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PREFACE

From an astronaut's point of view

Mountains loom large from my very earliest memories. Every summer, I would spend my holidays with my family in the region of the Ormonts, at the foot of what Michel Marthaler calls the 'Diablerets nappe'. The beauty of the place renders any description of mine redundant. Suffice it to say that it was towards the heavens, free of the impurities of urban life, that the tremendous peaks of the Alps of the canton of Vaud impelled our gaze as children and youths.

Later, I made my first astronomical observations from the Gornergrat observatory. The landscape, of course, was sublime. Facing my vantage point, the rock and ice of the Matterhorn towered vast, magnificent and proud among peaks which, though perhaps even higher and more difficult to climb, could not be compared with the austere splendour of the monarch of the Alps. Above it all stretched out the widest, clearest sky in central Europe. All of this, as the author of the book describes, once bathed in an African ocean from which the Matterhorn 'raft' emerged. The story of how the glorious harmony of the present scene came into being strikes me as being little short of miraculous.

In many ways, the attraction of mountains is close to that of space. Both demand total commitment and unflinching discipline. Neither difficult climbs nor space flight can be embarked on without exhaustive training, and equipment that will stand up to extreme conditions. Nor can we allow our attention to stray from the situation in hand for even a split second. This similarity impressed itself on Jeff Hoffmann, a fellow astronaut, and myself when, accompanied by close friends and family, we climbed the Matterhorn together after two flights into space. We revelled in the shared effort and our sense of pushing ourselves beyond our usual limits.

None of my space flights took me over the Alps. In orbits close to the equator, however, they afforded me frequent views of the Himalayas and, above all, of Everest, with its impressive white pyramid set amidst an extraordinary filigree of valleys and mountain ranges, all apparently frozen for eternity. Without doubt, this is one of the most spectacular sights that Earth offers viewers from space.

As an astronomer, I fully expected to get the shock of my life when I first saw the universe from a space shuttle in orbit. I was not disappointed. The ineffable blackness of deep space and the brightness and sharpness of the stars are among the greatest rewards for those who escape from the bonds of gravity for the first time. Yet, the blue planet, over which we skimmed at an altitude of 300 to 600 km, remains the most precious pearl of the cosmos and the star of our personal film viewed in continual close-up – a vision of ethereal beauty, infinitely delicate and fragile.

As Michel Marthaler so expertly demonstrates in this book, the planet has evolved constantly over time and even more so now through the actions of those who inhabit it. Inhabit, however, does not necessarily signify destroy. The Earth, of which we are mere ephemeral tenants, must allow all life forms the opportunity to pursue the arduous path of their evolution. This is one of the lessons I garnered from my excursions into space and which I would like to share with the readers of this beautiful book.

CLAUDE NICOLLIER
Astronaut, European Space Agency

FOREWORD

From a geologist's point of view

Of all the world's mountain ranges, the Alps were the first to be studied and have been the most intensively researched. Several generations of Alpine geologists have laboured to unravel the secrets of their complexity. This was how they discovered 'overthrusts', the first great units of rock displaced over vast distances. Similarly, the principles of sound palaeogeographical reconstruction were developed in the Alps. Despite the extremely complex details of the geological genesis of the Alps, advances in geophysics and oceanic geology have made it comprehensible. It was the evolution of these disciplines in the 1960s that permitted a global theory of mountain formation through the theory of plate tectonics.

Nevertheless, though it is now possible to reconstruct the geological and topographical evolution of the Alps, summarising the process relatively simply in a limited number of pages remains a very formidable task. Yet this is exactly the considerable achievement of Michel Marthaler's book. His captivating text, accompanied by magnificent panoramas, as well as numerous drawings, maps and diagrams, relates the birth and subsequent disappearance of the oceans and continents that contributed to the formation of the Alps. Despite the accessibility of his prose, Michel Marthaler's precise explanations accurately represent our current understanding. In addition, comparisons drawn from examples of processes currently occurring all over the globe help the reader grasp the phenomena that precede and control the formation of a mountain region such as the Alps. This book thereby illustrates the link between local and global geology.

As far as possible, the use of scientific jargon has been avoided; and wherever such usage is unavoidable, footnotes give straightforward definitions of the geological terms employed. Both author and editor are to be congratulated on pitching the text and images at an appropriate level. Finally, Michel Marthaler succeeds in giving a very real sense of the slowness of geological processes and the immense span of the Alpine narrative as compared to the stressful hastiness of modern life.

Michel Marthaler's book is indispensable reading for teachers and students of the natural sciences, for geologists unfamiliar with Alpine geology and, above all, for anyone interested in science and nature and wishing to know more about the origins, development and erosion of mountain ranges such as the Alps. It is a book for all who love, travel through or live among mountains, unaware of the fascinating history of the landscapes and the rocks that lie right beneath their feet.

ARTHUR ESCHER
Professor emeritus
Universities of Lausanne and Geneva

How to get the most from this book

The history of the Alps is complex. To describe it, we need to draw on scientific terms and numerous episodes in the geological record. This book seeks to explain them in the form of a narrative or drama. A good many 'actors' have to play their parts before the Matterhorn can stride upon the scene. Non-geologist readers should therefore familiarise themselves with their names, because it is these actors, among others, that created the Alps. To reduce the deterrent effect of words such as Briançonnais, Piemont and Valaisan used in unfamiliar ways, the glossary, drawings and captions help the reader get to grips with these scraps of ancient continents and oceans. Charts, maps and cross-sections show successive stages in the development of the Alps. They appear both at the appropriate points in the text and then again at the end of the book to give a summarised overview of the geological scenario.

After an introduction on the incredibly long memory locked into the landscape and rocks of our mountains, the first chapter deals with the gigantic geological forces that originate deep within the Earth, drive our planet today and, for that matter, have driven it since the beginning of time. Volcanoes and earthquakes happen not only on land but also in the depths of oceans. Readers should take the time to familiarise themselves with several key concepts, such as the distinction between active and passive continental margins, illustrated by the cross-section of our planet on page 14. This fundamental concept is then illustrated by maps of the floors of the Atlantic and Pacific Oceans. In the course of this grand tour of our planet, readers should also try to acquire sufficient basic geological terms (in bold print) to allow them to grasp the core of the matter: the great voyage that carried the African rocks of the Matterhorn to Europe as the Tethys Ocean widened and then disappeared.

As this narrative will cover some 250 million years, stretching from the end of the Palaeozoic to present times (the Quartenary), the introduction ends with the image of a film that unspools through geological time (p. 12). This image is revisited in subsequent chapters to help readers find their bearings in the five principal stages (corresponding to Chapters II to VI) of the Earth's history and geography that led to the creation of the Alps.

I wish all readers a 'bon voyage' through both the space and time of our magnificent planet!

About the bibliography

Superscript figures in the main text link to references in the bibliography at the end of the book. The bibliography is intended to give an overview, not to be exhaustive. It contains just over a hundred references on the geology of the Alps and planetary geodynamics. This is both few and many.

Many, because the non-specialist is generally content with references to books and papers at a popular level (these are cited with the publication date last, after the editor). Scientific articles (cited with the publication date after the authors) are frequently too specialised.

Few, because my geological peers would find the bibliography incomplete. For them, it would need to cite more than a thousand references. I trust they will forgive me for a selection that is frequently partial. However, it is worth noting that there are comprehensive bibliographies in some of the overview publications cited (Results of PNR 20, *Deep Structure of the Alps*, Fonds national suisse de la recherche scientifique, programmes ECORS France, CROP Italy), as well as in the explanatory notes to the geological maps of the Swiss Federal Office of Topography (Swisstopo).

An extraordinary story lies behind the ineffable beauty of any mineral landscape (here, the Libyan Desert).

The ice and snow covering the north faces of the Mönch (on the left) and the Jungfrau conceal an accumulation of limestone sediments laid down in a warm tropical sea 100 to 150 million years ago.

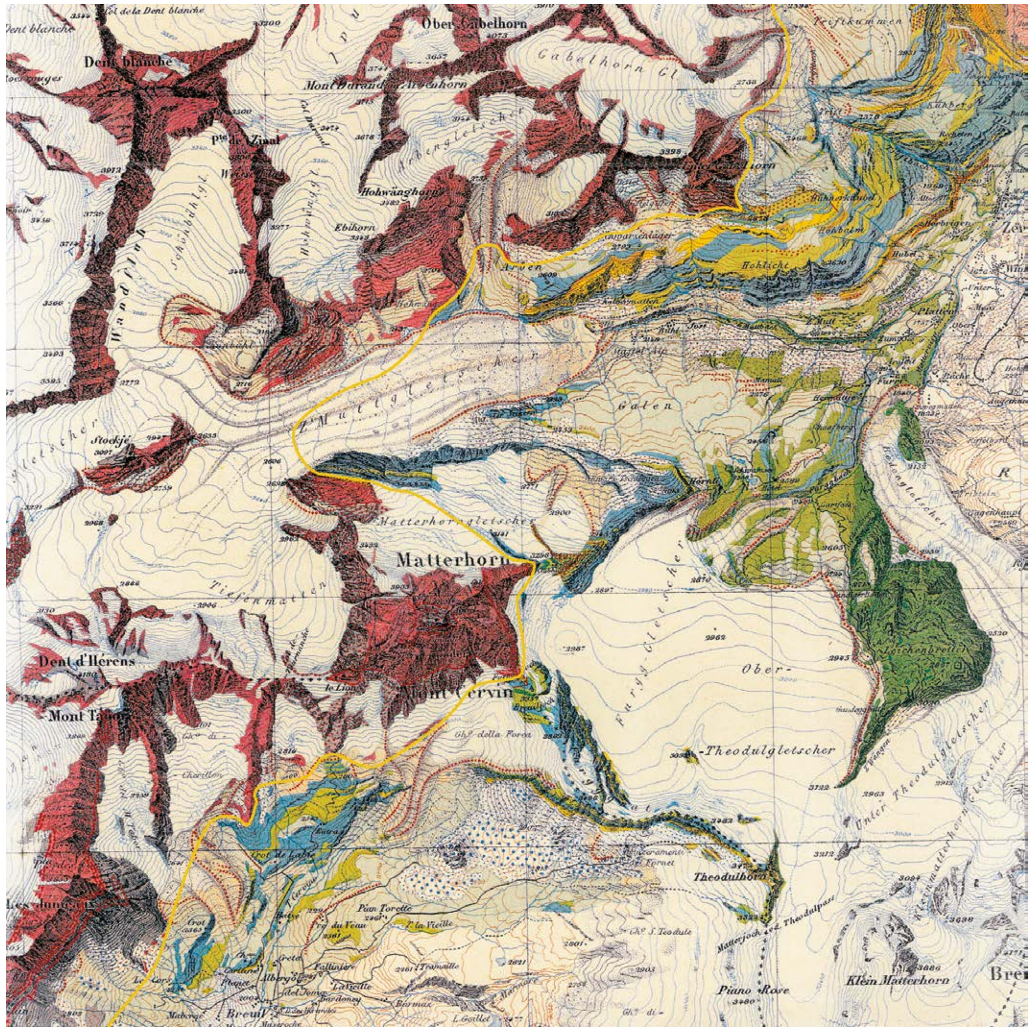
INTRODUCTION

Our Earth's prodigious memory

Did you know that the most prodigious memory on Earth is that of the Earth itself? The planet's vast history is inscribed in the stones of which it is made. However, nowadays, this history is usually hidden beneath a landscape of snow, vegetation and human settlements. In deserts and mountains, more impudent rocks thrust through the surface. Even here, however, they are not extremely forthcoming; every now and then a traveller may catch a fleeting glimpse of the ancient tales that underlie the breathtaking beauty of these mineral landscapes. The icy northern faces of the legendary Eiger and its sisters, the Mönch and the Jungfrau, for example, are in fact vast accumulations of limestone sediments laid down patiently in a tropical sea during the **Jurassic** and **Cretaceous** periods, 100 to 150 million years ago.

Jurassic: middle period of the Mesozoic era that lasted from −200 to −145 Ma. This long period, famous for the numerous dinosaur fossils it has bequeathed to us, is further subdivided into three parts: the Lower Jurassic (or Lias), the Middle Jurassic (or Dogger) and the Upper Jurassic (or Malm).

Cretaceous: third and final very long period of the Mesozoic era that lasted from −145 to −65 Ma. The Cretaceous ended with one of the most devastating mass extinctions of species our planet has ever known. In particular, all dinosaur species disappeared from the land while all ammonite species disappeared from the oceans.



Extract from Emile Argand's geological map (1908)[1]

Scale: 1:75,000

Continental gneisses of African origin are coloured in orange-red. Oceanic sediments are coloured blue, and submarine lava, green. Even though the rocks are partially covered by glaciers and their attendant moraines, the yellow line added here helps us visualise where the limit between the continental and the oceanic rocks lies. This is in fact one of the aims of geological cartography: to locate the points of contact between different rocks hidden under **Quaternary** formations (glaciers, moraines, rockfalls).

The rocks of the Matterhorn were imported from Africa long before the mountain assumed its famous symbolic pyramidal form. The Swiss geologist Emile Argand[1] was the first to discover and explain the mountain's strange paradox: the rocks so eagerly scaled by the world's climbers are ancient **gneisses**, several hundred million years old, which – turning chronological history quite literally on its head – overlie much softer rocks, the remains of a young ocean that disappeared at the end of the Cretaceous period, only 60 to 80 million years ago.

Previous page: The rocky pyramid of the Matterhorn (seen from the north here) resembles a small continental raft run aground on strata of marine sediments that were laid down in a long-vanished ocean. The ocean/continent border is outlined in yellow. Eighty million years ago, this border was shifting but was hidden under the edge of a continent. Nowadays, it is visible, albeit set in the mountain face.

Gneiss: metamorphic rock whose narrowly banded surface has a mirrored aspect due to the preferential orientation of the minerals it contains. These are for the most part **quartzes** and **feldspars** in the light-coloured bands, and **micas** and **amphiboles** in the dark ones.

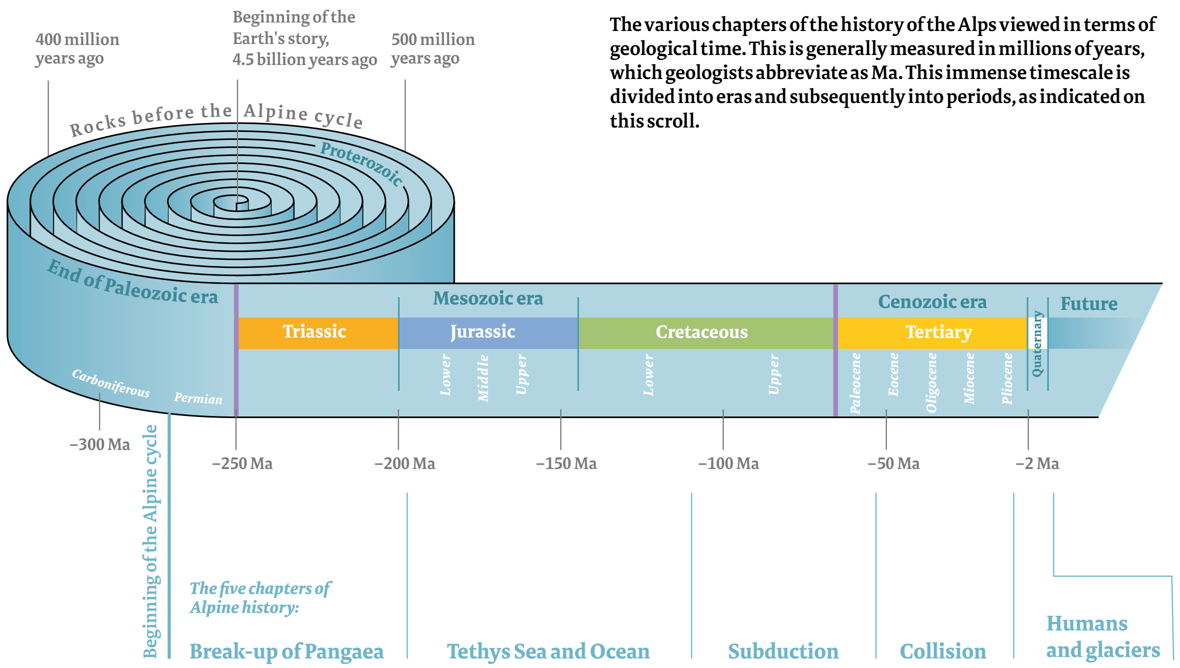
Quartz: very hard, common mineral, rich in silicium (SiO_2), grey to translucent, forming hexagonal pyramids when perfectly crystallised[108].

Feldspar: group of white or pinkish minerals, abundant in magmatic and metamorphic rocks.

Mica: group of layered, flaky, glittery black or silver-hued minerals.

Amphibole: needle or rod-shaped mineral, usually dark green in colour.

Quaternary: current, most recent period in the geological timescale, from −2 Ma to today. Once ranked a geological era, it has now been affixed to the Cenozoic era.



The various chapters of the history of the Alps viewed in terms of geological time. This is generally measured in millions of years, which geologists abbreviate as Ma. This immense timescale is divided into eras and subsequently into periods, as indicated on this scroll.

Mountain landscapes, so familiar to us and so apparently immutable, have fabulous tales to tell. They bear the traces of a living **geodynamic**. Not only in space but also through time, one landscape can hide another and, for the geologist, the sea is not so much behind the mountains as inside them. By the same token, common stones, and not just scintillating crystals, provide precious clues to our planet's immense history and **paleogeography**.

Time seems to speed up

As we will narrate the events of over 250 million years in a hundred or so pages, the unfurling of our planet's history may seem to race along at breakneck speed. Imagining such immensities of time is not easy, given that just one million years represents something like 40,000 generations of human life. The period that we will be examining began long after the creation of the universe, over 15 billion years ago[2], or that of the Earth, some 4.5 billion years ago[3], or even the inception of terrestrial life, about 3.5 billion years ago[4]. When our story does finally begin, a mere 250 million years ago, planet Earth had already been around for quite a while. During the seemingly interminable Proterozoic and Paleozoic eras, the continents had already drifted apart and come back together again a number of times[5]. The story related here is, in fact, only the very latest episode in the long travels of the continents and the oceans: the Alpine **orogenic cycle**.

Before beginning, we should outline some basics on which to found our explanation of one of the great paradoxes of the science of geology, i.e. that mountains are born of the depths of the ocean and of seashores. If we seek to understand the origins of a mountain chain, we must first seek to find out how an ocean emerges, matures, grows old and finally dies. To put it another way (and this constitutes one of the principal interests of Alpine geology): to study the past of the Alps is also to better understand our planet's present existence[6].

Geodynamics: discipline of Earth sciences studying the forces, movements and changes that affect our planet and more particularly its surface: continental drift, opening and closure of oceans, the creation of new topographies.
Paleogeography: study of the historical geography of the Earth's surface, generally of physical landscapes and the changing positions of continents, seas and oceans over geological time.
Orogenic cycle: sequence of events related to the formation and erosion of mountains.

CHAPTER I

The long trek of continents and oceans

Towards the end of the 1960s, a scientific revolution shook the world of Earth sciences: the innovative concept of 'plate tectonics'[7] successfully rehabilitated the brilliant ideas of Alfred Wegener[8] and Emile Argand[1] about continental drift. This discipline is now called geodynamics. It studies the forces that drive the transformations of our planet, which appear slow on a human scale: the opening up, drift and closure of oceans[9]; the crumpling, growth, drift and rifting of continents[10, 11]; the uprush of islands and mountains[11] emerging from ocean spray and land[12]. Because of this, our planet is perhaps an exception in the universe, as it possesses some of the traits that characterise a living organism: slow circulation, respiration and digestion – of which we perceive only the sneezes and belches in the form of earthquakes and volcanic eruptions.

An enormous thermal machine

In many ways, the globe's structure resembles that of a living cell. In its heart lies a very hot (5,000°C), dense (12 times heavier than water) core that is solid at the centre (the inner core) and liquid at the edges. This core is rich in iron and heavy atoms and is highly energised. This energy probably originates from nuclear disintegration as well as from the extension of the solid inner core[3]. The nuclear energy generated by the Earth, however, is not comparable to that produced by the sun, whose temperature approaches one million degrees thanks to nuclear fusion. Our planet's core is surrounded by a hot, viscous **mantle** which circulates in gigantic convection currents comparable to the great cyclonic movements of the atmosphere. These convection currents drive the thin sections of the **lithosphere**, which constitutes the outer membrane of our cell, called lithospheric plates. This term '**plates**' is perhaps not very evocative; 'skin', 'outer membrane' or 'rock rafts' would be more appropriate.

Raft-like plates

Let us now examine this skin or these rock rafts more closely. On a simplified map of the world (p. 15), the lithospheric plates resemble pieces of a puzzle whose edges are mostly found on ocean beds and sometimes along continental boundaries, along the western edge of the Americas for example, and even occasionally in the middle of a continental mass, as in the case of the Indo-Eurasian boundary. Geologists are particularly interested in this last example as it constitutes the environment in which mountain chains[11] such as the Himalayas and the Alps[6] arise and augment deep in the Earth's crust.

Mantle: major part of the Earth's interior substance, situated between the Earth's crust and its core. The mantle is composed principally of iron and magnesium silicates. The rocks originating in the mantle's very outer levels (the lithospheric mantle) are known as peridotites (see page 32). The mantle's density increases from 3 at the base of the crust to 5 just above the core. Its temperature also increases, rising from 1,000°C near the surface to 4,000°C at its base. In addition, owing to the mantle's natural radioactivity, this steep geothermal gradient is one of the causes of the immense convection currents that stir the whole mantle. The term mantle is now somewhat dated. Nowadays, it would be more correct to distinguish the lithosphere, which is the rigid uppermost layer of what used to be called the mantle and which is associated with the Earth's crust, from the asthenosphere (the upper relatively fluid part) and the mesosphere (the lower viscous part).
Lithosphere: Earth's solid and rocky external envelope (from the Greek *lithos*, meaning stone). This envelope is, however, subdivided into a number of plates, rendering it mobile and discontinuous. The lithosphere is about 100 km thick on average, but is much thinner in the vicinity of the mid-oceanic ridges. On the other hand, the lithosphere is much thicker than average, and even up to twice as thick in mountainous areas. The lithosphere is made up of the Earth's oceanic or continental crust on its surface, with the uppermost rigid and cold part of the mantle underneath. Below passive margin zones, the lithosphere assures the solidity of the link between continental and oceanic crusts.
Plate: large mobile sections of lithosphere at the surface of the globe. These are limited and outlined by oceanic ridges, subduction zones or rifts. A plate may be oceanic (e.g. the Pacific plate) or continental and oceanic (e.g. the African plate).

Schematic cross-section of the terrestrial globe, on a plane bisecting the Alps

This diagram shows the Earth's concentric structure, its interior heat source, the convection currents that churn the mantle, and the movements of the lithospheric plates that prop up the drifting continents and ocean beds. Lithospheric plates float all around our planet, spreading away on either side of mid-oceanic ridges and continental rifts. When continental and oceanic crusts converge on the same plate, the boundary between them is known as a passive margin. However, with an active margin, one of two plates will dive under the other, and be drawn down into a subduction zone. The descending plate slowly melts as it thrusts into the hot viscous mantle. Our planet's active volcanism[14] is related to three different geodynamic circumstances: immense fountains of heat rising through the entire mantle; the ensuing melting of the asthenosphere; and the resultant abundant magma piercing the lithosphere. This is the continuously effusive basaltic volcanism associated with hotspots such as the Hawaiian Islands and Réunion. Diverging plates cause continental rifting (East Africa's Great Rift Valley) and mid-oceanic ridges. The latter produce abundant effusive submarine volcanism. Iceland is exceptional in that it is both an emerged ocean ridge and a hotspot. Finally, converging plates in subduction zones cause a more explosive form of volcanism. Mount St. Helens is a good example of this. Stromboli, situated to the south of the Apulian plate, is also well known for its frequent small explosions.[15]

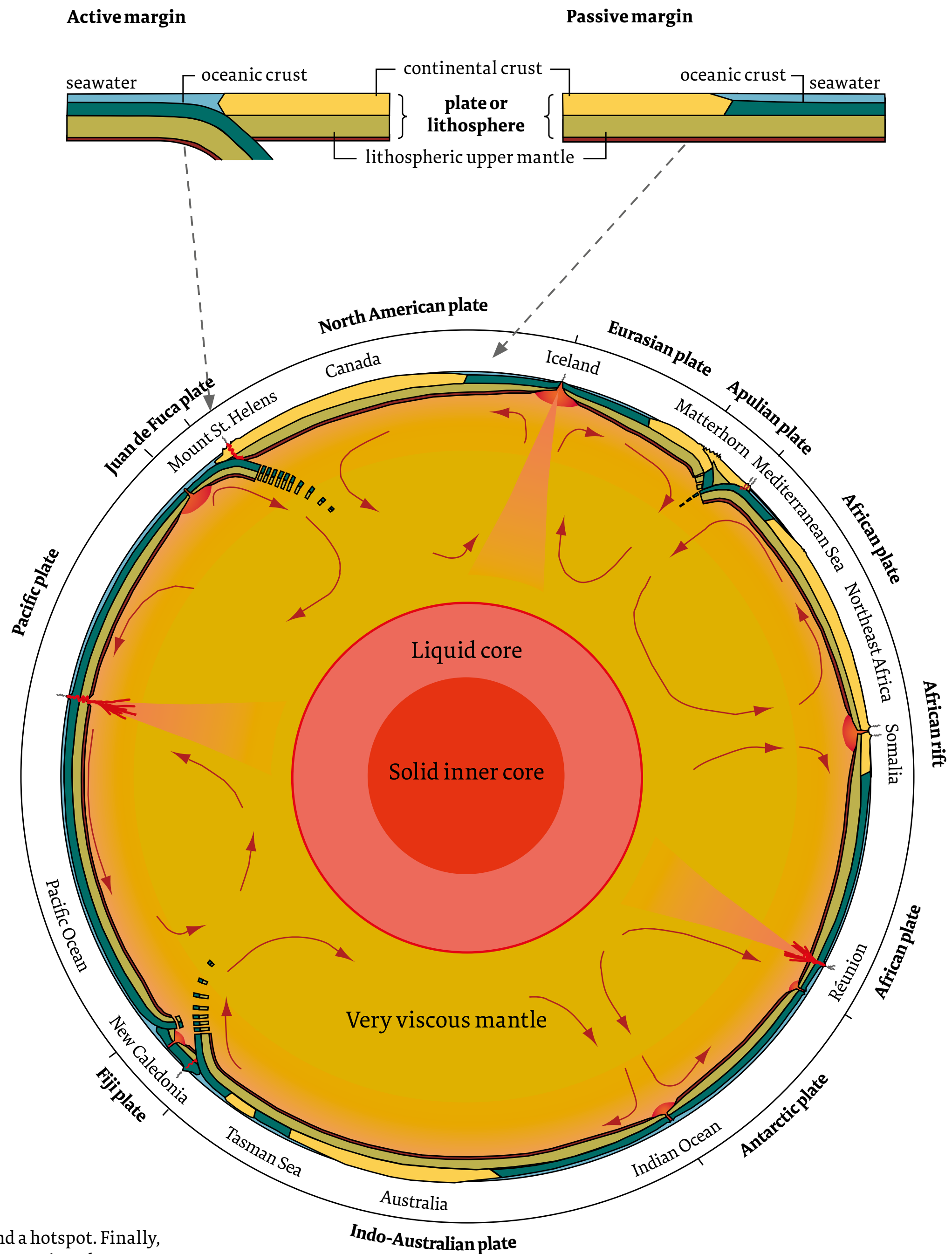
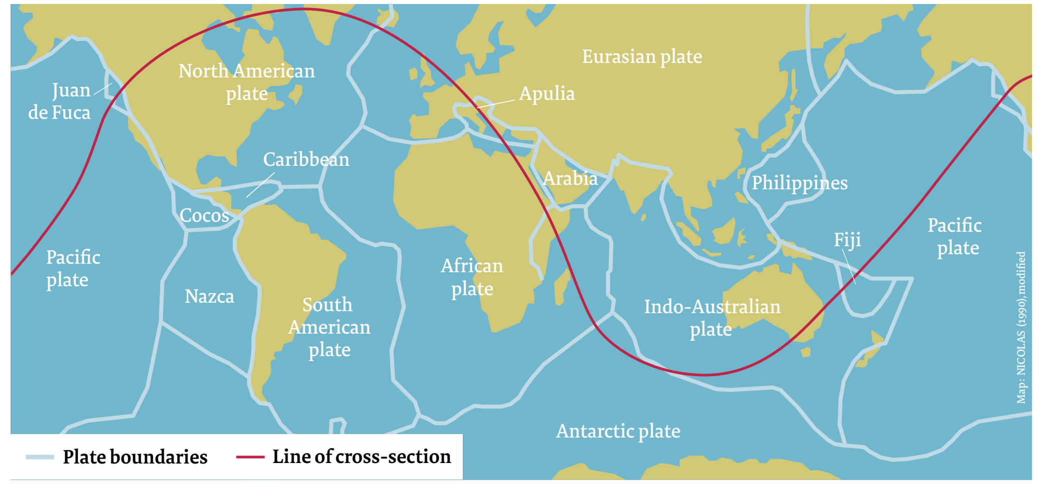


Plate thickness amplified four times in relation to the viscous mantle



Simplified map of the world

This map outlines the principal lithospheric plates and shows the line of the cross-section featured on the previous page.

When viewed in cross-section, the plates look like thin rafts made up of two slightly arched layers: one, the **Earth's crust**, and the other, the lithospheric mantle. The arching conforms to the Earth's curvature but is significantly accentuated in **subduction** zones where the plates plunge down into the mantle and melt from the heat of the **asthenosphere**. The relative weight of the plates as they are engulfed is one of the main forces driving the rafts' movements. These rafts do not then always remain on the surface as, like the Titanic, lithospheric plates do sometimes sink, particularly when they run into the edge of a continent. This is because the Earth's crust does not have the same composition in the heart of a continent as it does on an ocean bed. The relatively light **continental crust** is composed mainly of light-coloured rocks of the **granite** and gneiss family, while the composition of the denser, darker **oceanic crust** is dominated by **basalts** and **gabbros**.

This is why entirely oceanic rafts, such as the Pacific Ocean plates, are more likely to sink, as there are numerous subduction zones all around the margins of this great ocean. The contact between the Pacific Ocean and the continents that adjoin it is

Earth's crust: Earth's rocky surface mainly comprising two distinct types of rock: continental and oceanic.

Subduction: plunging of lithospheric plates, because they have become too heavy, first into the asthenosphere and then into the lower mantle or mesosphere. As a rule, subducted plates are oceanic in nature. A continent (as happened with the Indian continent) may also be partially drawn into a subduction zone, following on the heels of an ocean that has disappeared. Subduction zones are usually located on the boundary between continents and oceans. They are responsible for setting off numerous earthquakes. They can also be situated mid-ocean; the very deep trenches of Tonga and the Marianas are examples. In both cases, several million years after it began[14], the subduction process gave rise to a chain of volcanoes.

Asthenosphere (from the Greek *asthenos*, meaning soft): upper part of the mantle, situated directly under the lithosphere. The asthenosphere is hot (average temperature 2,000°C) and partially molten. It can be compared to a hot sea on which the lithospheric rafts float and drift. The asthenosphere is stirred by convection currents which affect the entire mantle.

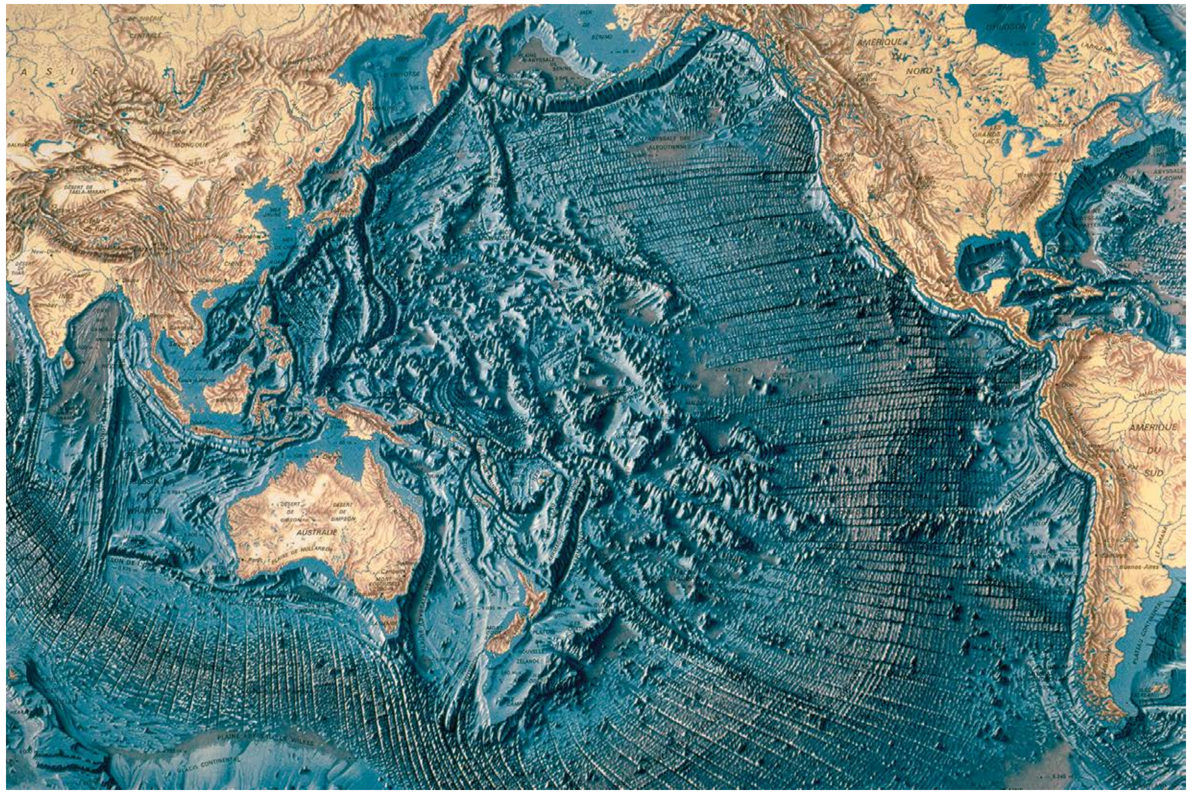
Continental crust: upper layer of the lithosphere, sometimes outcropping (exposed) on the surface of continents (in Australia, Canada, Scandinavia, the Alps), but generally found beneath sedimentary rocks. On average about 30 km thick, and lower in density (2.7) than the oceanic crust (3.0), the continental crust comprises mainly gneisses and granite.

Granite: magmatic rock comprising several light-coloured minerals such as quartz and large pink and white feldspars, as well as some dark sparkling minerals such as black mica. Characteristic of the continental crust, granite is formed at depth when silicon-rich magma cools very slowly (over a million years), thus forming distinct crystals clearly visible to the naked eye.

Oceanic crust: uppermost layer of the lithosphere, usually forming ocean bedrock beneath oceanic sediments. It comprises pillow basalts, gabbros and serpentinites. Oceanic crust and lithosphere originate from the cooling of magma that oozes out from mid-oceanic ridges. They slowly migrate across the ocean floor, getting thicker and heavier until they finally plunge into subduction zones[9].

Basalt: most abundant volcanic rock in the Earth's crust. Black or dark in colour and relatively heavy (density 2.9 to 3.0). Basalt is formed by the spreading and cooling of magma on continental and oceanic bedrock. The structure of submarine basaltic flow is visibly formed of stacked pillow lavas (see page 32).

Gabbro: magmatic or igneous rock of the same density and mineral composition as basalt, but which has crystallised at depth. Generally dark in colour, featuring stocky black crystals of pyroxene and speckled with white crystals of feldspar.



The Pacific Ocean floor, bordered by long, deep subduction trenches, from Tierra del Fuego to New Zealand via Alaska and Japan
This subduction gives rise to the Ring of Fire and frequent earthquakes along the edges of the continents. The shores of the Pacific form an immense belt of active margins. The Kermadec and Tongan trenches to the north of New Zealand, as well as those of Japan and the Kuril Islands (North Pacific), are particularly striking. These are the places where the dense Pacific plate buries itself under the seaward edges of the Australian and Asian continents. The long volcanic chain that now ends with Hawaii stands testament to the slow drift of the Pacific plate to the northwest. The ongoing volcanic activity that has been associated with this hotspot for over 100 million years still gives rise to new submarine volcanoes to the southeast of the island. In the same way, the ring of active volcanoes surrounding the Pacific will persist for as long as the subduction process continues – certainly for several million years to come. Note also the Eastern-Pacific ridge which constitutes the separation front between the Pacific plate moving off to the west and the relatively small Nazca and Coco plates to the east. The ridge can be seen disappearing under North America. Finally, in the southwest, the northward drift of the Indo-Australian plate continues. The northern edge of the Indian subcontinent has already plunged beneath Asia, while Australia is about to set off on a track that will take it under the eastern end of the Indonesian volcanic chain. On its southern side, this extended archipelago is also bordered by a deep subduction trench.
Exerpt of the map of ocean floors, © Hachette Livre – Guides bleus

therefore constantly shifting, shaken by innumerable earthquakes. Moreover, as it dives under the continents and into the asthenosphere, the oceanic plate heats up and dries out[14]. In doing so, it provokes the fusion of the base of the overlying plate under which it becomes buried, and the resulting **magma** rises through the Earth's crust before gushing from the mouths of numerous volcanoes[15]. This is the Pacific's famous (or infamous) Ring of Fire; geologists, however, talk of an **active margin**.

Magma: mixture of liquid and gas whose temperature can rise to around 1,300°C. Magma forms by the partial fusion of the upper mantle (or asthenosphere). As it travels through the lithosphere, it may be enriched (or contaminated). When a volcano erupts, the magma suddenly violently loses the gases it contains as they are dissolved by decompression (explosive volcanism). It then flows out over the surface in the form of lava flows (effusive volcanism)[14].

Active margin: active and shifting boundary between a continent and an ocean (and sometimes between two parts of an ocean) based on different plates. The oceanic lithosphere is subducted under the active margin (or edge) of a continent or volcanic chain. An active margin is subject to numerous earthquakes and dotted with active, and usually explosive, volcanoes.

Mount Stromboli staging a superb display of magmatic explosions at night
In this famous volcano, situated in the Lipari or Aeolian Islands off the southern coast of Italy, a huge bubble of compressed gas percolates at high pressure to the top of the double chimney several times an hour. The magma is projected high into the air in the form of vapour and fine particles of incandescent basaltic lava. The Lipari volcanic chain owes its existence to the subduction of the northern edge of the African plate under the Apulian plate.

Oceanic and continental drift visible on the bottom of the Atlantic Ocean

The mid-oceanic ridge (in the centre of the picture) constitutes the zone from which the European and African plates on the one hand and the North and South American plates on the other originate and diverge. It is here that the submarine basalts ooze out, building up the new oceanic crust in an accumulation of pillow lavas.

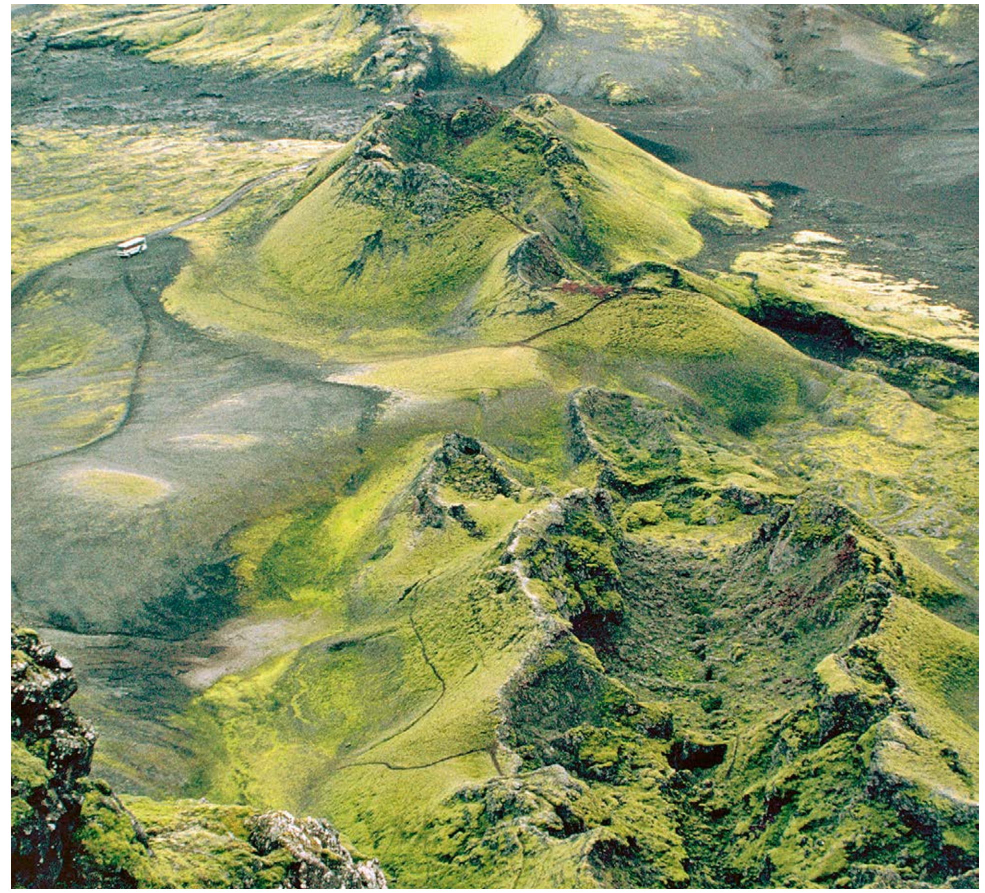
We can clearly observe how the ocean's breadth diminishes northward of its central region (off the coast of the Sahara). This suggests that its opening has been progressive, at an average speed of 3 cm a year, i.e. 3,000 km in 100 million years.

Thus, the further an ocean crust lies from the mid-oceanic ridge, the older it is. The crust off Iceland is presently several million years old, while that off the coasts of Spain and Canada dates from circa −100 Ma and the crust off Morocco and the USA from −180 Ma.

It should be noted that the ocean shoreline is displaced onto the continental mass. That part of the continent covered in water (coloured light blue) is called the continental shelf. It constitutes a passive margin. The actual solid boundary separating the oceanic crust from the continental crust is hidden by sediments laid down at the foot of the continental slope.

To the east, the Red Sea is actually a small ocean in the process of opening up.

Exerpt of the map of ocean floors, © Hachette Livre – Guides bleus



Volcanoes in Iceland, recently emerged above water into the open air

This chain of recent volcanoes along the mid-oceanic Atlantic ridge follows a major fissure called the Laki (Lakagigar region) that runs down the middle of Iceland. An enormous effusive basalt eruption took place there 200 years ago. The fissure continues to open up today, while current volcanic activity has moved northwards along the line of the fissure, under the Vatnajökull glacier[14].

Drifting oceans

The juxtaposition of continental and oceanic crusts forms the majority of drifting lithospheric rafts at the surface and down to a maximum depth of about 30 km. It is just as appropriate, therefore, to speak of **oceanic** drift as of continental drift. Africa, for example, drifts while attached to half of the Atlantic to the west, half of the Indian Ocean to the east and a little piece of the Mediterranean to the north. This solid connection of continent and oceans, also known as a **passive continental margin**, is due to the presence of a second, more continuous layer situated at the base of the rafts: the relatively cold and rigid lithospheric mantle. The entire raft is just light enough to not sink into the asthenosphere. When the raft does become too heavy, it is always the oceanic part that goes down first. Sometimes, however, the edge of a continent passively following the ocean that precedes it may also

Ocean: in geology, the concept of an ocean includes not only a vast expanse of water but also – and especially – the ocean bottom and its rocky substratum forming the oceanic crust, usually basaltic pillow lavas. This idea of crust or ocean floor is important because seas such as the Eastern Mediterranean and the Red Sea can also be small oceans. The former is actually closing, while the latter is growing. An ocean, therefore, is a shifting geological entity whose size changes over time because its edges or its centre constitute plate boundaries. On the other hand, a sea that is said to be epicontinental, such as the English Channel and the North Sea, the Baltic Sea and the Adriatic Sea, is a stretch of shallower water covering a continent whose crust is thicker and more stable.

Continental margin: transitional or boundary zone between continental and oceanic crusts. Due to present high sea levels, the continental margin does not correspond exactly to actual shorelines, which are usually found overflowing onto the continent. A shallow sea overlies the margin or continental shelf – as with the English Channel and the North Sea, for example. A **margin** is said to be **passive** (as opposed to active) when the two crusts, continental and oceanic, are supported by a single continuous lithosphere or, to put it another way, where continent and ocean belong to the same plate and are thus welded together. In such cases, there are neither earthquakes nor volcanoes. Good examples of these are the African, European and East-American margins on either side of the Atlantic Ocean.