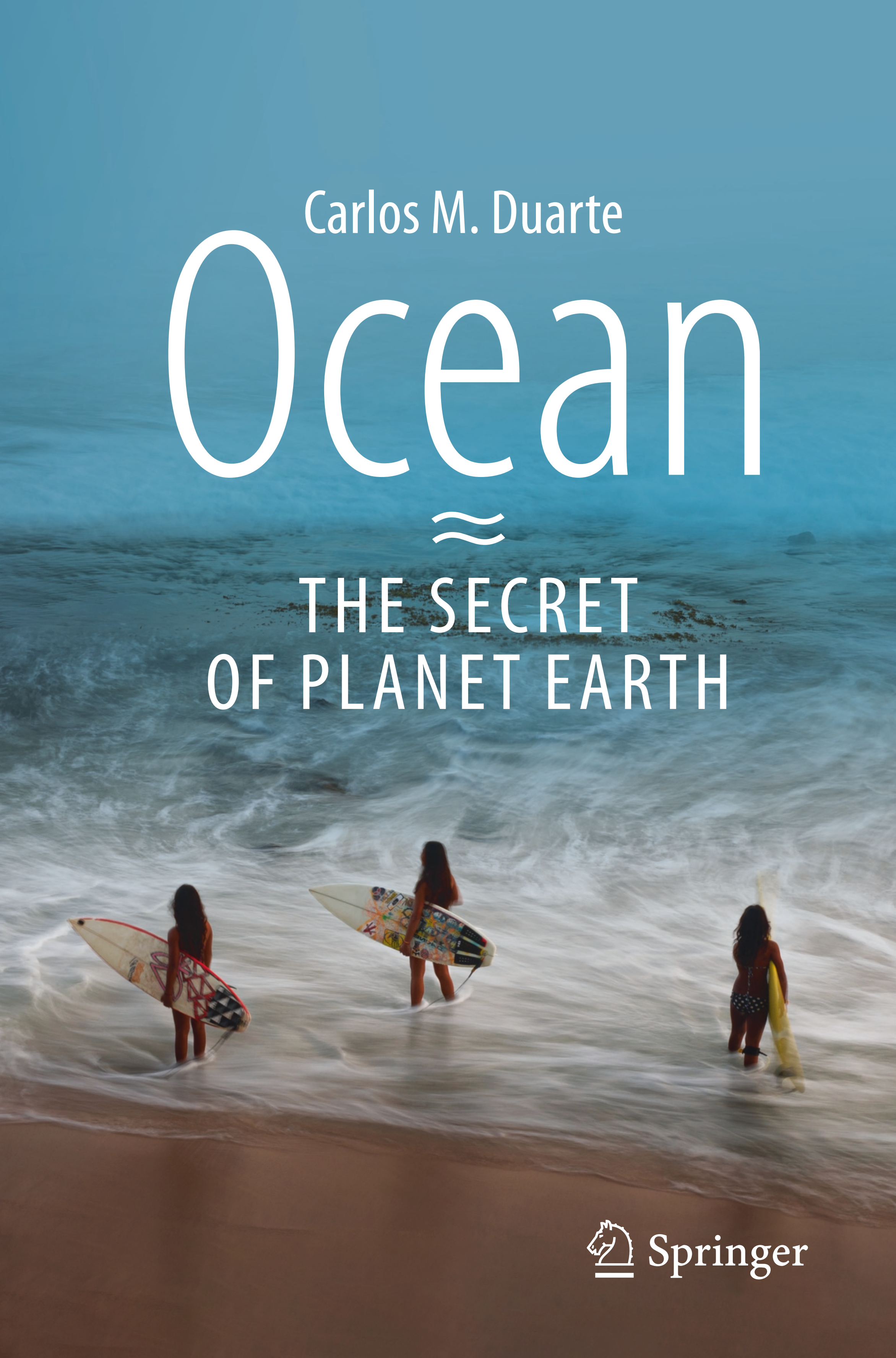
Carlos M. Duarte

Ocean

THE SECRET OF PLANET EARTH



Springer

Ocean - The Secret of Planet Earth

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ISBN 978-3-031-55978-5 ISBN 978-3-031-55979-2 (eBook)
https://doi.org/10.1007/978-3-031-55979-2

Translated, updated and expanded from the Spanish language edition: "Océano - El Secreto del Planeta Tierra" by Carlos M. Duarte, © The Author, Carlos M Duarte 2010. Published by CSIC. All Rights Reserved.

Photograph by Cristina Mittermeier Heavenly, Virtuous, and Miracle Makaha, Hawaii "On one of my first National Geographic assignments, I photographed these three young Hawaiian women standing on the brink of the same ocean their families have surfed for generations. They gaze out at the horizon, anticipating the rising waves with their boards clutched beneath their arms. Across the globe, our young leaders are looking towards the future and it's up to us to take action today to create a better world for them tomorrow."

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To my wife and colleague, Susana, my companion in my path to explore the oceans, which she carries in her eyes.

Preface

My earliest memories inevitably place me on the beach, playing happily with the waves and the sand. The ocean accompanied me every summer and, between visits to either the Atlantic, near my native Lisbon, or my mother's Mediterranean in Malaga, the ocean provided food for my fantasies, in books and films. Books as impressive as Herman Melville's *Moby Dick* and Jules Verne's *20,000 Leagues Under the Sea* and films like Victor Fleming's *Captains Courageous*; *The Mutiny on the Bounty*, in the version directed by Lewis Milestone and starring Marlon Brando as Officer Fletcher Christian; or, as a teenager, Steven Spielberg's *Jaws.*

This playful relationship with the ocean extended over a couple of decades as I progressed in my academic training until I graduated in Biological Sciences from the Autonomous University of Madrid (Fig. 1). My interest in water and ecology led me to work in aquatic ecology, first in irrigation canals in the Tagus River estuary and later in lakes in Canada. While researching the ecology of these lakes, my contacts with the ocean, still playful, were taking on new dimensions, with a growing curiosity about its functioning, the life it harbours and its role in the biosphere. With my PhD diploma under my arm, and following the advice of the distinguished Catalan oceanographer and ecologist Ramón Margalef, whose international named award was presented to me in 2019 (https://presidencia.gencat.cat/en/ambits_d_actuacio/premis/detalls/20191128_lliuramentduarte), I leaped towards the study of the ocean when I returned to Spain to continue my research under the direction of the CSIC oceanographer Dr. Marta Estrada, a disciple of Ramón Margalef. This leap turned out to be absolutely definitive, and submersed me in the ocean for life: first from its shores, investigating different aspects of the ecology of coastal ecosystems (seagrass beds, mangroves, coral reefs, etc.) and, later, with

Fig. 1 The author by the beach. Photographs: Author's personal collection

the help of my colleague and wife Susana Agustí, an experienced oceanographer, into its interior, to study the open ocean and the ecosystems it harbours in its depths.

In oceanography I found a field of science in which the search for knowledge and the component of adventure that this entails are manifested in complete harmony. The 35 long years that I have dedicated to research marine ecology and oceanography have given me a kaleidoscopic experience of the ocean. In my work in coastal ecosystem ecology, I have spent thousands of hours SCUBA diving in seagrass meadows and coral reefs, off the coasts of the Mediterranean, the Caribbean, Australia, SE Asia and the Red Sea. Diving in the ocean is a vital experience that we should all experience at some point, as it is the discovery of a different planet, a secret planet within our own. The sensation of flying weightless suspended in the water; the pressure on our ears and how we can easily control it; the different soundscape of the ocean; its bluish, diffuse light; the dance of the plants and the light to the rhythm of the waves; the careless curiosity of its creatures and the accelerated beating of my heart in encounters with dolphins, sharks, turtles, manatees, sea snakes and humpback whales jumping alongside my small boat; the beauty of coral reefs; seeing an amphora in a wreck protected by a *Posidonia* cover; the absence of red colours, seeing my own dark green blood at 30 m depth… There is no limit to the number of emotionally impacting experiences one can have while diving in the ocean, and there is no limit to the exciting discoveries that still await us in the ocean's depths. A reflection of this are the revolutionary discoveries that have been made since I began my career in marine science (Table 1). All these discoveries and many that are yet to come make oceanography a vibrant field for scientific research, in which I found full satisfaction of the intellectual and even physical adventure I was looking for in science.

My work has led me to sail almost all the oceans: the Atlantic, the Indian Ocean, the two Polar Oceans and the Pacific, the Mediterranean Sea and the Red Sea, and lead a Circumnavigation Expedition, the Malaspina Circumnavigation Expedition that sailed the subtropical and tropical oceans between 2010 and 2011 (Fig. 2). The sensation of sailing on the high seas surpasses, in intensity, that of discovering the underwater planet. Contemplating the immensity of the ocean; the star-studded skies in the darkness of the night, interrupted by the flashes of fluorescent light from the plankton excited by the turbulence of the propellers; riding on great waves that clearly have a fado rhythm; the overwhelming power of the ocean in the great storms, with waves of more than 14 m in the Drake Passage sailing towards Antarctica; the majestic and imposing shapes of the tremendous masses of its icebergs; the experience of sailing in the dark through a labyrinth of ice with my friend Alberto as pilot; walking on the infinite ice shelves of the Arctic Ocean; and the sensation of swimming suspended over 5000 m of water. In short, the infinite freedom of feeling in the middle of the only immense and untamed wild landscape that still exists on our planet, its best kept secret.

This intimate, I would say even spiritual, contact with the ocean was not only an awakening to its beauty, but also brought unpleasant surprises: to see how the millenary *Posidonia* seagrass meadows disappear from our coasts in a few years leaving practically no trace of their presence; to see the scars of anchors and trawling gear on the ecosystems of our seabed; to dive on seabed full of rubbish that will remain there for centuries, an excrement of our wasteful civilization; in tears at seeing whole coral reefs bleached in the Southern Red Sea under heat waves aggravated by climate change; shocked by dynamite explosions used for coral reef fishing, savagely destroying these works of art and killing hundreds of animals for every one caught; dolphins, dugongs, sharks and turtles agonizing in the death traps of drift nets; the beaches of

Table 1 Examples of ocean discoveries produced since I initiated my university biology degree

Year	Discovery	Significance
1984	Discovery of hydrothermal vents	These chimneys, first discovered at 3200 m depth, release magmatic fluids on the ocean floor, with temperatures up to 400 °C, rich in sulfides, methane and hydrocarbons
1985	Discovery of the smallest photosynthetic organism, the cyanobacterium *Prochlorococcus* (0.0005 mm cell size)	These tiny cells, virtually invisible under optical microscopy, turned out to be the trees of the ocean, as they were responsible for 30% of all photosynthetic activity in the ocean
1997	Discovery of ecosystems, in the deep sea, powered not by solar radiation but by the oxidation of reduced fluids	Scientists were puzzled by the observation of complex ecosystems, teeming with life associated in the deep ocean, where no light penetrates to produce organic matter by photosynthesis. They discovered that these organisms contained bags loaded with bacteria capable of synthesizing organic matter using chemical energy released by oxidizing the strongly reduced compounds emitted by hydrothermal vents on the seafloor. These deep ocean ecosystems were called chemosynthetic ecosystems
1990s	Discovery of the ubiquitous presence of deep-sea corals	While coral reefs were thought to be restricted to the shallow coastal areas of tropical oceans, in the last 30 years it has been discovered that extensive white (i.e. free of photosynthetic symbionts) coral reefs, first described in the eighteenth century, exist in deep, cold waters, down to 6328 m, throughout the entire ocean, including Antarctica
1990s	Discovery that the deep ocean presents the largest abundance of *Archaea*	Archaea, which constitute a new domain of life, were discovered by microbiologist Carl Woese in 1977. The discovery that the largest habitat in the biosphere is dominated by the Achaea, meaning “the ancient ones”, indicates the extent to which the deep ocean still resembles the habitat in which life on Earth developed 3.5 billion years ago
1990s	Discovery of the new metabolic pathway Annamox	The discovery of new metabolic processes in the ocean, such as the Anammox process, which involves the anaerobic oxidation of ammonium to produce nitrogen gas, is indicative of the surprises on the machinery to support life that awaits to be discovered in the deep sea

Year	Discovery	Significance
2004	Discovery that a cubic metre of seawater contains over 70,000 novel microbial genes	The massive sequencing of 2000 L of water from the Sargasso Sea in 2004 by the team of the American biologist Craig Venter reflects the diversity of life forms that billions of years of microbial evolution has left in the ocean are also reflected in the discovery of more than 70,000 new genes after
2005	Giant squid photographed alive for the first time	After decades of fruitless searches, Japanese scientists managed to photograph, for the first time, a live giant squid. That we had to wait until well into the twenty-first century to observe for the first time one of the largest and most mythical animals on the planet says a lot about the extent to which our ability to explore the ocean is still limited and the many surprises that still await us
2012	Discovery that the Mediterranean seagrass *Posidonia oceanica* is the longest-lived organisms on Earth	The finding of seagrass clones over 10 km in length near Ibiza, Spain, led to estimates that these clones were formed by seagrass seeds likely sprouting in the seafloor nearly 200,000 years ago

Fig. 2 The author through his research career: (**a**) leading the Malaspina Expedition, circumnavigating the ocean on board Spanish research vessel Hespérides; (**b**) leading an expedition to the Arctic in the International Polar Year of 2007; (**c**) tagging a tigger shark in the Bahamas to help us map its vast seagrass meadows; and (**d**) on a submersible in the Red Sea while leading the Red Sea Decade Expedition on board research vessel OceanX. Photos: Author's personal archive

Bolinao, on the Philippine island of Luzon, teeming with hundreds of thousands of dying boxfish; the desolation of the bottom devoid of life under poorly managed aquaculture farms; the ocean surface and beaches covered in oil and petroleum; plastics floating in the most remote waters; the instruments revealing ever higher concentrations of CO_2 as I start a new oceanographic campaign; and, finally and with particularly acute personal impact, witnessing the first abrupt melting (18 km per day on average) of Arctic sea ice occurring in my life time.

Beyond what I see and experience directly, what I know as a scientist impels me to try to warn about what is happening in the ocean and its inexorable and unconscious destruction by humanity, to awaken consciences, to share experiences and knowledge and at the same time to try to explain my fascination for the ocean. To transmit my conviction that in a healthy ocean resides in good measure the future of humanity, as it could have been the cradle that gave birth to our origin as a species. I know that this plundering is based not on ill will but on ignorance, because citizens do not have information on the scope of these changes and impacts comparable to what we have within the scientific community. I cannot shy away from the responsibility of conveying this message.

I am concerned, in writing and ultimately delivering this book, to strike a balance between conveying my fascination with the ocean and my concern about the pressures to which we are subjecting it. I do not want the reader to feel overwhelmed by the exposure of impacts to the point that the book, rather than impelling them to better know and love the ocean, to better protect it through this knowledge, leads to despondency and a sense of helplessness, overwhelmed by the scope of the impacts. It is not my desire to "scold" but to inform, because I am convinced that if ignorance is the guarantor of the destruction of the ocean, knowledge is the guarantor of its conservation. We can only love what we know, and we can only protect and conserve efficiently from this knowledge. I hope that this book will help the readers to get to know the ocean better and to find in this knowledge a greater support to rationalize the attraction that they undoubtedly already feel for it and to contribute, even if only with their demand to those who have the direct responsibility, to the conservation of this immense blue-green jewel with which our planet has been graced, its best kept secret, and which also lives in the colour of my wife Susana's pupils.

Palma de Mallorca, Santa Ponça, Cala Tirant, Cala Barques, Las Cruces, Thuwal and Montreal

2024

Thuwal, Saudi Arabia Carlos Duarte

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1

Introduction

About 4600 million years ago, the planet Earth arose from a mass of dust and gases derived from the formation of the star we know as the sun. Initially a dry planet, water began to accumulate in its atmosphere as it cooled. The initial mass of water grew due to the contribution of ice derived from comet impacts and other internal processes that increased the volume of water on the Earth's surface until it formed the oceans, which currently cover three quarters of our planet containing 97.2% of the water, giving it its characteristic bluish colour when observed from space (Fig. 1.1), which differentiates it from any other planet in the known universe and which led the science fiction author Arthur C. Clarke to affirm "How inadequate is call the planet Earth, when in reality it is Ocean".

The number of confirmed planets that have been discovered to date exceeds 5000, a number that increases every year. But no planet with the abundance of water that characterizes ours has yet been discovered. Among all these new planets, only Gliese 581, the third planet from the red dwarf star Gliese 581, some 20 light-years away from Earth, seems to present conditions suitable for life, although its temperature may be too high to contain liquid water. In fact, planet Earth is unique both in the abundance of water and in its predominant presence in liquid form, which occurs in a very narrow temperature range (between 0 and 100 °C), compared, for example, with the range of surface temperatures of the planets of the Solar System (−218 °C in Neptune to 480 °C in Venus).

The search for water, or for evidence of its existence in the past, is a fundamental driver of the exploration of the universe because its presence

C. M. Duarte, *Ocean - The Secret of Planet Earth*,
https://doi.org/10.1007/978-3-031-55979-2_1

Fig. 1.1 Image of the Earth. Source: NASA/Goddard Space Flight Center

is a requirement for the existence of life as we know it. Life appeared on our planet in the ocean about 3500 million years ago, radically modifying the composition of the atmosphere and facilitating the appearance of a huge diversity of life forms deployed entirely in the ocean to colonize later, about 2600 million years ago, the continents. Even the organisms, animals and plants that managed to colonize the continents maintain within their cells an environment that can be characterized—due to its composition and salt content—as almost marine. For example, the human body contains more than 65% water, so it could be said that we are two-thirds liquid, and our tears and sweat are very similar, in their saline composition, to seawater up to the point that the verse in which Spanish poet Federico García Lorca wrote that we cry tears of the sea is not without scientific basis. Thus, the legacy of the origin of life in the ocean is internalized in each of our cells.

The appearance of our species took place in close association with the ocean, as a source of food and as a corridor and bridge from which to spread to all continents. This early and sustained relationship with our species explains the fascination we feel for the ocean, reflected in its ubiquitous presence in our culture and its artistic expressions.

Entering the third millennium, the relationship between humanity and the ocean continues to be fundamental to our civilization, but numerous signs indicate that it is at a crossroads. Since the growth of the human population has occupied the continents, the ocean appears as a source of fundamental services for society, as well as the last frontier yet to be explored, colonized and domesticated. Recent developments, such as the explosive growth of marine aquaculture production, the vertiginous growth of the production of water for human consumption from the desalination of seawater, the appropriation of the diverse cellular machinery that evolution has been accumulating in the ocean as a support for the rapid development of biotechnology and the use of the coast as a support for our leisure, show a growing dependence on the ocean. At the same time, the increase in ocean pollution and the biodiversity crisis resulting from overfishing, pollution, the destruction of coastal habitats and climate change point to the existence of serious problems in the current relationship between humanity and the ocean.

In this book I elaborate the thesis that the development of humanity during the third millennium leads us to the domestication of the oceans and that a good part of the solution to the obstacles to development resides in the rational use of the resources that the ocean harbours, which humanity will find and access, sooner rather than later. The more than 10,000 years of delay in undertaking this domestication, in relation to that of the continents, should serve to make us more aware of the consequences of our actions and to use the oceans responsibly and sustainably. Only in this way will we be able to undertake this task and make the growing need to use the ocean compatible with the conservation of its ecosystems and the biodiversity that they house and on which we depend.

When approaching this book, it is important to remember some facts about the ocean that help us understand the arguments that make up the thesis that I present here. I will start with a brief description of the evolution of the relationship between humanity and the oceans from multiple perspectives to describe what services and risks are derived from the ocean to today's society. At this point it is important to understand how human activity is transforming and impacting the oceans and where the challenges lie for their conservation. Based on these elements, I will point out the central role that the ocean has to play in the future of humanity, a radical change in our relationship with the ocean that has already begun, is taking place before us, and whose development will lead it to become one of the key events in the history of mankind.

2

The Ocean in Figures

To better understand the thesis of this book, it is necessary to review some data about the ocean and the resources it harbours (Fig. 2.1). These key data are well known, but are scattered along multiple sources, and it is convenient to review them synthetically.

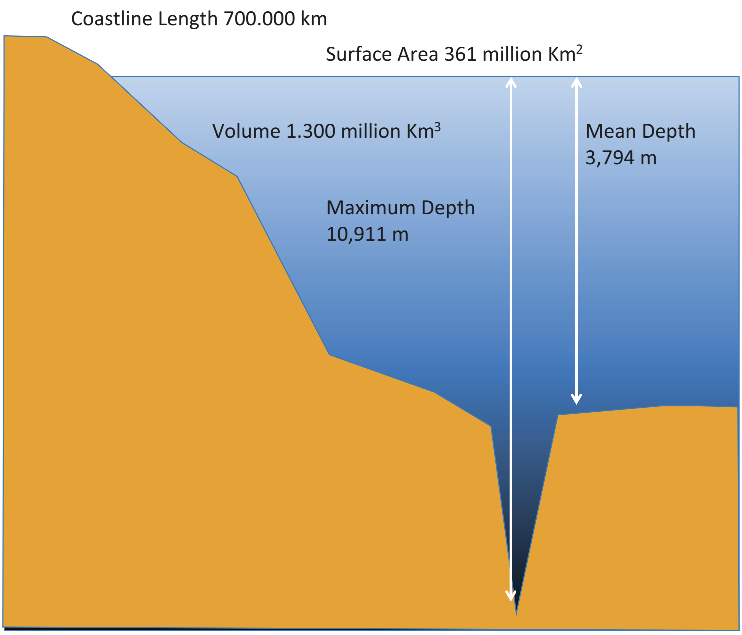

Fig. 2.1 Schematic of the ocean showing its surface area, mean depth, maximum depth, volume and the length of the global coastline

C. M. Duarte, *Ocean - The Secret of Planet Earth*,
https://doi.org/10.1007/978-3-031-55979-2_2

2.1 Brief History of the Ocean

The ocean is thought to have formed primarily from water inputs from the gaseous nebula that gave rise to the creation of the planets of the solar system after the formation of the sun. This theory about the mechanisms of ocean formation has been reinforced by NASA's Spitzer Space Telescope's observation of a forming planetary system (named NGC 1333-IRAS 4B) with enough water vapour to fill the Earth's oceans five times over. The volume of the oceans grew with the contributions of ice from comets and water-rich asteroids that impacted our planet, as well as by the slow release by photolysis processes of water initially trapped in the rocks. Of all these possible sources, the contribution of ice from comets and asteroids seems to be the most important. Recently, NASA has discovered a comet, named LINEAR, with a nucleus almost 1 km in diameter containing 3.6 million cubic metres of water, with an isotopic composition (hydrogen and oxygen exist in forms of different atomic weights, called isotopes) very similar to that of the water in the Earth's ocean.

Thus, we could think of the ocean, the cradle of life on planet Earth, as a gift from outer space that has come to fertilize it. In fact, this theory, based on current scientific knowledge, does not deviate much from the intuition of the ancient Greeks, as they considered that the ocean was the fruit of the relationship between Heaven, Uranus, and Gaia, the Earth. The volume of water that makes up the oceans would have been completed from these extraterrestrial sources during the first 1000 million years of existence of planet Earth, approximately when the first forms of life developed.

The initial ocean had little to do with the current one, as it lacked continents, which emerged to form a first supercontinent, Rodinia, about 1100 million years ago. The German scientist Alfred Wegener (1880–1930) demonstrated conclusively that the continents are not static but that they move due to movements of convergence and divergence of the plates that constitute them and that entail the sinking of some of these plates in the ocean and the extension of others. This theory was formulated in his book *The Origin of Continents and Oceans* published in 1915, which raised strong criticism and controversy, but represented such a scientific revolution that it is studied as a model of paradigm shifts in the field of philosophy of science. The fragmentation of Rodinia led to the formation of early continents that came together again 350 million years ago to form the supercontinent called Pangea, which aggregated the current continents into a single one surrounded by a huge ocean, separating later from the growth of continental plates by the activity of the mid-oceanic ridges that opened oceans between them.

The oceans' conformation close to the present one was reached in the Miocene, about 14 million years ago, although evidently the process of continental drift continues to modify the conformation of the continents. The oldest ocean floor is located in Indonesian-Australian waters, about 180 million years old, while the ocean floor continues to grow from the activity of mid-ocean ridges, which increase the seafloor at a rate of a few centimetres per year. This growth is fast enough to be measured directly (e.g. with high-precision GPS techniques), but too slow to cause noticeable changes on time scales of human lifetimes, although they sometimes cause earthquakes and tsunamis that generate devastating impacts. The Red Sea, where I am based at times while writing this book, is the newest ocean, just 13 million years ago, and is growing in width at a rate of a few centimetres per year. If we would equate the lifespan of a full-grown ocean basin to a human lifespan, we could say that the Red Sea is an infant ocean, equivalent to about 6 years old in human age.

The depth of the ocean has undergone significant fluctuations in which sea level was up to 400 m above present sea level (Fig. 2.2a), due to changes in the shape of the surface of the Earth's crust associated with the process of plate tectonics. However, it has continued to change after the formation of today's oceans due to changes in the volume of water trapped as ice at the poles and in glaciers as well as changes in ocean temperature, as warmer waters are less dense and occupy a larger volume for the same mass. The ocean level was 125 m below the present level when ice extent peaked in the last ice age, about 20,000 years ago, while sea level was as much as 20 m above the present level during past interglacial epochs (Fig. 2.2b). Sea level is currently rising as a result of ocean warming and, particularly, ice loss since the end of the last ice age, just over 10,000 years ago, and this rise is accelerating in recent decades due to climate warming. The melting of the Greenland ice sheet would cause sea level to rise by 6.5 m, and the melting of the West Antarctic ice sheets would lead to a sea level rise of 8 m. The melting of all the ice that exists today could raise sea level by up to 80 m above today's level.

These changes imply that the position of the coastline has migrated great distances. With an average slope of 1% (i.e. 1 m change in elevation every 100 m linear distance from the coast), the 125 m elevation change between the minimum sea level of the last glaciation and the current maximum represents a horizontal retreat of the coastline of 12.5 km on average. In the gentlest topography areas of the planet, this distance reaches hundreds of kilometres. To give a closer example, the Balearic Islands, now a group of five inhabited islands, where I am writing part of this book from my home in Mallorca Island (Spain), came to form a single island, instead of the current five, in the period of minimum sea level.

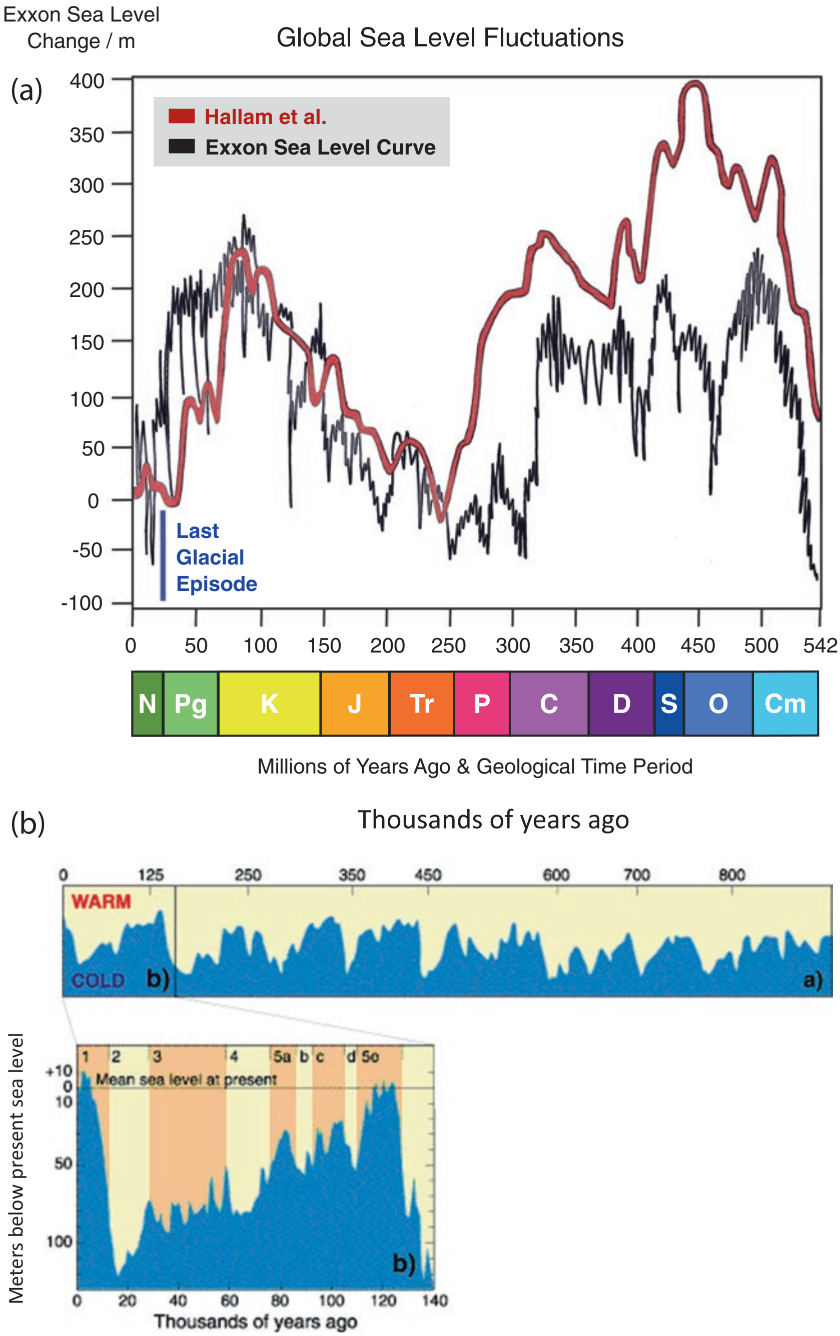

Fig. 2.2 (**a**) Reconstruction of global ocean level change over the past 500 years and over the last 500 million years (**a**) and over the last 1,000,000 and 140,000 years. Modified from data compiled by Robert A. Rohde. (**b**) Reconstruction of sea level changes. Source: US National Oceanic and Atmospheric Administration

The extraordinary dynamics of sea level and the great range of the position of the coastline over time must be considered when interpreting historical data and facts. For example, remains of ancient *Homo sapiens* located today far from the nearest coastline could have been found on the coastline when these humans lived, placing the habitat of these ancestors in the coastal zone, which—as we will see later—has important implications, and much of past human heritage is flooded, accessible only through submarine archaeological techniques. Oscillations in sea level and its minimum levels seem to have played an important role in the diaspora of our species, facilitating spread of early humans across straits and territories between islands taking advantage of past periods of minimum sea level.

2.2 Ocean Extent

The ocean covers an area of 361 million km^2, occupying 71% of the Earth's surface (Fig. 2.1). Of these, 26 million represent the continental shelf, with a global coastline extending along some 700,000 km, and the remainder represents the open ocean. The oceans are typically divided into five, connected oceans, the largest and smallest of which are, respectively, the Pacific Ocean and the Arctic Ocean (Table 2.1), with distinct sub-basins, what we usually call seas, in each. Sea ice shelves, which would lead to ocean if the ice was to melt, occupy between 19 and 27 million km^2, occupying a volume of 0.019–0.025 million km^3 in the ocean.

The average depth of the ocean is 3794 m, more than five times the average height of the continents, and the deepest point of the ocean is the Mariana Trench in the Pacific Ocean, which is 10,911 m deep (Figs. 2.1 and 2.3).

The ocean contains chasms, seamounts and valleys and has a more rugged topography than that of the continents (Fig. 2.3). The mid-ocean ridges are mountain ranges derived from major volcanic activity from which magmatic materials emanate, contributing to the growth of the continental plates and the associated drift of the continents discussed above. Just as there are very

Table 2.1 Extent and minimum and maximum depth of each of the oceans

	Surface	Depth	
Ocean	Millions of km^2	Average (m)	Maximum (m)
Arctic	14.05	1038	5450
Atlantic	106.4	3338	8605
Indian	73.5	3890	8047
Pacific	169.2	4280	10,911
Antarctic	20.33		7235

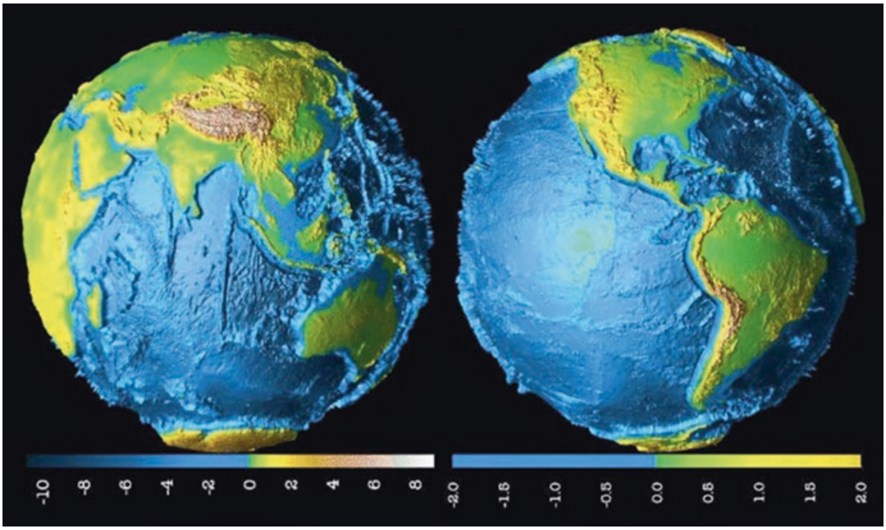

Fig. 2.3 Topography of planet Earth. The scale shows the elevation as km above or below present sea level. Source: NASA

deep chasms, there are also very extensive carbonate platforms, such as the Bahamas carbonate platform, which, with a thickness of about 4500 m, extends over 125,000 km^2.

2.3 Ocean Composition

Water is an extraordinary solvent, capable of dissolving many compounds, including gold. As a result, the ocean contains a significant load of dissolved salts of approximately 35 g per litre of seawater. These salts are dominated by chlorine, sodium and sulphate, but include all kinds of elements, such as compounds essential for life (nitrogen, phosphorus, iron, iodine, etc.). All these compounds have been derived from the erosion of rocks on land, transported to the ocean by rivers or the deposition of atmospheric dust, and the input from submarine volcanism and hydrothermal vents, located on the seabed, through which terrestrial magma flows into the ocean. Biological activity has significantly affected the chemical composition of the ocean, as well as that of the atmosphere.

Seawater is relatively alkaline, with a pH close to 8.1, which, added to the high concentrations of inorganic carbon and calcium, favours carbonate deposition. Many organisms, such as bivalve molluscs, planktonic microorganisms, corals and others, actively use this tendency for carbonate deposition to build shells, skeletons, carapaces and other structures for shelter, protection or support. The deposition of this biogenic carbonate is of such magnitude that it represents a fundamental process in the geological carbon cycle and rock formation. Much of the rock in three coastal areas where I have lived, the Balearic Islands, the coast of Western Australia and the Saudi coast of the Red Sea, are made of Pleistocene coral reefs. In addition to ions in solution, the ocean contains a significant particulate load, such as inert particles, including colloidal organic particles, organismal debris and inorganic particles, and the living organisms of plankton.

The ocean floor is usually covered with fine sediments, which in the coastal ocean may be terrigenous, i.e. generated on land and washed into the ocean by rivers, or biogenic (formed by the deposition of carbonate or silicate skeletons produced by marine organisms). In the open ocean, sediments are biogenic, but also contain terrestrial materials delivered with atmospheric dust deposition.

2.4 Marine Currents

The ocean is in perpetual movement, by currents that transport water, with the properties (solutes, heat and plankton) that it carries, on the surface and at depth. These currents have different components. There are global currents set in motion by differences in density between water masses located at different depths, which may be due to differences in temperature and in the salt load of the water masses. This current system is technically known as the global thermohaline circulation, driven by the sinking of cold surface water, and therefore denser and heavier, in subpolar areas when warmer and therefore less dense water masses are found. The area where the most important surface water sinking occurs is located southeast of Greenland. This place of deep-water formation was already known by the Vikings, who in the sagas that narrate their voyages to North America speak of the dangers of the *Mahlstrom*, a whirlpool that engulfs water, ships and whales and that they placed in the position where the most important point of water sinking in the deep ocean is located. There are also regional currents, set in motion by interactions between prevailing winds blowing over the ocean and coastline features and/or differences in the height of the ocean surface that can reach several metres between distant points.

Estuarine circulation is also an important driver of the circulation of semi-enclosed seas, and it can be of two, opposite kinds. Where the semi-enclosed basins receive large freshwater inputs, the lower salinity, and density, of the