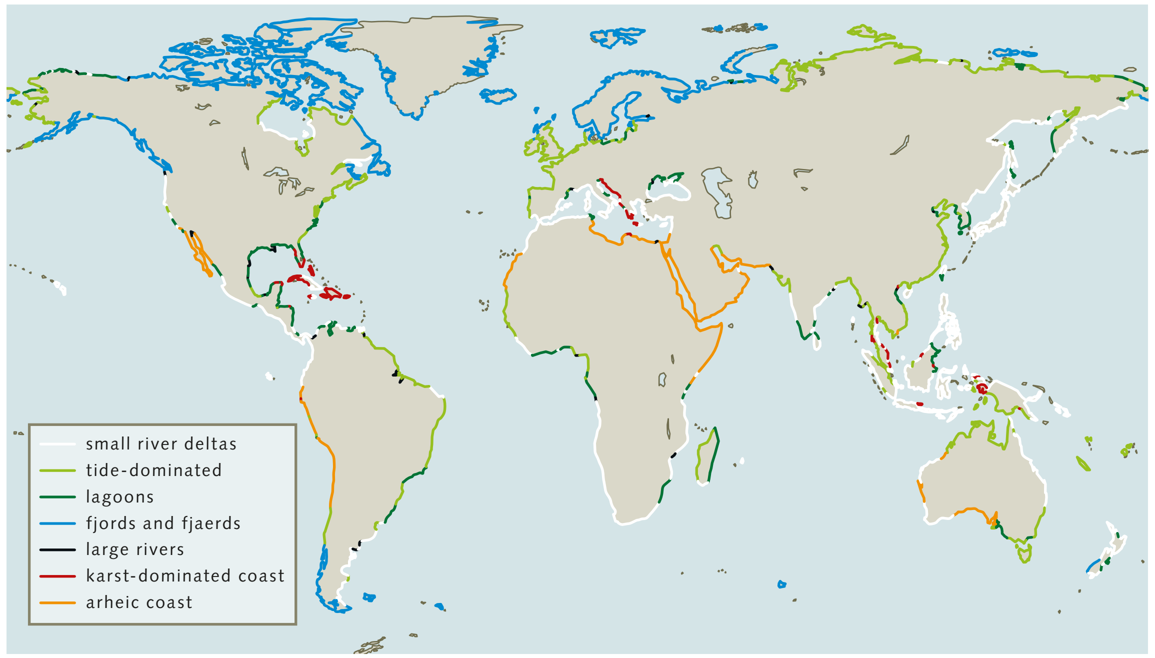
Because wave and current action are virtually absent in lagoons, the water is relatively quiet. There is thus more time for suspended material to sink and be deposited. Lagoons often have narrow openings to the sea so that salt water and seawater mix to create brackish water. Chemical reactions can occur in this mixing area that result in a fine precipitation of flocculated material, which is then deposited in the sediment.

- **Fjord:** Generally, fjords are valleys that were formed by glaciers. These often very steep and deep valleys were flooded with the rise of sea level. Many fjords are closed off from the sea by coarse debris. This commonly consists of a deposit called moraine that was piled up by glaciers. The German term, "Förde", refers to a feature similar to a fjord that is also formed by glaciers, but is generally wider, shallower and more branching. Because no large rivers flow into the fjords as a rule, the currents are weak and material can also be deposited here.

Coasts with an inactive filtering function

- **Coasts with rapidly flowing rivers:** In many cases large rivers flow with such a high velocity that, even though they carry a heavy load of sediment, the material is not deposited near the coast but carried out to sea in a kind of suspended cloud. To the extent that this occurs, the filtering effect of the river mouth is limited. An example of this is seen in the Columbia River in North America.
- **Karst-dominated coasts:** This kind of coast consists primarily of limestone. It was formed over millions of years from the carbonate shells and carapaces of marine organisms. Plate tectonic forces lifted these chalk masses up out of the sea, where they then consolidated and hardened over time to limestone. As a result of chemical weathering caves and passages are typically formed within the limestones, and rain and river waters flow underground through these into the sea. Karst landscapes form and rivers carve deeply into the rock. In some locations the karst landscapes have been flooded by rising sea level since the last glacial period. One example of this is the world famous Ha Long Bay in Vietnam, which was originally a river and karst landscape, but was later flooded by the rising sea level. Today, former cliffs on the river banks project out of the water as islands. Karst-dominated coasts are characterized by a paucity of sediment deposition due to their typical craggy structure and wave action.
- **Arheic coasts:** The coasts in very arid regions and deserts where precipitation is so low that no water at all flows into the ocean are called arheic coasts. The name derives from the geological term for rivers

1.27 > The karst cliffs in the Ha Long Bay in Vietnam are world famous. Tourists ride on boats through the archipelago.



1.28 > Coasts can also be differentiated based on how strongly they filter sediments that are delivered by rivers from the inland.

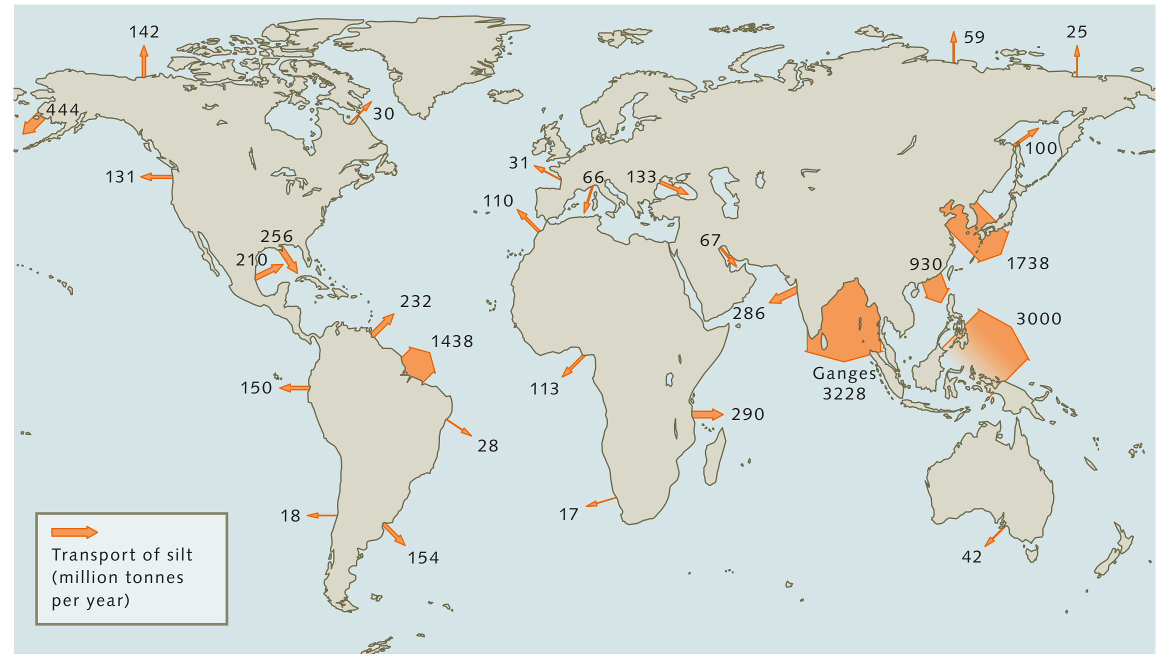
whose waters seep into the ground in a desert or salt flat before they can reach an ocean. These rivers are called arheic.

The amount of sediment transported into coastal waters annually is immense. The material basically originates as a weathering product of rocks on the land. It is eroded by rainwater either directly from mountainous regions or washed out of the soils in the flatlands. Over millennia the landscape is gradually flattened. The leading transporter of material is the Ganges River, which carries 3.2 billion tonnes annually into the ocean. It transports mostly silt particles from the central Asian highlands that are dislodged from the substrate by physical weathering. The same process occurs in the Yellow River in China, whose distinctive colour is derived from a particular type of silt particles.

Degradation and accretion

Depending on local conditions coasts can grow or shrink. While some coasts increase in volume with sediment deposition, others are eroded over time due to current or wave action, as evidenced on the Norfolk coast of England. The village of Happisburgh here, with a population of about 1400 living in 600 houses, has achieved a sad measure of fame as a result of its location. At the end of the 19th century Happisburgh was located several hundred metres from the coast. Because of perpetual erosion of the coast, the village now stands directly on the edge of a ten-metre high cliff at the coastal margin. It continues to break off due to its composition of a soft mix of clay, silt and sand. Large pieces break off when strong east winds pound heavy waves against the coast. A number of houses have already fallen into the sea. Within the next decade Happisburgh could lose its Norman church, its lighthouse and a 14th century manor house to the sea. Attempts were made to counteract the erosional forces by constructing breakwaters, but these have proved ineffective. It is thus only a matter of time before Happisburgh falls completely into the North Sea.

Accretion or degradation of a coast depends on various factors. A more detailed classification of constructive and destructive processes follows, whereby different time scales must be taken into account:



1.29 > The sediment loads that rivers carry to the sea can be enormous. The world record is held by the Ganges River in Asia with a load of 3.2 billion tonnes annually.

Destructive processes

- **Endogenous erosion:** destruction induced by the coasts themselves. This includes cliff slump and cracks (faults) resulting from earthquakes, or the collapse of volcanic islands, for example, when old craters cave in.
- **Mechanical erosion: abrasion** produced by wave action and drifting ice. This can generate many different coastal forms. Cliffs are one example, steep walls of rock that are by no means immutable, for even hard rocks are eroded over time. Cliffs begin to form when waves undercut the rocks at the base of a steep wall. The wall thus becomes unstable and breaks off, forming the typical high cliffs. Another coastal form caused by abrasion is the flat coast. This is characterized by a broad area in the littoral zone sloping gently seaward. Depending on the material, these can be categorized as sand, pebble, or rocky shores. On sandy beaches the shore is the gently sloping, wet part of the beach that is shaped by the forces of water. Seaward of rocky cliffs a flat wave-cut shore is found. These are recognizable by parallel deep ridges in the rock that are created when the bedrock is composed of different individual rock layers. Because the different materials are eroded at different rates by the energy of the surf, deeper and shallower areas result, creating a profile of ridges defined by the boundaries of the rock layers. Erosion can also wear away coasts in other ways. An example is the undercut cliff. These begin as notches in rocky coasts at the level of the water line caused by wave action.
- **Scouring of the coastline:** destruction that occurs on frozen coasts such as those with permafrost or glaciers. In the permafrost regions of the northern hemisphere summer thawing leads to softening of the soil that was frozen during the winter, making it more susceptible to erosion by the waves. This kind of destruction, called thermoabrasion, changes the coastline. In the Arctic and Antarctic, the coastline changes primarily due to the breaking off of large fragments of glaciers. Because of their massive weight, continental glaciers slide slowly from the land into the sea where they can sometimes project several kilometres out into the water as **shelf ice**. Because the ice is less dense than water, the glaciers float on the sea

1.30 > On the southern coast of Wales, near the city of Cardiff, abrasion has cut a flat shore into the limestone.

surface in spite of their great weight. Large chunks break off continually because the glacial mass is being pushed from the land out into the sea. This is called glacier calving.

- **Bioerosion:** destruction of hard substrates by microorganisms that slowly break down the rocks through their metabolism. This occurs, for example, in undercut cliffs.

Constructive processes

- **Endogenous build-up:** the formation of new coastal areas due to plate tectonic processes whereby land masses are uplifted. These include volcanic eruptions that through time release sufficient magma from the Earth's interior to create islands. In other cases new coastal segments are created when large amounts of lava from a volcanic eruption flow into the sea.
- **Potamogenic origin:** formation of deltas, tidal flats or wetlands by material imported by rivers.
- **Formation by ice:** accretion produced by coastal or pack ice shoving material together. The driving forces are provided by waves or tides pushing ice toward the coasts.
- **Formation by wind:** build-up of coastal dunes from loose sand that is piled up by wind.
- **Thalassogenic origin:** formation by materials that are deposited on a coast by waves, tidal currents or ocean currents.
- **Biogenic origin:** construction of coasts by living organisms. These include corals, which build solid and durable structures, or mangroves, which can abruptly curb the wave and current energy so that fine particles are deposited and tidal flats are formed. Not only do organisms contribute to the construction of coasts, however, but also to their protection. Corals and mangroves are natural breakwaters. Kelp forests can also absorb large amounts of wave energy. Furthermore, these plants also consolidate the sediments so that they cannot be washed away again by strong currents. Salt marshes also act as natural current barriers to protect the inland regions.

The extent to which these natural formation processes act is very well illustrated by the deltas of large rivers. Over time, the Mississippi River has transported so much material that the delta has grown to a width of around 200 kilometres. The weight of the sediments is so great that the delta is continuously subsiding. In addition, water is being squeezed out of the sediment, which represents a kind of compaction. In geological terms, compaction refers to the compression and decrease in volume of sediments, due in part to the pressure created by overlying sediment layers. The subsidence was formerly compensated by fresh material being constantly transported in. Human activity, however, has disturbed this compensatory process. Dams have been constructed along the river, trapping large volumes of material before they can reach the delta. Sediment replenishment at the coast has been thus cut off. But because the delta continues to subside under the weight of the old sediment packages, humankind is now exposed to the problem of a significant increase in the frequency of floods.

Conclusion

The shape of our coasts – a long and changing history

Coasts have a special significance for humankind. More than 90 per cent of global fishery is carried out in coastal waters. They are important transportation routes and significant sites for industrial and power plants. They are popular destinations for global tourism as well as a source of mineral and fossil resources. They are thus very attractive as working and living areas, which is evidenced by the fact that 75 per cent of all megacities with a population of more than 10 million are located in coastal areas.

Coasts are generally viewed as a thin line where the land and sea meet. They are transitional areas that are constantly subjected to change that can take place at very different rates: over millions of years through continental drift, in phases of tens of thousands of years through the alternation of interglacial and glacial periods, and over recent centuries through their settlement by humans.

Over relatively short periods of geological time, the fluctuations of sea level are primarily responsible for changes in the shape of the coasts. Because large amounts of water are sequestered in the form of ice and snow on the land during a glacial period, and the amount of water flowing from the land into the sea is diminished, sea level drops. Around 20,000 years ago, during the last glacial, sea level was about 120 metres lower than it is today. Many areas that are flooded today were dry at that time and the global area of land masses protruding from the water was about 20 million square kilometres greater than at present. Australia and the island of New Guinea were connected then by a land bridge and America was presumably being colonized by people from Asia over a land bridge across today's Bering Strait.

The formation of coasts in the northern hemisphere, however, was also strongly influenced by glacial ice. The Norwegian fjords, for example, originated when immense ice masses flowed from land into the sea and gouged out the bedrock. After the glaciers thawed and sea level rose, these grooves filled with water.

Over millennia, the movement of glaciers and numerous other processes have been instrumental in creating a large number of coastal types: bare granite coasts like those in Scandinavia, permafrost coasts frozen several metres deep in Arctic regions and dense mangrove forests in tropical areas. Scientists organize this diversity into a range of categories. For instance, coasts can be classified according to whether their form is heavily or weakly influenced by wave action and currents.

Coasts can also be categorized by the material that they are composed of, or by how strongly the material is eroded by the sea. They can be classified, furthermore, by how well they are able to trap sediments that are brought in by rivers or currents. This ability is referred to as the filtering function of the coasts. There are regions where large amounts of sediment are deposited on the coasts, such as the Mississippi Delta in the Gulf of Mexico. These coastal areas are often highly productive with abundant fish because the water receives a large volume of nutrients along with the sediments.

The amounts washed into the sea by individual rivers are sometimes gigantic. The Ganges River, for example, carries an extremely large load of material from the Himalayas to the Gulf of Bengal – around 3.2 billion tonnes annually. In many cases people have intervened in the natural sedimentation processes through various kinds of construction projects. The resulting changes have caused problems in many locations.