Coastal Research Library 2

Anja M. Scheffers
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# The Coastlines of the World with Google Earth

## Understanding our Environment

Springer

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# Coastal Research Library

VOLUME 2


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*For Yanik and Emile*

# Foreword

Our living environment in all its grandeur, diversity and different scales from global to local can best be represented visually, as compared to any possible verbal descriptions. The coastlines of the world, with their total extent of at least one million kilometres, offer an excellent model for such a visualization. An overview must include the most important variations that occur in different latitudes, different geologic settings, through time and sea level changes or climatic parameters. Such detail can only be presented by the use of high resolution satellite images. Google Earth imagery mostly has such a resolution that allows visualization of individual features down to view altitudes of 500 m, which corresponds to a scale of approximately 1:5,000 or a resolution per pixel of less than 1 meter. Therefore, we chose to base this book mainly on Google Earth imagery (captured in 2010), thus showing the present day situation. Additionally, terrestrial photographs and some oblique aerial photographs taken during our various field campaigns along the coastlines of the world are added, in particular to show small features down to micro-scales and those which are hidden in vertical pictures such as steeper slopes or perpendicular cliffs. For many coastal features, information regarding their spatial extension is added in world distribution maps and more details are provided on graphs. The book shows and explains landforms and geomorphic features of different dimensions and as a result of different formational agents and processes (wind, waves, currents, tides, extreme wave events such as storms and tsunamis or by anthropogenic changes).

In our view, it is crucial for now 7 billion of us on the planet to become more knowledgeable (in contrast to being informed) about the parts and processes that currently interact on our home in the universe – planet Earth. Our ancestors have always been interested and concerned with the local weather, climate or water availability, but with the fast rate of environmental change on a global scale during the last hundred years it becomes more and more important to appreciate and understand the interconnections and interrelationships that govern Earth and create our living environment on a global scale. During the last decades, technical advances, increasing computing capacity and more sophisticated numerical modelling have transformed almost every scientific discipline into a highly complex and technical research area. Today, most scientists are specialists in one ever-narrowing research field, on the other hand the emerging science of the Earth System is changing the way scientists study Earth. With this more holistic view of the way our planet works, we want to engage, stimulate and motivate the individual person to undertake their own research and follow up with open questions in specialist texts – or even take up a career in some aspect of our Earth system.

Although this book tries to present coastal features from around the world, there are some restrictions: the low resolution or the lack of high quality pictures close to the polar regions (depending on the angle of the satellite tracks), and the difference in the spatial resolution of the images in different regions of the world, which vary from excellent (have a look at New York, where you can see single cars on the streets) to very poor, clouds may cover parts of an image, reflections from surface features (water), an unfortunate angle to the sun's rays – all these parameters may influence visibility and quality of the image data. However, Google Earth is constantly developing its set of images, and more areas will continue to appear on Google Earth's virtual globe with higher resolution in the future. Consequently, the difference in picture quality and the mosaics of different pictures from different years or with different light conditions is an obstacle in the interpretation of details. Therefore pictures of very large areas are not chosen for presentation in this book.

For this project, we would like to acknowledge the generosity of Google Earth to give permission to publish Google Earth imagery and express our thanks to Ed Parson who helped to make the book possible. As this is not a textbook for students, references are used only to acknowledge sources for material and figures, and by citing books and articles such as reviews or those presenting the state of the art for certain aspects of coastal sciences.

We gratefully acknowledge the assistance of Springer Publishing and in particular the enthusiastic support of Petra van Steenbergen, Editor of the Earth Sciences and Geography section, in preparing all parts of this book, as well as the generous support by Charles Finkl Jnr. from the Coastal Education and Research Foundation in Florida (USA) regarding copyrights of Publications in the Journal of Coastal Research. The design and layout of the book was created by Hans van der Baan and Ingeborg Scheffers in the Netherlands. Thanks to you the book is visually stunning and of high quality. Southern Cross University in Lismore (NSW, Australia) supported their work with a substantial fund based on their vision that it is vital for universities to engage with communities in ways beyond the usual academic halls. Gudrun Reichert, cartographer at the University of Duisburg-Essen (Germany) created most of the basic graphs and world maps, and Anne Hager (University of Duisburg-Essen, Germany) supported the book in many ways with her energy in problem solutions and we thank Kelly Fox (University of Queensland, Brisbane) for patience and input in text editing. We are very grateful to Bob and his passion for communicating geology. His guidance, grace and professional acumen made this book educationally sound. Finally, it should not go without saying that we are grateful to our families, our colleagues and our students at Southern Cross University (Australia) and the University of Cologne (Germany). We love working together – thank you!

*Anja M. Scheffers* *Sander R. Scheffers* *Dieter H. Kelletat*

# About Google Earth

Virtual, web-based globes such as *Google Earth*, *NASA World Wind* or *Microsoft Virtual Earth* allow all of us to become travellers visiting the most remote places and tour our planet or even outer space at speeds faster than a rocket. Any computer user can easily, at no charge, download and use Google Earth (for both PC and Mac computers).

If you have not done so already, download *Google Earth,* version 6, from *earth.google.com,* install it on your computer, and prepare yourself to fly around the globe on your own research expedition (Fig. 1.1). You can travel to millions of locations and look for the context of all landscape features of interest to you (geography, geology, vegetation, man-made structures and more). You can also see these objects from different altitudes (i.e. in different scales), perspectives and directions; you can view a chosen area around 360° from an imaginary point in the air; and you can fly deep into canyons and craters. You can look straight down in a traditional 2D perspective or enable an oblique view in 3D, you can hover above one location, circle around or fly like a bird over countries, continents and oceans. In this book we focus on geologic and geographic features, but that is only a snapshot of what Google Earth is providing with their virtual globe. There is no room here for a complete tutorial, but you will find that the program is so easy to use and understand that you will be an expert after working with it for a few minutes. Please visit the Google Earth web page for a complete free Google Earth tutorial which is constantly updated to reflect the improvements in different versions of Google Earth (http://earth.google.com/support/bin/answer.py?hl=en&answer=176576).

We hope that the diversity of the coastlines of the world will come alive for you and stimulate your curiosity to become a coastal explorer of these fascinating places either as a hobby or profession.

# Table of Contents

# Introduction: Oceans and Coastlines

The most extended landforms on our planet are the coastlines; in natural scale certainly they are more than one million kilometres long. Along these vast boundaries between land and sea the variety and diversity of processes and forms leading to a coastal landscape we treasure today are immense. Some processes like the rising sea level after the melting of the large ice sheets from the last ice age are affecting coastlines globally, but some processes operate only in specific environments. Imagine for example the warm tropical waters of the lower latitudes where coral reef building organisms live and have created the largest geomorphological structure ever which can be even seen from space. These coastal environments differ completely from the ice and permafrost shaped coastlines of the Arctic regions. The coastal forms and processes we see today depend on the earlier geologic history, rock type, climatic province, sea level variations and the dynamic processes of the oceans such as waves, tides, or currents which themselves depend upon water depth, exposure, size of the ocean basin and many other factors. Coasts at the same time are regions with extreme morphological activity, comparable only with those of active plate boundaries where volcanism creates dramatic landforms or in regions where wind or ice and glaciers constantly form and sculpture the environment.

Along coastlines geology can be seen in action and you can observe forming and transforming processes even during a walk on the beach or surf in the waves. If you visit your favourite beach destination from year to year, you can trace the changes on an annual scale and often extreme events like storms change the coastline dramatically within a day or two creating new landforms or eroding large beach sections.

Whereas the surface forms under the oceans as well as those on land may be very old, from thousands of years up to tens of millions of years, all of the coastlines of the world are geologically young and represent only a tiny moment in Earth´s history, that will change dramatically in the next geological moment, and which were much different just a geologic moment ago. Sea level during the last Ice Age, about 23,000 to 18,000 years ago, was 120 m deeper than today. As the climate got warmer and the ice melted sea level reached its modern position not longer than 7,000 years ago and possibly as recently as about 6,000 years (Anthony, 2009; Bird & Schwartz, 2010; Carter, 1988; Davidson-Arnott, 2010, Kelletat, 1995; Schwartz, 2005; Woodroffe, 2003).

Scientists love to classify and categorize, seeing patterns and order in the complexity of our natural world. They invent taxonomies (Taxonomy is the art and science of classification) for plants, animals, bacteria or soils and coastal scientists are no different: They classify coastlines in attempts to characterize dominant features in terms of physical or biological properties, modes of evolution, or geographic occurrence: Is the coast advancing or retreating, emerging or submerging; do we see constructive or destructive processes operating; is the coastline rocky or sedimentary; tropical or extra-tropical; with or without sea ice; a shallow water coast or a deep water coast; exposed or sheltered; does it have high or low tide regime or it is exposed to high or low wave energy? – To give few examples!

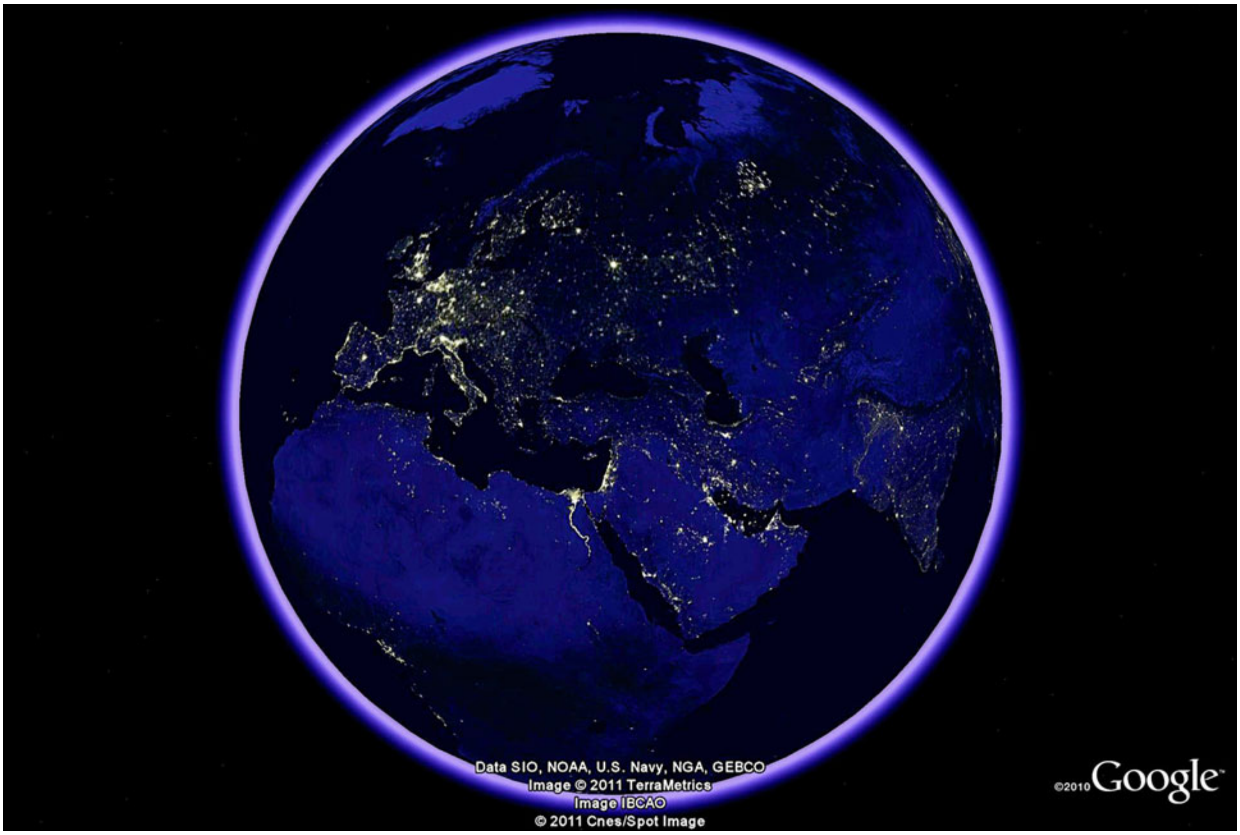


Fig. 1.1 Earth at Night (Credit: ©Google Earth). You'll find a Layers section in the sidebar. Expand the Gallery Content folder and the NASA subfolders. Then click on the small rectangles next to each option to enable it.

Another classification distinguishes between "*primary coasts*" and "*secondary coasts*". Primary coasts have preserved their initial form from terrestrial processes and now appear partly drowned by the postglacial sea-level rise. They do not show any significant transformation by coastal or marine processes since the last rise of sea level whereas the forms of secondary coasts reflect modern littoral/coastal/marine processes, mostly either by destruction (e.g. a cliff), or by construction (e.g. a beach, barrier or delta). In general, all terrestrial landforms – when partly submerged by the postglacial sea level rise – can appear as coastlines and give them their typical aspect, glacial roches moutonnés (as skerries), glacial valleys (as fjords), cone karst (as drowned karst towers), dunes and deflation depressions, river gorges (narrow rias) and many other forms. In the coastal classification system they have been given special names if they appear as coastal features.

Cities tend to grow along coastlines and transportation networks as you can see in the Night Earth view of Google Earth. Even without the underlying map, the outlines of many continents would still be visible (Fig. 1.1). They are the place where more than 45 per cent of the world's population lives and works and 75% of the mega-cities with populations over ten million are located in coastal zones. Thus, people, infrastructures and economics in coastal zones are potentially vulnerable to natural marine hazards such as storms or tsunamis as the devastating effects of Hurricane Katrina in US (2005), Cyclone Yasi (Australia, 2011), the Indian Ocean Tsunami 2004 or the powerful tsunami that hit Japan in March 2011 have shown.

Surprisingly, an unsolved question hitherto is: What is a coastline? There is no standard definition of what constitutes "the coast" because it depends largely on one's perspective or the scientific question – the coastal zone can be considered more the sea, or more the land. Imagine you have to draw the coastline of your favourite holiday destination on a map with a scale of 1:100,000. This will be easy, if there are perpendicular cliffs, but in all other cases it is difficult and needs some convention for comparison and overlap to neighbouring maps. In particular along flat depositional shorelines with high tides and storm wave impacts the actual shoreline or limit between water and land may shift for many kilometres or even tens of kilometres horizontally, at some places twice a day! If the detail of our maps is large enough (e.g. 1:10,000 to about 1:100,000), a low water coastline (MLW = mean low water) and a high water coastline (MHW = mean high water) can be differentiated, but with less detail this mostly is impossible. We can also argue that the definite limit between land and sea is along a line where sea water will never reach, but this may be far inland from the mean high water level and will differ from place to place significantly. Nevertheless these are important legal aspects, for coastal management or risk protection measures from the sea. In the following sub-chapters we will briefly present processes from the hydrosphere (the oceans), which influences the formation of coast, including organisms.

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# 1

# The Oceans

**ABSTRACT** As far as our present knowledge goes, Earth is unique in the solar system: It is the only planet with water in all three forms – solid, liquid and vapour – that coexist on its surface. Most of us have experienced landscapes along our vast sea shores, but in general humankind knows much less about conditions at the other side of the shoreline, in the oceans which cover 70% of Earth's surface! Before the 20th century little was known about the origin of oceans, their topography and depth or about life in them and we are only gradually coming to understand the oceans with all their geologic diversity – a fragile environment that holds a large part of Earth's biologic heritage. In the last decade, 2700 scientists from more than 50 nations participated in the "*Census of Marine Life, a Decade of Discovery*". Click on the Census of Marine Life Layer in Google Earth to learn more. The work realized by this Census, while substantial, has only scratched the surface of what remains to be learned about what lives and may live in the world's oceans. ***The Age of Discovery is not over!*** This chapter discusses our knowledge of water movement in the oceans as currents, tides and waves and we briefly overview how sea level variations have created many coastal landforms that attract us for holidays, adventure or economic reasons.

## 1.1 Extent, Origin and Topography

The oceans are the main features on the Earth´s surface: they cover about 70.8% of it, which is nearly 362 million km² (Figs. 1.2–1.5 and Table 1). On the northern hemisphere, also called our land hemisphere, oceans cover 53.6% of the surface area; on the southern "water" hemisphere the vast oceans comprise 88.4% of the surface. Explore for yourself, spin the Google Earth globe and hover over both the North Pole and South Pole. This uneven distribution of land and water between both

| Ocean | area in Mio. km² | content of water mass in km³ | max. depth in m | mean depth in m |
|---|---|---|---|---|
| Pacific Ocean | 181 | 714,000 | 11022 | 4028 |
| Atlantic Ocean | 82,400 | 323,500 | 9219 | 3926 |
| Indian Ocean | 65,527 | 284,340 | 7455 | 3963 |
| Arctic Ocean | 14,090 | 13,700 | 5527 | 1205 |

Table 1 Dimensions for the present oceans of the world (Kelletat, 1999). We say present because the dimensions of the ocean basins change over long geologic time spans driven by plate tectonics. Also the volume of seawater in the oceans (at present 1.37 billion cubic kilometres) may change on shorter timescales over thousands of years, mainly because of the growth and melting of ice sheets and glaciers.

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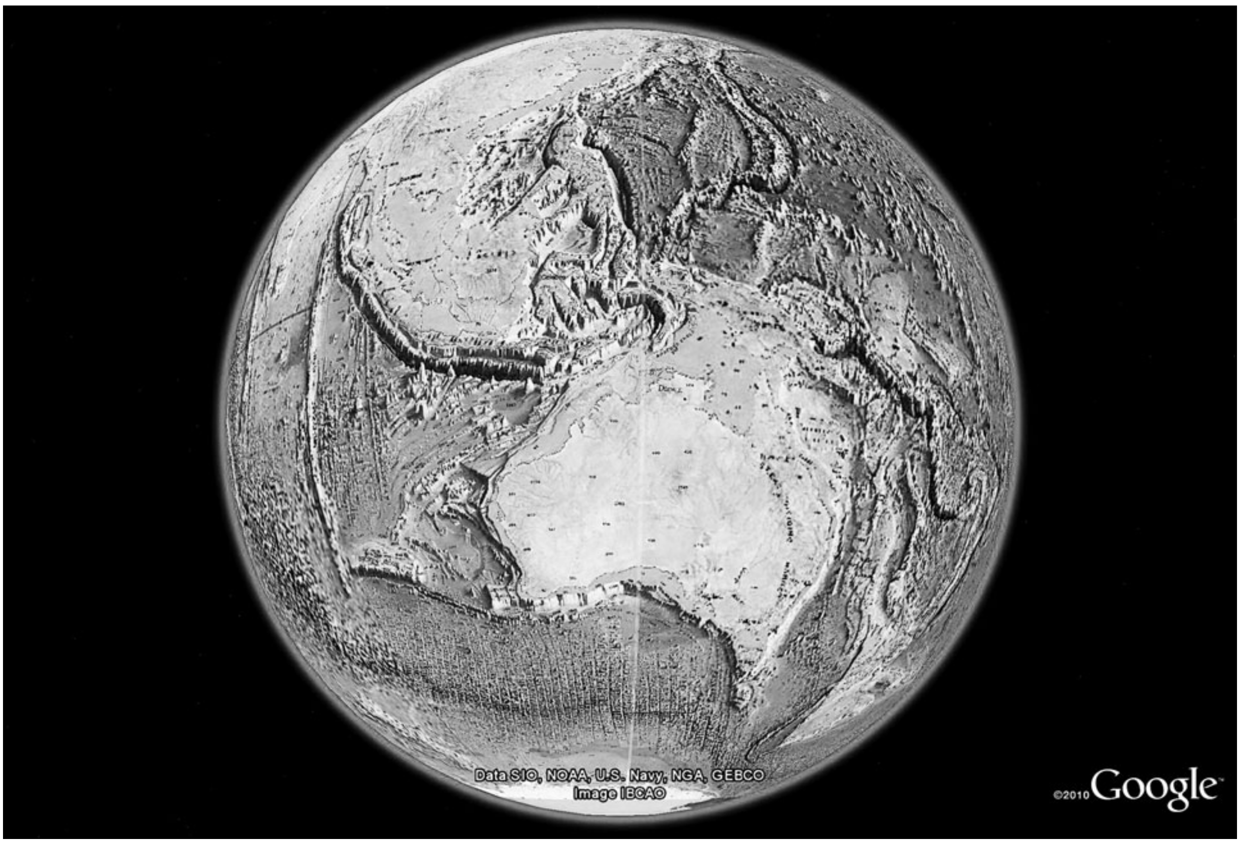
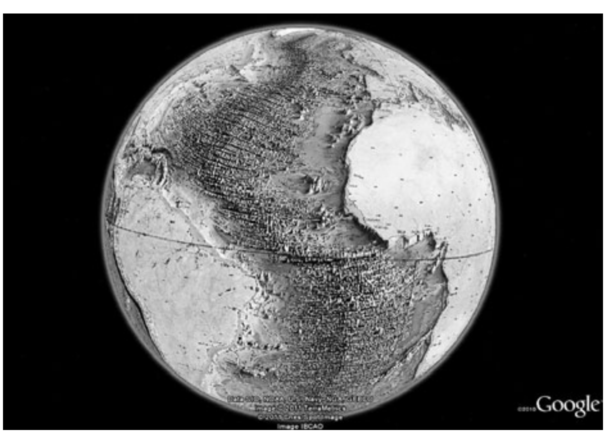
hemispheres plays an important role in determining the circulation in the open oceans and its marginal seas. Most of all water that exists on our planet is contained in four large interconnected basins: The Pacific Ocean, Atlantic Ocean and Indian Ocean, and the smaller Arctic Ocean. The Pacific, Atlantic and Indian Ocean are connected with the Southern Ocean, a body of water south of 60°S that encircles Antarctica and with which the Antarctic Treaty Limit coincides.

These figures include the large epicontinental seas, more or less open to their oceans like the Gulf of Mexico, the Caribbean and Hudson Bay to the Atlantic Ocean and also the Black Sea via the Mediterranean Sea, or the Persian Gulf and the Red Sea as parts of the Indian Ocean. With a total volume of about 1.37 billion km³ (which is a cube of water about 1100×1100×1100 km!) the oceans alone form 99% of the living space on our planet!

The changing geography of the oceans is due to an ever shifting pattern of tectonic plates of lithified or brittle crust (the lithosphere, Fig. 1.6) drifting on fluid rock (magma). During the last 4 billion years there were phases with super-continents and a single super-ocean, but also several break-ups into different drifting continental masses with interconnecting



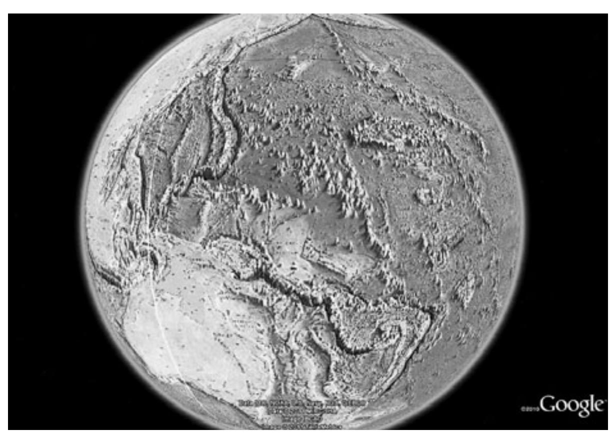




Fig. 1.2 Topography of the world's ocean floor, showing the mid ocean ridges as the main feature. This map was compiled by a path breaking team from Columbia University, i.e. Bruce Heezen and Marie Tharp. (Credit: ©Google Earth 2010: In Google Earth, click on Layers on the left, then click on Ocean; then double click on Marie Tharp Historical Map. The world will spin, and land in New York. An icon will appear for Marie Tharp Maps, LLC, double click that, and a large window opens with information on the company, as well as a link to download the map as a Google Earth layer).

seas. The formation or birth of an ocean is a rare event, yet it is unfolding today in different corners of our globe. For example, Africa is splitting apart at the seams. A plate capped by a continent, such as the African Plate, heats up from the magma below in the asthenosphere, expands and eventually splits to start a cycle of spreading. The Red Sea is a new, linear ocean that is forming where Arabia is separating and moving away from Africa. From the southern tip of the Red Sea southward through Eritrea, Ethiopia, Kenya, Tanzania and Mozambique, the African continent is rifting or splitting apart along a zone called the East African Rift. This spectacular geologic unraveling, already under way for millions of years, will be complete when saltwater from the Red Sea floods the massive rift, probably in some ten million years from now. You may also fly with Google Earth to other spreading zones, such as the Gulf of Baja California in NW Mexico.

The main process of ocean formation is called seafloor spreading. Oceanic crust of the lithosphere splits apart due to upwelling of magma and moves laterally away from the oceanic ridge. New magma rises from the mantle to fill the gap, forming new ocean crust along the ridges (Fig. 1.6). The process may unfold with a rift first appearing in a continent which becomes a graben (A *graben* is a down-thrown block which is bounded by faults along its sides) that is subsequently drowned by the ocean. A central fissure opens steadily as the lithosphere plates on both sides drift apart. Such a rift is evident in the central graben of the Mid Atlantic Ridge (Fig. 1.2). One important consequence of the spreading is that the oceanic crust far from any ridge is older than the crust nearer to the ridge.

Consider now what happens when this outpouring of basalt on the ocean bottom cools. All the minerals crystallize above 700°C – well above the point where the mineral magnetite, a component of basalt lava, crystallizes. As the lava continues to cool below 580°C, the magnetite minerals become tiny permanent magnets with the same north-south orientation (also called *polarity*) as the Earth's magnetic field at that time in history. Thus, this ancient magnetism revealed in the rocks of the ocean bottom provides a record of Earth's magnetic field of this time. Scientists studying palaeomagnetism have demonstrated that the orientation of the earth's magnetic field has frequently reversed in the Earth's geologic past resulting in parallel bands of similar magnetic properties flanking the central graben of the mid ocean ridge. This results in patterns like symmetrical bar codes reflecting the growth of the oceanic plate. The chronology of the magnetic polarity reversals can be dated very accurately so that the magnetic striping of the sea floor provides not only a tool of how old the world's oceans are, but also a means of estimating the speed with which the sea floor has

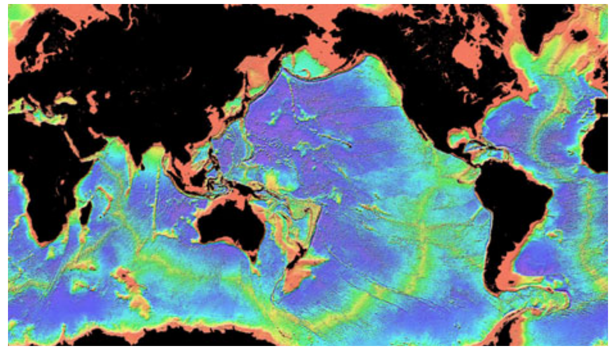


Fig. 1.3 Map of the global sea floor topography measured and estimated from gravity data using satellite altimetry and shipboard depth sounding. This map displays single undersea mountains and guyots as well as long island chains far away from the coastlines, resulting from hot spot volcanoes. (Credit: Smith, W., and Sandwell, D., 1997, Measured and Estimated Seafloor Topography, World Data Center for Geophysics & Marine Geology, Boulder Research Publication RP-1, poster, 34"×53").

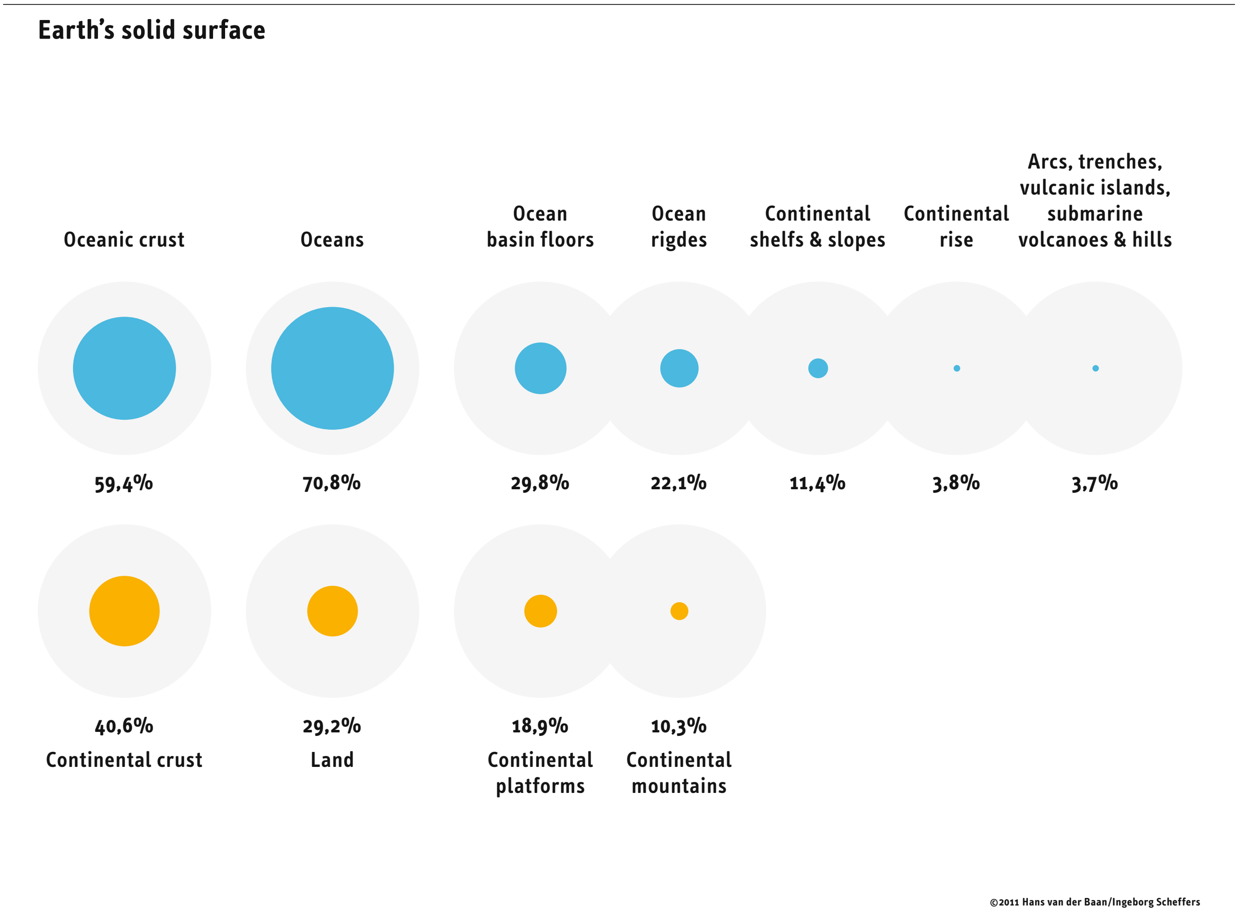



Fig. 1.4 Distribution of the main topographic features in the ocean basins.

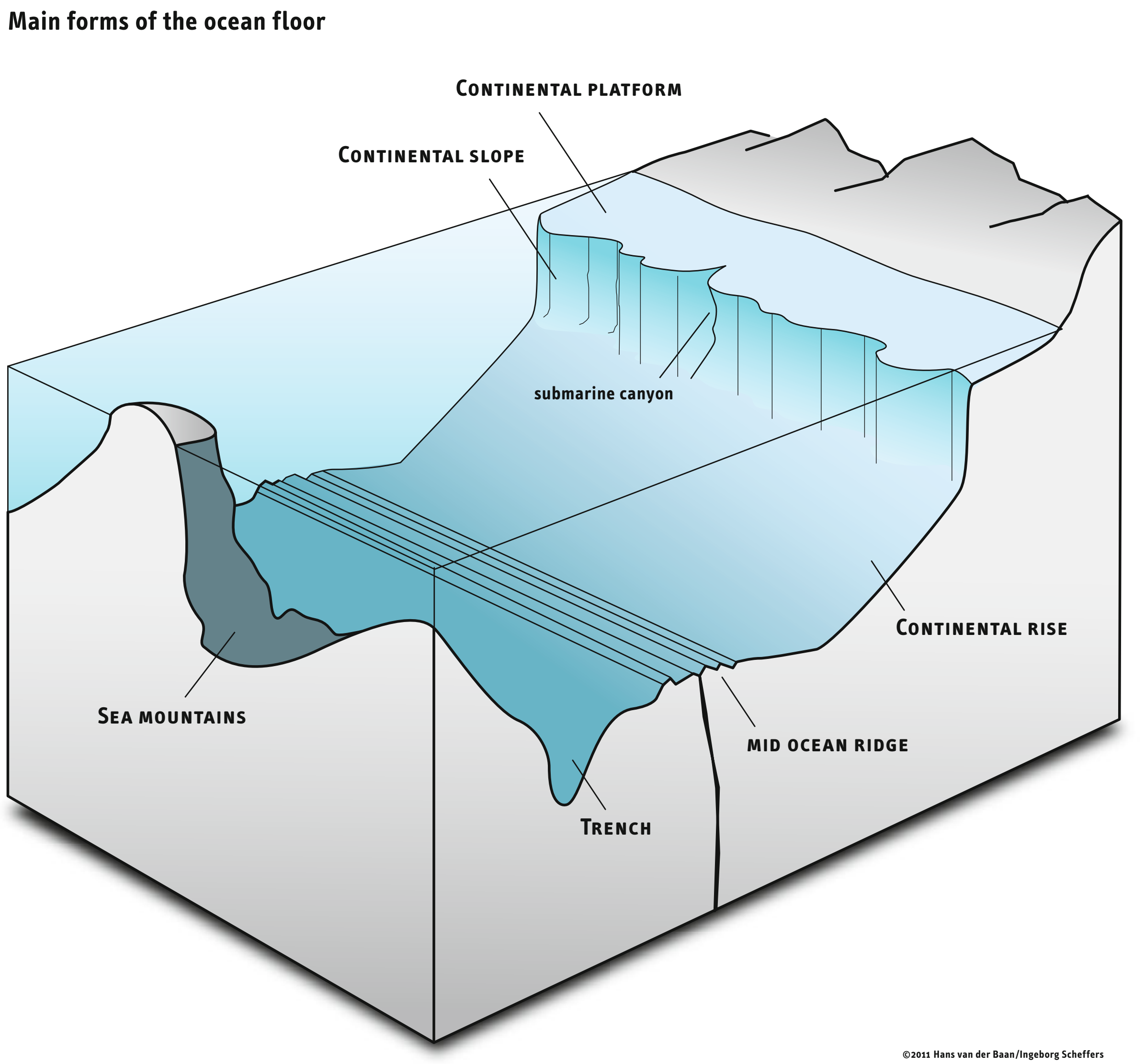



Fig. 1.5 Main features of the ocean floor.

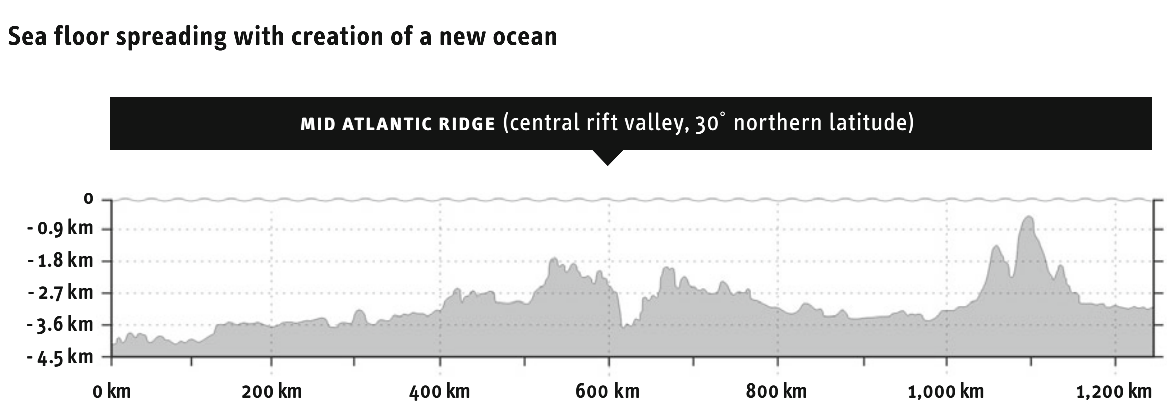



Fig. 1.6 Sea floor spreading generates new ocean floor: the rigid lithosphere drifts as plates on the asthenosphere. At the line of spreading an undersea mountain ridge (with a mid-ocean rift) is created. (Image credit: NOAA, http://sos.noaa.gov/datasets/Land/sea_floor_age.html).

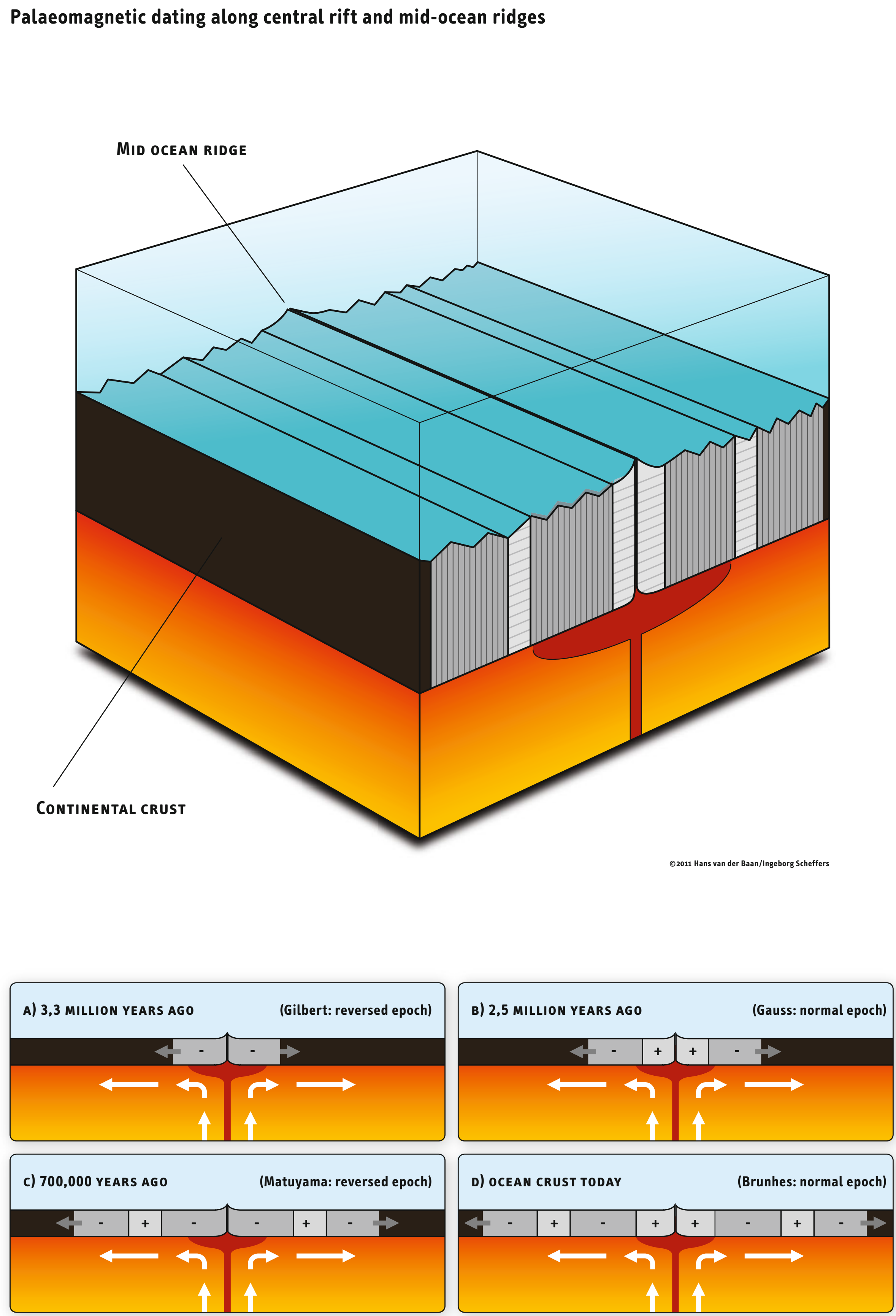



Fig. 1.7 The palaeomagnetism pattern shows symmetry in sea floor ages along both sides of the central rift of the mid-ocean ridges.

moved (Fig. 1.7). In some places, this movement is remarkably fast with velocities of 10 cm/year. It proves easy to calculate that an ocean about 4000 km wide (like the Atlantic Ocean) may have a maximum age of about 200 million years, and that the spreading rate averages several centimetres per year.

You can take a plunge beneath the surface with the Ocean Layer in Google Earth and explore what is discussed next: Along the central spreading lines in the oceans there are mid ocean ridges with a central graben. These topographic features, built by sea floor spreading, are the largest morphological element on earth, with more than 60000 km total length, relative altitudes (under water) of up to 3000 m, and widths of many hundreds of kilometres (Couper, 1983; Seibold & Berger, 1982). Iceland is one of the few places on Earth where a mid ocean ridge is above sea level (Fig. 1.8). In terms of plate tectonic framework this ridge marks the boundary between the Eurasian and North American plates. Accordingly the western part of Iceland, west of the rift zones, belongs to the North American plate and the eastern part to the Eurasian plate.

Have a look at the coastlines of Africa and South America – Their outlines are very similar, evidence that inspired the German meteorologist Alfred Wegener to formulate the continental drift hypothesis. The edges of these continents are the two sides of the rift along which the continent Gondwana first began to split and expand to form the Atlantic Ocean. However, modern shorelines most often do not coincide with the original rift because ocean water may submerge the true edges of the continents.

The flooded margin of a continent is termed the continental shelf from where a sharp drop-off (about 50 times steeper), called the continental slope, merges to the continental rise. This is an area of gently changing slope where the seafloor becomes more flat and continental crust meets oceanic crust – the true edge of the continents. The continental shelves are home to shallow sea bordering continents, mostly with very flat bottom and sloping down to water depths of about 200 m, (Fig. 1.5). The continental shelves cover about 10% of our planet and are regions where currents and waves as well as sunlight are important for inorganic and organic processes and where chang-


Fig. 1.8 The Mid-Atlantic Ridge, a divergent plate boundary, surfaces above sea level in Iceland (Image credit: ©Google Earth 2010).

ing sea levels have imprinted their morphological markers. On the continental slopes are valley-like features, the submarine canyons. They seem to be the result of erosion by sediment loaded flows called turbidity currents that are triggered by submarine slumps and which may gain high velocities (more than 100 km/h). Their load is dumped at the foot of the continental rise as wide sediment fans.

If ocean basins are continually changing their shapes and sizes, how does this affect the size of our planet? The process that keeps the balance is called subduction. Subduction takes place at destructive plate boundaries, where old crustal material is consumed, destroyed or we can say recycled. Here, slabs of lithosphere sink back into the asthenosphere along down-going arms of convection cells in the Earth's mantle (Figs. 1.9 and 1.10). In our modern geographic world, most of the subduction zones are located around fringes of the Pacific plate and thus, most oceanic lithosphere is destroyed in the Pacific. The Pacific is steadily getting smaller, while the Atlantic and the Indian Ocean are growing in size! Scientists have estimated that 200 million years into the future the Pacific Ocean will have disappeared and as a result, North America and Asia will collide. Subduction zones are places where immense geologic forces are evident in the form of earthquakes and active volcanoes. Around the edges of the Pacific Plate, in a zone often referred to as the Ring of Fire, about 90% of the world's earthquakes (and 81% of the world's largest) occur. The Ring of Fire is home to

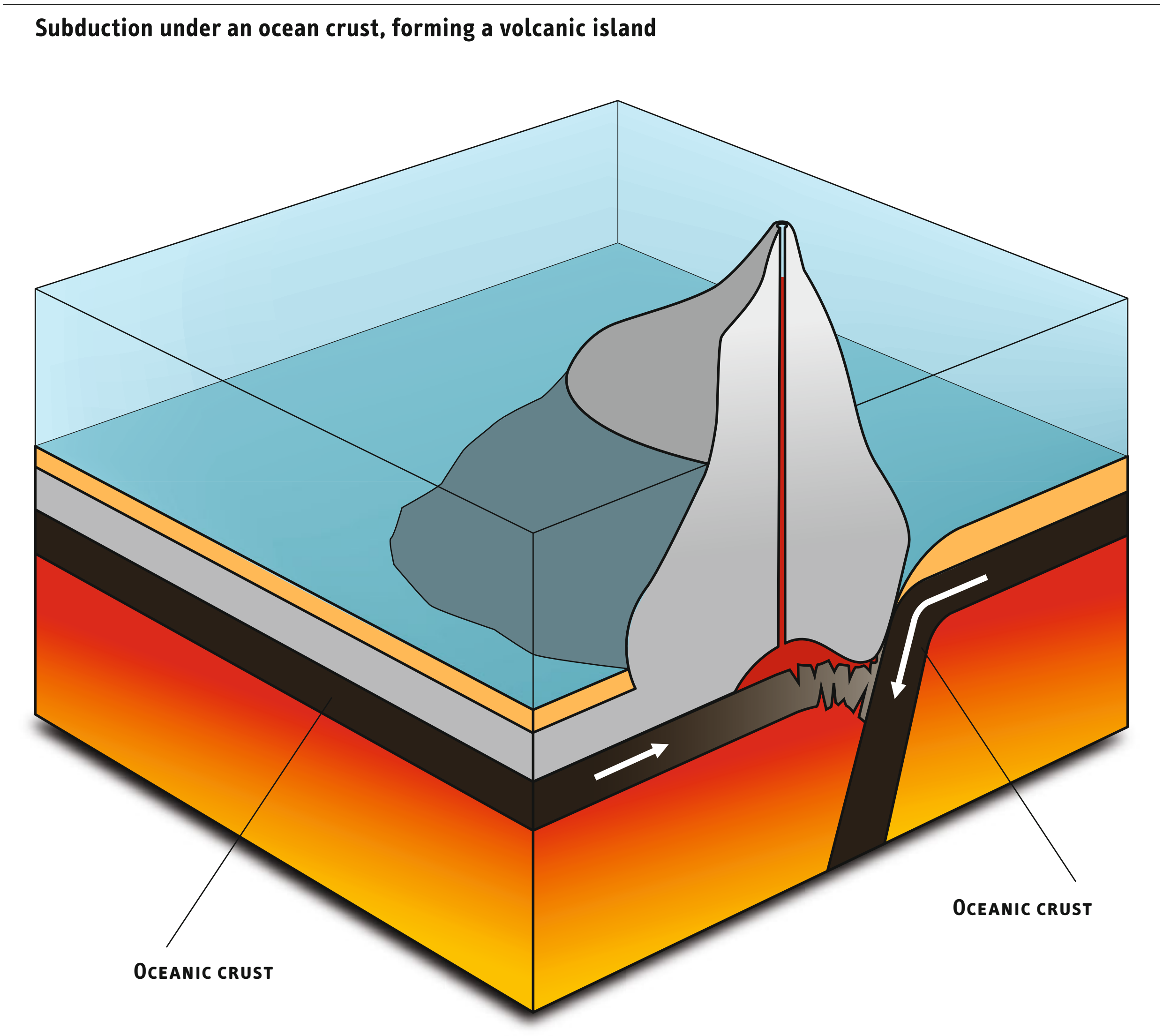



Fig. 1.9 Subduction under ocean crust, forming a volcanic island arc.

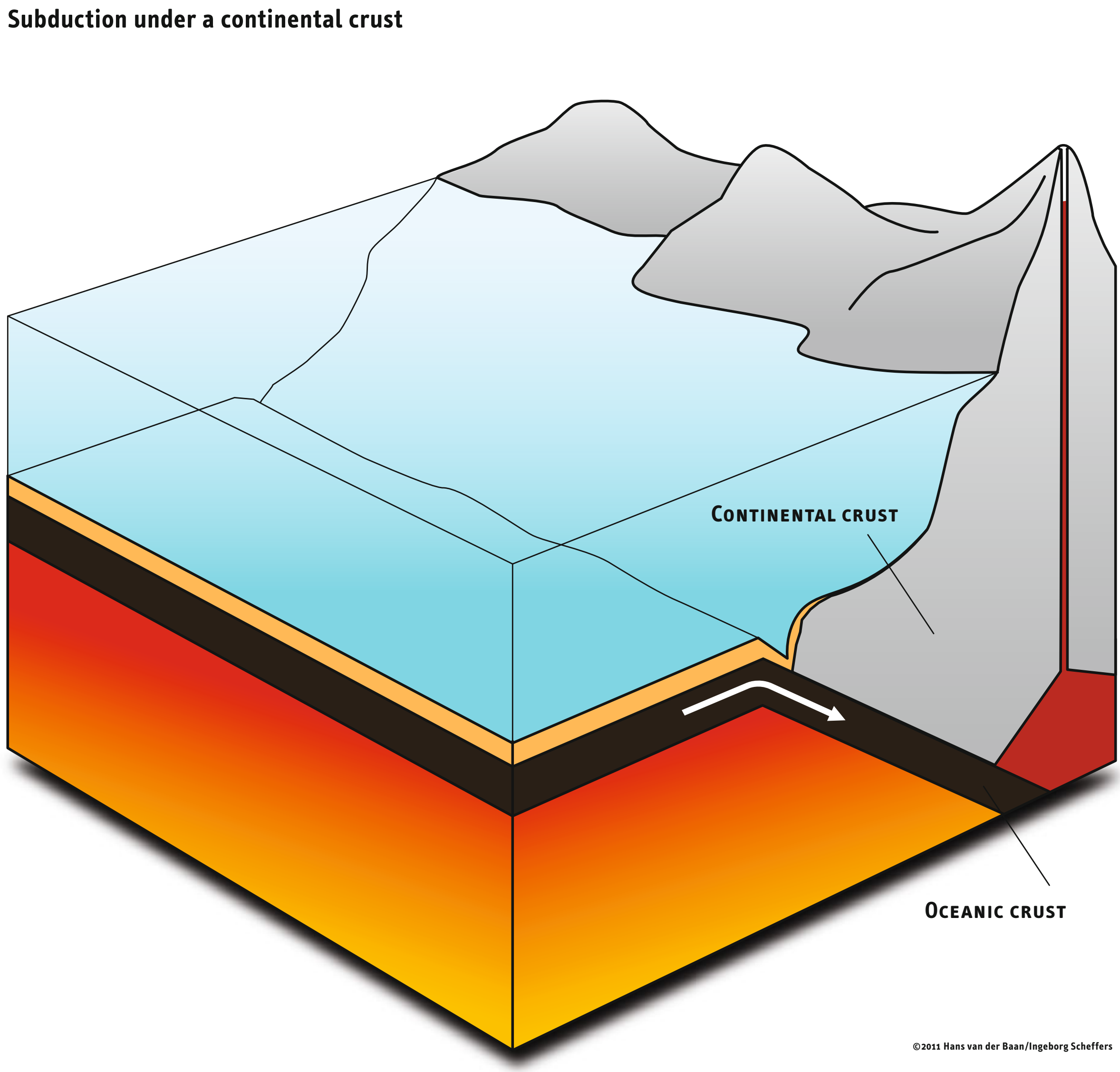



Fig. 1.10 Subduction under continental crust, forming a new mountain belt with active volcanoes.

over 75% of the world's active and dormant volcanoes. Click on *Volcanoes* in the Gallery Layer of Google Earth to learn more about the Ring of Fire.

Typical geographic features in subduction zones are deep ocean trenches that mark the places where the oceanic lithosphere grinds back into the asthenosphere. These trenches are the deepest topographic features of the world's ocean floors with the 11022 m deep Marianas Trench off the Philippines being the deepest topographic feature on Earth. On the Google Earth globe the deep trenches are clearly visible as dark, low-lying features of the ocean floor (Fig. 1.11). As an indication that subduction is an ongoing process, oceanographers observe that the deep sea trenches over subduction zones are not filled up with sediments even if they are lying in close proximity to high mountain chains. Such is the case for the trench along the Andes in the eastern Pacific Ocean.

The enormous depths of the ocean floor have been known since the days of the *Challenger* expedition in the nineteenth century. However, back then the method used to determine its depth (i.e. sending a weight attached to a line down to the ocean floor 8 km or more below) meant that only a few random measurements could be made. When these measurements were used to construct contour maps, the ocean floor looked extremely smooth. It was not until the world's ocean had been crossed many thousands of times by ships carrying echo sounders during the last decades that the ruggedness of the ocean floor was appreciated. By far the largest regions in the oceans (Seibold & Berger, 1982) are the remote deep sea basins or abyssal plains, which even today are only poorly investigated. They are several thousand metres deep and mostly without significant topography for many hundreds of kilometres. Oceanographers have claimed that we know more about the backside of the Moon than the secrets hidden in our oceans! The deep ocean basins are older parts of ocean crust than the central spreading zones and altogether cover much more than 200 million km² of our globe. Abyssal plains are forming as a result of mud accumulating and burying the seafloor topography under a blanket of these fine sediments. Because the supply of sediment from the land is an essential condition of their formation, abyssal plains are abundant in the Atlantic and generally absent from the Pacific, where subduction-related trenches and marginal (back-arc) basins entrap most terrigenous sediment, with the exception of its north-east corner, adjacent to the North American continent. Their importance of abyssal plains around the Antarctic is a reminder that the Antarctic continent supplies enormous volumes of sediment to the oceans, because ice is such an efficient agent of erosion.

A close look at the ocean bottom topography with Google Earth will reveal large numbers of single mountains on the ocean floor, often hundreds of kilometres across, in the vast abyssal plain. These features are called seamounts or guyots and their origin is submarine volcanism (Fig. 1.2; 1.3 and 1.5). Seamounts are undersea mountains rising from the seafloor and peaking below sea level. Seamounts tall enough to break the sea surface result in oceanic islands, e.g., the islands of Hawaii, the Azores and Bermuda were all underwater volcanoes at some point in the past, but have developed into oceanic islands by ongoing volcanism.

When the action of plate tectonics moves a volcanic-formed island away from the hot spot that created it, the volcanism ceases and the ocean crust cools and sinks, resulting in the now extinct volcano sinking beneath the surface. These submerged, often flat-topped, seamounts are the guyots. Seamounts are hotspots of marine life in the vast realms of the open ocean. As they tower above the surface surrounding seabed they tend to concentrate water currents and may have their own localised tides, eddies and upwellings (where cold, nutrient-rich, deepwater moves up along the

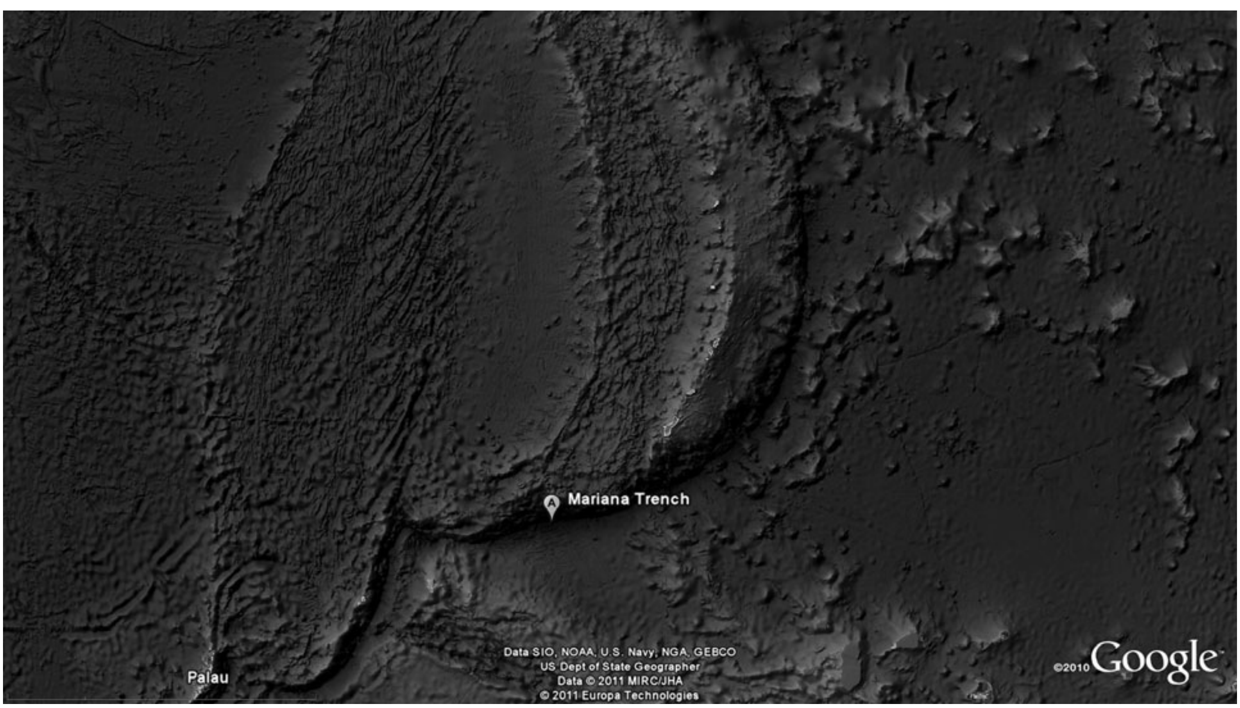



Fig. 1.11 The Mariana Trench is located in the Pacific Ocean where two oceanic plates converge and one descends beneath the other in a process known as subduction. The deepest part of the Mariana Trench is the Challenger Deep, so named after the exploratory vessel HMS Challenger II; a fishing boat converted into a sea lab by Swiss scientist Jacques Piccard. The Challenger Deep is the deepest part of the earth's oceans, and the deepest location of the earth itself. (Image credit: ©Google Earth 2010).

steep sides of the seamount). Therefore, plankton biomass is often high over seamounts which mean that they can attract large numbers of fish.

As the deep oceans are far from being sufficiently well understood, some of the processes are in a state of early exploration. Researchers were for example startled when they found natural hot springs in the sea (on land you may know natural hot springs such as Old Faithful at Yellowstone National Park). Similar phenomena occur under the oceans within mid-ocean ridge volcanoes where they are called deep-sea hydrothermal (hot water) vents or "black smokers" (Fig. 1.12). The latter are made up of sulphur-bearing minerals that have come from beneath Earth's crust. They form when hot (roughly 350°C) mineral-rich water flows out to the ocean floor at a mid ocean ridge volcano. Sulphide minerals grow or crystallize from the hot water and form a chimney- like sulphide structure through which the hot water continues to flow. As the hot, mineral-rich water mixes with the cold ocean bottom water, it precipitates a variety of minerals as tiny particles that make the vent water appear black in colour, hence the term black smokers. The water flowing out must exceed the high pressure of several thousand meters of water column, in which the bottom temperature is normally about 2°C. In spite of the extremely high temperatures, large tube worms, crabs, mussels and even fish live close to these vents feeding on chemo-autotrophic organisms. They represent a rare ecological niche separated entirely from the energy of sunlight.

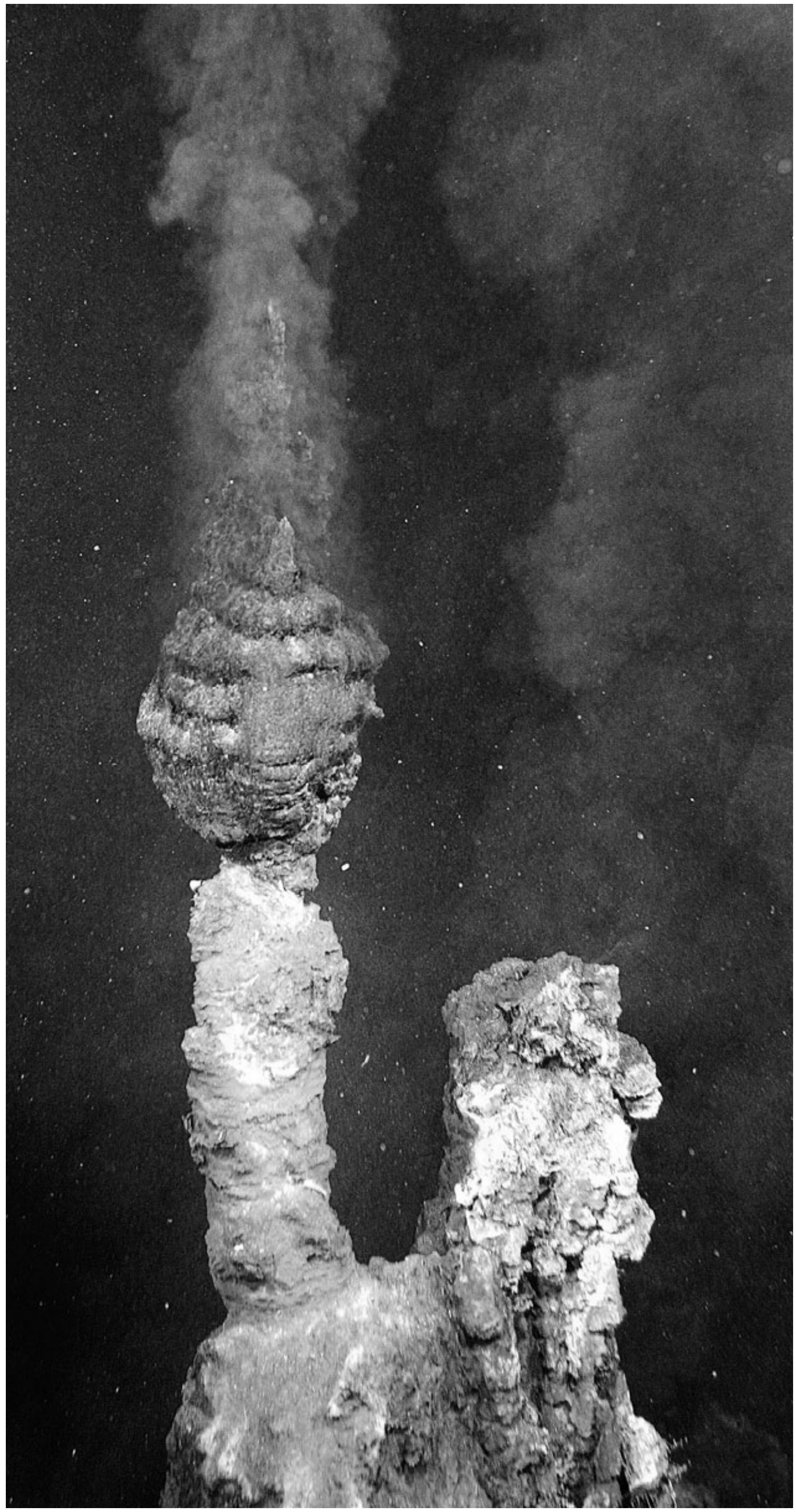


Fig. 1.12 In fault zones on the deep ocean floor "black smokers" send hot water up from the sea floor at more than 300°C as brines with dissolved metals. These chimney-like features are a habitat for a food chain starting with chemoautotrophic bacteria, and involves mussels, crabs, giant tubeworms and fish. (Photo credit: New Zealand American Submarine Ring of Fire 2007 Exploration, NOAA Vents Program, Institute of Geological & Nuclear Sciences and NOAA-OE).

## 1.2 Sediments in the Oceans

Over vast areas, the ocean floor is covered with thick sediments from different sources (Seibold & Berger, 1982). Lithic sediments that accumulate on the continental shelves and slopes consist of silts and clays that are delivered to the oceans by rivers from continental sources. Their load amounts to 18.3 billion tons/year. The focal points of sediment accumulation are river mouths and in particular deltas in tropical areas with a large discharge area from high mountains, such as the Ganges-Brahmaputra system or the Amazon basin. Other sources of lithic sediments are debris-laden glaciers and icebergs that raft sediments seawards of glacier margins (about 2 billion tons/year).

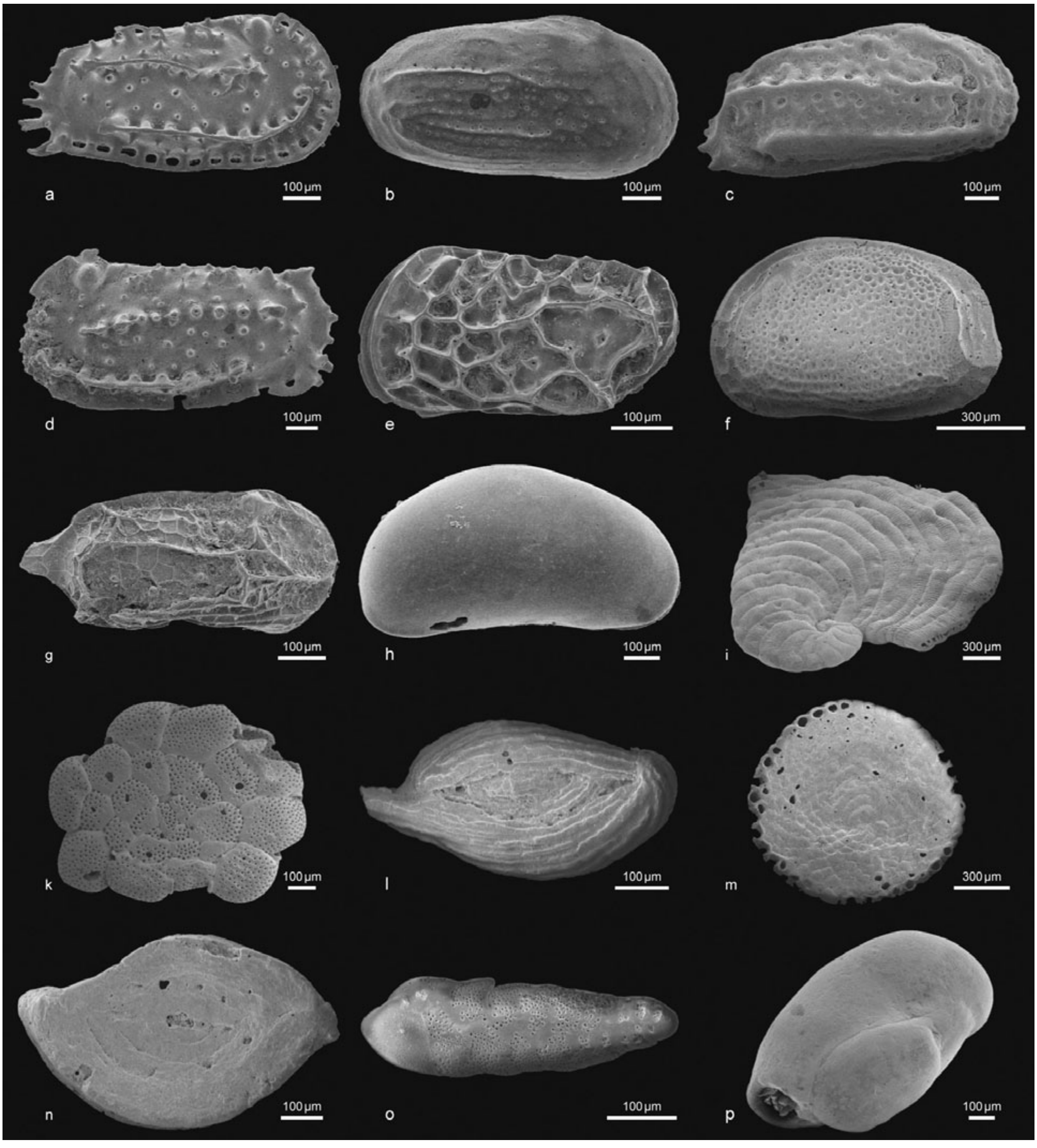



Fig. 1.13 Foraminifera made up of carbonate are mostly planktonic but may live on the sea floor. (Photo credit: Andreas Vött, University of Mainz, Germany).

Large areas of the deep sea floor are mantled with sediments that consist of the skeletal remains of tiny organisms such as single-celled planktonic animals. Warm surface waters in the low to middle latitudes favour the growth of carbonate secreting organisms like *foraminifera* (Fig. 1.13). Their tiny shells accumulate at an average rate of about 1–3 cm per thousand years at the ocean floor. Large volumes of carbonate crystals are also precipitated inside the intestines of marine fish and are then excreted at very high rates, releasing this lesser-known, non-skeletal carbonate into the marine environment. The source of the carbonate in the ocean is the product of solution of limestone by weathering processes. The calcareous oozes are not found where the ocean basins are very deep as cold, deep water (under higher pressure) dissolves more carbon dioxide. As a result, these deeper waters are more acidic than surface waters and they dissolve carbonate particles such as the shells of *foraminifera*. The depth at which this occurs is called Calcite Compensation Depth, or CCD, and in the Pacific is about 4000 to 5000 m, whereas in the Atlantic Ocean the CCD is somewhat shallower. Thus, all limestones that we now find in the terrestrial environment, even folded up into high mountains, were formed by the sedimentation of carbonates in rather shallow water. This is the case with corals at 3000 m above present sea level in the European Alps. In other regions, organisms that precipitate siliceous skeletons may dominate. These tiny *radiolarians* (animals) and *diatoms* (plants) (Fig. 1.14) are the major component of ocean sediments in regions with high biological productivity, as for example around the Southern Ocean or the equatorial Pacific and Indian Oceans. As sea water is undersaturated with respect to silicate, these shells would ultimately be dissolved, but this process is slow, and in nutrient rich coastal waters the bio-production is rapid, so that net accumulation normally occurs.

Far away from the continents and in regions of low productivity, the deep seafloor is covered with very fine grained clay, termed "red clay" as its colour is the result of oxidation of iron rich minerals in the sediment. The source of much of this clay is fine windblown dust that drifts over long distances with air masses from the continents over the ocean basins. Overall the sedimentation rate of these clays is very low with rates of only 1 mm to 1 cm over a million years!

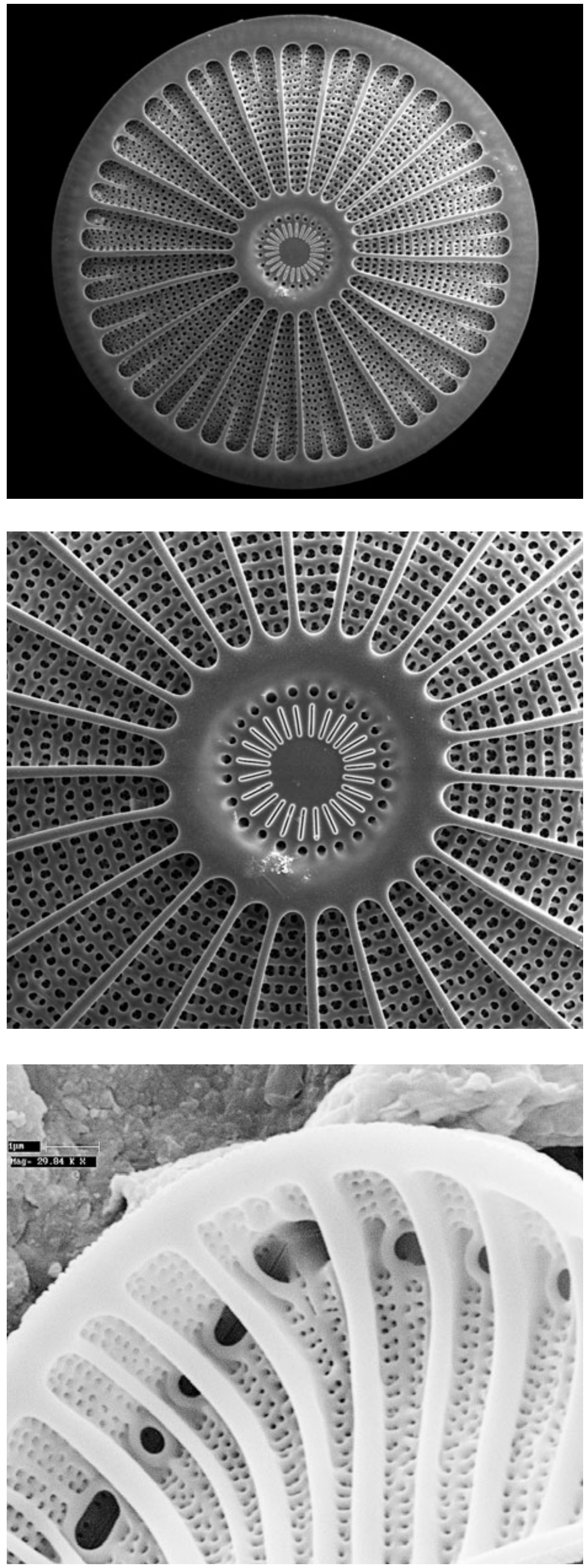


Fig. 1.14 Diatoms are made of silica and are common as plankton. (Photo credit: Jan Michels, Institute of Zoology, Christian-Albrechts-Universität Kiel, Germany; Kathryn Taffs and Jo Green, Southern Cross University, Australia).