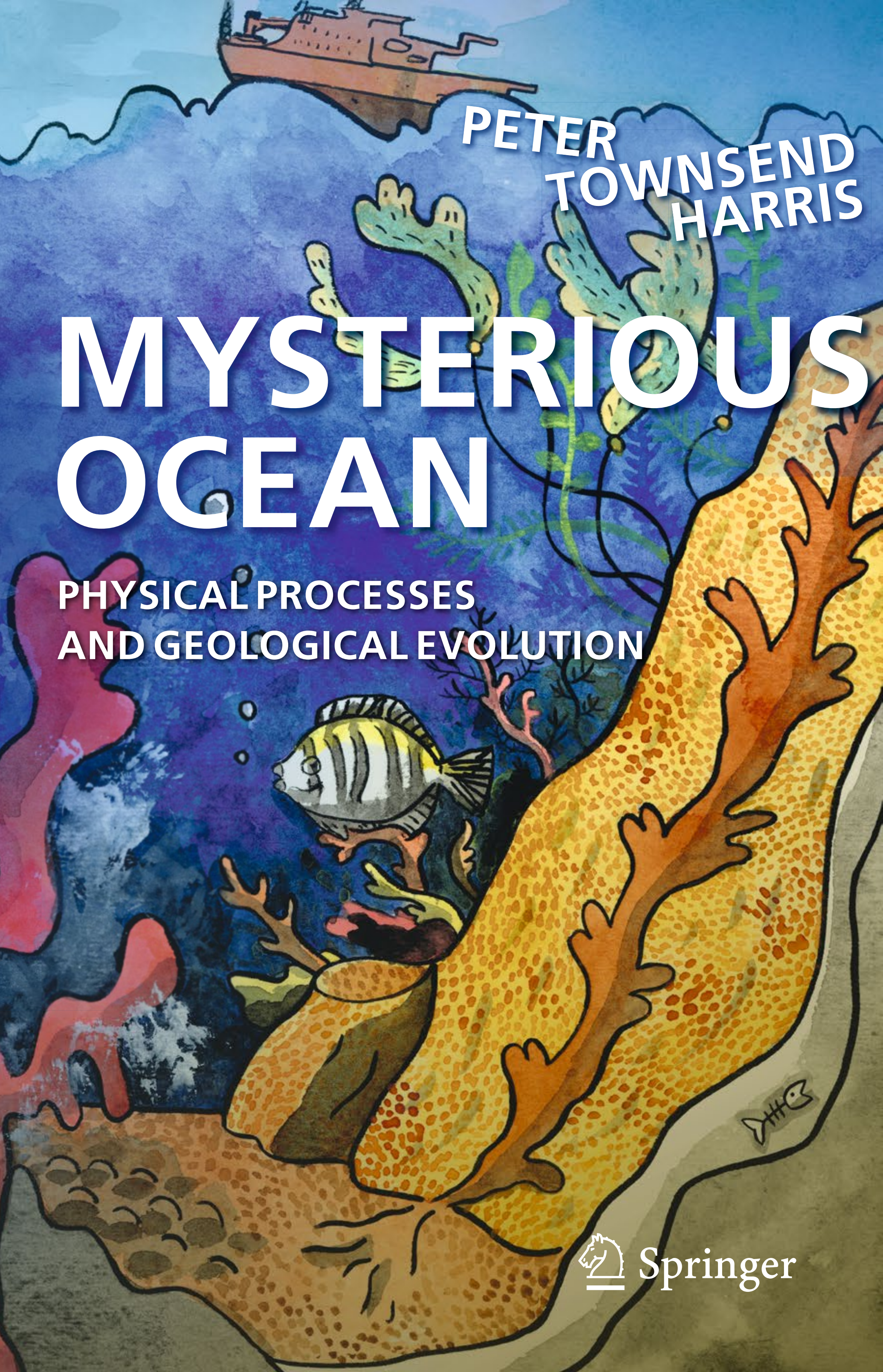

PETER
TOWNSEND
HARRIS

# MYSTERIOUS OCEAN

## PHYSICAL PROCESSES AND GEOLOGICAL EVOLUTION

Springer

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## Physical Processes and Geological Evolution

Springer

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Arendal, Norway

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# Prelude

Our perception of the ocean is surface deep.

The ocean is the blue horizon seen from the wave-battered coast. In our minds, the ocean surface *is* the ocean. We rarely think about what lies beneath the waves because the ocean is dark. It hides its secrets from our sight. The ocean is mysterious.

The moon, stars, and some planets are visible at night, while the ocean floor is invisible (out of sight, out of mind). Perhaps, this is one reason that the total investment in ocean exploration is only a fraction of the amount spent on exploring space. The reasons for this apparent bias are not economic. The offshore petroleum, shipping, and fisheries industries are clearly valuable to society (more valuable than space-based industries), so why is our investment in marine science not greater?

Is it because people believe we already know enough about the oceans, or as much as we need to know? If that is the case, then perhaps we need a reminder that we actually know very little about the oceans. We cannot explain with any certainty, for instance, how or when the oceans were formed. Geologists think it may have something to do with volcanic eruptions and comets hitting the Earth around 4 billion years ago, but they're not certain. Our map of the ocean floor is surprisingly crude; our images of the surface of Mars and Pluto are far clearer than what we have for most of the seafloor. We think the origins of the world's continental shelves (which produce 95% of all fish we eat and one-third of the petroleum we use) have something to do with rifting of supercontinents, sediment deposits, and changes in global sea level during the ice ages, but the puzzle is complicated and the story is not certain in most places. Tsunamis and earthquakes have caused incredible damage and loss of life. But although marine geologists developed the theory of plate tectonics around 1970 to explain why they occur, we cannot predict when they will happen with any certainty. We do not even possess an accurate map of the ocean's rift valleys, subduction zones, or plate boundaries, and we aren't exactly sure how the system works.

What about global climate change? The top 3 m of the ocean contain as much heat as the entire atmosphere, and the ocean contains 50 times more carbon dioxide than the atmosphere. Deep ocean circulation, a vital part of the Earth's climate system, is not that well understood by oceanographers. We think high levels of carbon dioxide in the atmosphere are being absorbed into the ocean making it more acidic, but we don't fully understand the transport of heat or storage of carbon dioxide and oxygen in deep ocean waters.

What about the diversity of life in the ocean? We think more species live in the sea than on land, but we don't actually know for sure. In 2010, marine biologists completed a global census of marine life and identified 230,000 marine species from about 30 million locations, but they also reported that there may be as many as 1 million species, mostly unknown to science. Ocean life is threatened by diverse human activities including global climate change, overfishing, pollution, and destruction of habitats. The cumulative impacts of these activities threaten the very existence of coral reefs, whales, and many important commercial fish species within the twenty-first century, but the full consequences are unknown.

In short, the oceans are a mystery to us. A brief survey of the unanswered questions that are currently being studied by marine scientists reveals the vast depths of our ignorance. In a world that is challenged by a growing human population needing more food, clean water, energy, and minerals while also needing to adapt to rising sea levels, climate change, degraded fisheries, earthquakes, and tsunamis, we cannot afford to remain ignorant about the oceans. Indeed, partly in recognition of this knowledge gap, the United Nations has proclaimed 2021–2030 the International Decade of Ocean Science for Sustainable Development.

This is a book about things that we don't know about the oceans but probably should. It is not a comprehensive review of ocean science by any means – that book would be far too long and is beyond my capability. I have instead tried to paint a broad picture of the oceans, their history, and the life they contain, with particular focus on unanswered questions based on my personal experience working as a marine geoscientist. There are some general facts about the Earth and ocean that I think everyone should know: For example, could you explain to a child how continents are formed? Do you know the name of the largest submarine canyon on the Earth? Do you know what the unit "Sverdrup" is a measure of? The most used commodity on the Earth is fresh water; do you know what the second most used commodity is? For answers to these questions, read on!

So why don't you join me on this tour of the ocean and its' 4-billion year history? Perhaps, it will make the ocean seem a little bit less mysterious. The ocean's story begins long ago, for there once was a time when the Earth did not have an ocean.

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Peter Townsend Harris

# Contents

# Chapter 1
# The Ocean Begins

*"Beginnings are apt to be shadowy, and so it is with the beginnings of that great mother of life, the sea."*
*Rachel Carson*
*The Sea Around Us, 1951.*

**Abstract** The origins of the Earth and moon and the evidence for the first ocean are discussed. We explore answers to the following questions: Were there any continents 4 billion years ago? What would the view from a beach look like 4 billion years ago? How large were the first tides? Was the first ocean salty? What color was the first sky? When did life first arise in the ocean? During its early history, the Earth became a snowball; was the entire ocean ever frozen solid? What is the "albedo effect"?

**Keywords** Solar system · Theia · Moon · Hadean · Ocean crust · Earth's core · Earth's atmosphere · Earth-moon distance · Ocean tides · Late heavy bombardment · Banded iron formation · Photosynthesis · Great Oxygenation Event · Albedo · "Snowball" Earth · Huronian glaciation

In front of the building that houses *Geoscience Australia*, the national geoscience agency in Canberra, there is an area of parkland that boasts a "geological time walk." You can stroll along its 1100-m (3400 foot) length, where each footstep represents about 3 million years of the Earth's four and a half billion-year history. Shaded by eucalyptus trees, there are samples of rocks from the different geological ages, and signs are placed on the sides of the path noting various significant events in the history of the Earth.

Close to the start of the walk, located about 4 billion years in the geologic past, is a sign that reads: "The bombardment of the Earth by comets and meteors continued with such intensity that at times the oceans boiled." The thought of boiling oceans, 4 billion years ago, seems quite amazing! But the other interesting point is

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that the oceans are truly ancient. Their existence dates back to the very earliest phase of the Earth's evolution.

The Earth is the only planet in our solar system that has an atmosphere and oceans of liquid water. Ganymede and Europa, two of Jupiter's moons, both have thin atmospheres, but the ocean on Europa is frozen at the surface. There is evidence that Ganymede has an ocean, but it is buried underground. Titan, the largest of Saturn's moons, has an atmosphere of nitrogen and seas on its surface, but they are probably made of liquid methane and ethane. Earth is unique in the solar system in having both an atmosphere and oceans made of water.

But it has not always been this way.

To tell the story of our oceans, we must start at the beginning of our planet's history, at the time when the oceans formed alongside the atmosphere. Earth's beginning is not completely understood, and there are many details of how the planet developed that are unknown. As Rachel Carson has pointed out, the ocean's beginnings are shadowy. There is of course very little hard evidence to go on, but we can work backward in time from what we know to have been the final products of the solar systems' formative processes to derive a working hypothesis of what is likely to have happened.

It is now believed that the Earth formed about four and a half billion years ago by accretion of gas, dust, and meteors at the time the solar system formed. The swirling mass arranged itself into the separate planets within the orbital plane, according to the laws of physics balancing the force of gravity against the centrifugal force. Matter was swept up by gravitational attraction, either by one of the orbiting planets or by the sun itself, which ignited once a critical mass was attained.

Around 100 million years after it formed, the Earth collided with a Mars-sized planet, romantically named "Theia" by scientists. The collision created a huge cloud of debris that coalesced and became Earth's moon. In Greek mythology, Theia is the mother of Selene, the goddess of the moon, so the name is appropriate since the collision of Theia and Earth gave birth to our moon.

The collision released so much heat that the Earth melted. This period is aptly known in geologic time as the Hadean Eon, which means "Hell like." It was a critical time in the formation of the Earth, because this is when the heaviest elements like iron and nickel sank into the interior forming a metallic core, and the different layers of molten mantle arranged themselves in order of increasing density. The lightest rock material then present, basalt, rose to the surface as erupting volcanoes and massive basalt flows. The surface of the moon retains basalt flows exposed on its cratered surface that have been dated to this approximate time (four and a half billion years ago), thanks to samples collected by the astronauts of NASA's Apollo missions.

As the Earth's surface cooled, the basalt hardened forming a crust. When geologists refer to the Earth's crust, they are talking about the solid layer of rock that is between about 5 and 40 km in thickness, which lies on the planet's surface. Beneath the crust we find the next layer (like the layers of an onion), called the mantle. The Earth is made mostly of mantle, about 84% by volume. The mantle is molten rock, and it becomes gradually hotter and less viscous the deeper into the Earth you go.

At the center of the Earth is a solid iron-nickel core. Its temperature is around 6000 °C. Heat from the center of the Earth is trapped, insulated by the upper layers of mantle and crust from the absolute zero temperature of space. The crust on the surface, exposed to the coldness of space (absolute zero is −273.15 °C!), forms as soon as enough heat is radiated back into space. But in the beginning of Earth's evolution, after the collision of Earth and Theia, there was no crust, and the mantle was exposed at the surface.

A solid layer of crust, a few kilometers thick covering the mantle, must have taken many millions of years to form and stabilize. This period of time is the only stage in Earth's history when there was no ocean.

When did the oceans form?

The secret of when the first ocean appeared on the Earth is revealed by sand grains comprised of the mineral zircon ($ZrSiO_4$). Zircon is a remarkably useful mineral. It is resistant to mechanical erosion and chemically insoluble in fluids, and its age can be radiometrically measured by the amounts of uranium and thorium that are incorporated into its structure at the time it crystallizes. The oldest zircon crystals that have ever been found on Earth are from a place called the Jack Hills in Australia, and they are 4.375 billion years old (give or take 6 million years).[1] This is the age when we first had igneous rocks (crust) on the surface of the Earth. The age of the oceans is revealed by the oxygen atoms inside the zircon crystal.

Oxygen comes as different isotopes: normal oxygen-16 (99.76% of atoms) and less common oxygen-18 (0.204% of atoms). The ratio of these two isotopes is very revealing. It turns out that zircons that are formed directly from mantle rocks have a very consistent oxygen isotope ratio. But zircons that formed in crustal rocks where water is present can have higher oxygen isotope ratios, greater than 30 per mil in some cases. Dating progressively younger zircons, we find that prior to 4.2 billion years ago, there are no zircons with oxygen isotope ratios greater than 5 or 6 per mil. But after 4.2 billion years ago, we find zircons having greater oxygen isotope ratios, indicating the presence of water. And the presence of water in the crust is explained by the presence of oceans. We can therefore conclude that there may have been oceans on the Earth since 4.2 billion years ago.

The first step in producing our oceans must have been to first produce an atmosphere, because without an atmosphere, there could be no liquid oceans. Water exposed to empty space would simply boil away because if there's not enough force (atmospheric pressure) to keep the water in a liquid phase, then there's nothing to hold the water molecules together. We can therefore deduce that the first water present was in the form of a gas (water vapor), mixed into the early Earth's atmosphere with other gasses. Earth's earliest atmosphere is thought to have been comprised of helium, hydrogen, and hydrogen compounds like ammonia and methane and probably some small amount of nitrogen.

But where did the atmosphere (and water) come from?

It is believed that the ocean and atmosphere originated from water molecules in the cloud of gas and dust that gave rise to the solar system. According to this theory,

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[1] Valley et al. (2014).

as the Earth formed, water molecules became trapped in porous rock deep inside the molten planet. Then, for hundreds of millions of years, volcanoes erupted water vapor along with carbon dioxide, ammonia, and methane into Earth's atmosphere, enough to envelop the entire planet in a thick, gaseous blanket. Volcanoes are, to this day, still expelling water with each eruption, as measured by volcanologists. It is estimated that at present there may be enough water trapped in the mantle to fill the oceans three more times![2]

The surface of Earth gradually cooled over many millions of years until the crust solidified. Water vapor accumulated in the atmosphere, and when the surface temperature fell below 100 °C or 212 °F (at one atmosphere pressure), the first liquid water could be present on Earth. At just below this temperature, liquid water rained down onto the surface and pooled in depressions. This is when the oceans began to form. We can only speculate that scalding hot rain must have continued to fall for thousands of years, gradually filling the basins and eventually covering the entire surface of the Earth by around 4.2 billion years ago.

Water was also added to the atmosphere and oceans during the bombardment of Earth by comets and meteors. Meteors and comets are commonly composed partly of ice crystals that include frozen water, methane, and other compounds. Every comet impact added a little more water to the oceans as the basins gradually filled over millions of years. This is when the oceans boiled, around 4.2 billion years ago, as described in the geologic time walk outside the *Geoscience Australia* building.

At this early stage of the Earth's evolution, the basaltic crust was a relatively flat surface, devoid of the continental landmasses we have today. The oceans would have covered this surface to a more or less uniform depth. But to what depth? Or to put forward a simple question, was the volume of water greater or less than it is today?

Water is added to the oceans as it is expelled from volcanos and falls as rain. But water is also lost into space. When $H_2O$ evaporates the separate hydrogen atoms and oxygen atoms are able to escape Earth's gravity. The high-energy Hadean sun could have caused a lot of water to have been lost from the early ocean.

Our knowledge of the Earth's early history is very fuzzy, but an intriguing idea is that, for some period of time, perhaps lasting several hundreds of million years, the oceans covered the entire surface of the planet. This idea stems from the likelihood that the Earth's continental crustal plates had not yet completely formed. And we also know that if the present land and seafloor surfaces were flattened to a single, globally uniform level, the volume of the oceans would cover the Earth to a depth of about 2600 m (5000 feet).

Astronomers have discovered that around one third of planets that are the size of Earth or larger have oceans; they are "ocean worlds." Earth's ocean accounts for about 0.02% of its mass (0.12% by volume), but some planets have oceans that are a much greater percentage. Imagine a world in which water accounts for 1% or 50% of the volume of the planet. Oceans on such planets would be hundreds or even thousands of kilometers deep!

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[2] Schmandt et al. (2014).

Earth was fortunate to be able to keep its' ocean. Planets larger than Earth with stronger gravity lose less water into space, whereas smaller planets (like Mars) readily lose water and over billions of years are unable to retain their oceans. And so it is entirely possible that the early ocean on Earth may have been much deeper than it is today. Planet "Ocean" 4 billion years ago was the precursor to planet Earth.

Even when covered in ocean, Earth would not have been completely devoid of all land because there would have been a scattering of small continents and volcanic islands where the largest volcanoes rose from the seafloor to pierce the sea surface, like Hawaii does today. If you could stand on the shore of one of those islands, 4 billion years ago, the vista would bear little resemblance to our modern Earth.

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What a scene you would behold standing on an ancient shore 4 billion years ago! The early atmosphere was rich in methane and hydrocarbon molecules, which would react to ultraviolet radiation to create an orange hue. Space probes have observed that orange is the color of the atmosphere on Titan, which is relatively methane-rich. Therefore, we can deduce that the ancient sky on Earth was probably orange.

The waves lapping the shore look reddish-pink in the sunlight. This is because the ancient ocean contained abundant dissolved iron. A decrease in dissolved iron will occur once life has evolved, but this has not happened yet.

The sun moves quickly across the orange-colored sky because the Earth revolved faster. A day lasted only about 16 hours – sunrise and sunset would only be 8 hours apart. The other extraordinary image would be the larger-sized moon, much larger than it appears today. This is because the moon was at least 20% closer after its formation and was perhaps only about half the distance that it is today.[3] The lunar surface facing Earth would be clearly visible at that close distance. On a clear night, the moon's craters and even erupting volcanoes may have been visible. Being closer to Earth, the moon orbited more quickly taking about 10 days at that time[4] compared with 29.53 days at present, so the phases of the moon would change rapidly, from new moon to full moon 5 days after that.

What caused the moon to move further away from the Earth, to the distance it is now? The answer is tidal friction.

The Earth rotates in the same direction as the moon orbits the Earth, but the Earth spins much faster than the moon orbits the Earth: 1 day versus one lunar month. As the Earth rotates, the face of one hemisphere moves toward the moon, while the other hemisphere is receding away from it. The gravitational pull of Earth is divided into the two hemispheres; the side moving toward the moon exerts slightly less gravitational pull, whereas the side that is receding is literally dragging the moon with it by the force of gravity (Fig. 1.1).

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[3] It could not have been any closer to Earth than three times the Earth's radius, which is known as the *Roche limit*, the minimum distance from the center of the planet that a satellite can orbit without being destroyed by the severity of the tidal forces.

[4] Williams (2000).

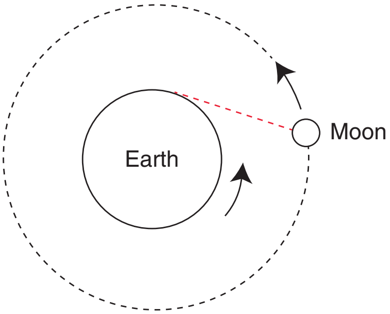

**Fig. 1.1** Diagram showing the rotation of Earth and lunar orbit viewed from above the North Pole. The red-dashed line represents the gravitational pull of the receding face of Earth which acts to pull the moon into a higher, longer-duration orbit

Over billions of years, this dragging force has caused the Earth's rotation to slow down so that 1 day now lasts 24 hours, while at the same time, it has pulled the moon into a faster, higher orbit around the Earth. With each orbit the moon has moved gradually further away. Using lasers, scientists have accurately measured the distance between the Earth and the moon over several years (the distance varies because of the moon's elliptical orbit). We know now that the moon is currently moving away from the Earth at a rate of 3.78 cm/year.

But there is a paradox – think about the collision of Earth and Theia. We know that right now the moon is (on average) 385,000 km from the Earth and computer modelling of that collision indicates that the moon afterward settled into an orbit that is closer to Earth. Since we also know how fast the moon is receding from Earth today, we can work backward to estimate the approximate timing of the collision of Earth and Thea.

And the answer is – around 1.5 billion years.

But the moon was supposed to have been formed over 4 billion years ago! This is the paradox. The logical explanation is that the rate of the moon in moving away must have been slower in the geologic past than it is today; how much slower, why, and when this happened are still further mysteries.[5]

Standing on that ancient shoreline 4 billion years ago, you would need to be careful how close you stood to the surf because the rising tide would be racing toward you at great speed. Ocean tides on the ancient Earth may have been extraordinary. The relationship between the Earth-moon distance and tidal height is nonlinear. At a distance of 200,000 km (i.e., about half the present distance), the ocean tidal range would have been more than 5 m (15 feet), and because of the shorter, 16-hour, day, the twice-daily tidal rise and fall was much faster. The rapid exposure and covering of intertidal flats are thought to have provided the perfect environment for the evolution of life.[6] When the Earth-moon distance was about 320,000 km,[7] the ocean tide would have been about twice its present (around 2 m) amplitude.

Would the sea water be salty or fresh?

The ocean 4 billion years ago was interacting with the thin ocean crust as shown by the oxygen isotopes stored in zircon crystals. This implies that crustal plates

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[5] Bills and Ray (1999).

[6] Lathe (2004).

[7] Varga et al. (2006).

were subducting one over the other, bringing water into the mantle for recycling. Crust-forming rocks include chlorides, sulfates, and carbonates formed at low temperature (i.e., cooler than the mantle, within the crust), and leaching of these rocks supplies salt to the ocean. Perhaps there was a period of time when the oceans were freshwater followed by a later salty phase, but we don't really know for sure. Salt has been added gradually to the ocean from the time it formed; we'll come back to this topic later on.

The sky would provide an interesting spectacle, with lots of shooting stars. The so-called late heavy bombardment of the Earth and moon by meteorites was at a peak around 4 billion years ago and would not taper off for another 200 million years. Thanks to plate tectonics the Earth's surface is constantly renewed, and scars of impact craters do not linger. By contrast, the moon's cratered surface bears testament to impacts of millions of meteors from the late heavy bombardment and later times.

Standing on that ancient shoreline, the beach beneath your feet is made of black volcanic sand. There are no shells in the sand because mollusks and other shell-making organisms have not yet evolved, and there are no coral reefs or fish either. But there could be a strong breeze blowing waves on the ocean. Surfing would be feasible but probably a bit uncomfortable without protective clothing. That's because the ocean temperature might be a bit too hot for a pleasant swim; remember the oceans have only just recently been boiling from those comet impacts. Ultraviolet and solar X-ray radiation levels from the young sun were several orders of magnitude higher than today, and you'd have to hold your breath because the early atmosphere contained no oxygen. The best advice would be to wear a good spacesuit with built-in thermal regulator system, UV shield, and oxygen supply.

You might be standing on an island shore on the Earth, but the place you are standing is as alien and hostile to human life as the surface of Mars is today.

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Hundreds of millions of years after the oceans boiled, life arose. There are dozens of books that speculate about how this may have happened. Amino acids, the building blocks of proteins, are easy to make. This was shown in the 1950s by the famous Miller-Urey experiment, which zapped a mixture of water and simple chemicals with electric pulses to simulate lightning strikes. More sophisticated experiments and theories have been developed since then, but there is no doubt that life did arise in the ocean because we have the evidence.

The oldest, indirect proof of the age of life in the oceans is recorded in 3.8-billion-year-old sedimentary rocks called the "banded iron formation" or "BIF" for short. These rocks consist of alternating bands of iron-rich (such as hematite and magnetite) and iron-poor (typically chert) sedimentary rock. The bands range in thickness from less than a millimeter to more than a meter.

Rocks of the banded iron formation are believed to have been deposited underwater, precipitating directly from seawater onto the seafloor. The precipitation of iron requires the presence of oxygen. And the source of the oxygen?

Life!

It is thought that the first oxygen came from microbes around 3.8 billion years ago that photosynthesized but that did not release free oxygen. The first free oxygen was produced probably before 3.5 billion years ago by photosynthesizing cyanobacteria, or blue-green algae, but the exact timing is not well understood. All such microbes and cyanobacteria must have been dwelling in the surface ocean because sunlight does not penetrate far into the depths, and all marine photosynthesizing organisms live in the "photic" zone, confined to the upper 100 m or so. The banded iron formation, therefore, tells us not only of the time of first oceanic oxygen but also the age of the earliest occurrence of photosynthetic microbes followed by early cyanobacteria.

The oldest banded iron formations are exposed in southwest Greenland at a location called *Isua*, and although they are also found at many other locations around the world, they appear to have only formed during certain phases of Earth's history. They first appear around 3.8 billion years ago, become common by about 3.5 billion, are abundant around 2.5 billion, and vanish by about 1.8 billion years ago. Banded iron formations made a brief comeback around 1 billion years ago, but none are being produced today.

In Earth's early history oxygen was absent from the atmosphere. Oxygen is a by-product of photosynthesis, so the Earth (and oceans) had to wait for the evolution of cyanobacteria (and eventually plants) before oxygen could be produced in sufficient quantities for the chemical process of oxidation to occur. The first living organisms neither produced nor consumed oxygen. Indeed, they would have been unable to tolerate the presence of oxygen: oxygen is a very reactive gas, and it is poisonous to organisms that are not adapted to its presence. For example, the bacterium *Clostridium botulinum* (a modern relative of early life) can only survive in the near-total absence of oxygen.

Life quickly adapted to make use of sunlight as a source of energy through photosynthesis that can be described by the chemical equation:

$$6CO_2 + 6H_2O \rightarrow 6O_2 + C_6H_{12}O_6$$

which in English means six molecules of carbon dioxide plus six molecules of water are transformed (by photosynthesis) into six molecules of oxygen (gas) and one molecule of carbohydrate (sugar). This simple formula underpins all life on Earth, and as we shall see, it has profound consequences for the evolution of our planet.

This leads us to an explanation for the iron-rich layers found in banded iron formations. Elemental iron dissolves in water, whereas the various oxides of iron ($Fe_2O_3$) precipitate out (become solids). The early oceans would certainly have had sources of iron, such as those emitted today from submarine volcanoes and liberated from rocks by chemical weathering (dissolving in water). The train of logic goes like this: when organisms arose that produced oxygen, iron that was dissolved in the oceans combined with dissolved oxygen to form iron oxides (the oceans "rusted") which would then have precipitated out and settled to the ocean floor. Blooms of planktonic cyanobacteria settled to the seafloor when they died, their decaying cells providing the silica (chert). Together these processes produced the layers of iron oxides and chert that characterize banded iron formations. The period of time when the banded iron formations were first deposited, about 3.8 billion years ago, is therefore the time when the oceans first contained dissolved oxygen.

Once most of the iron had been removed from the ocean, oxygen levels could build up until it was eventually added to the atmosphere. It was not until around two and a half billion years ago that the atmosphere contained its first trace amounts of oxygen, and it took another 2 billion years before the Earth's atmosphere changed from being oxygen-poor to oxygen-rich, like the atmosphere we have now.

Evidence suggests that atmospheric oxygen concentration was not more than about 10% up until around 800 hundred million years ago.[8] It is no coincidence that the Cambrian explosion in life on Earth did not occur until after this time, when oxygen levels rose to permit life that depends on breathing oxygen. Why did the atmosphere start to become oxygen-rich two and a half billion years ago? The simplest explanation is that it took around a billion years to use up all the free iron dissolved in seawater that was deposited in the banded iron formations. Once the iron was gone (or mostly gone), oxygen began to escape into the atmosphere. This episode in Earth's history, when oxygen first started to become rich in the atmosphere, is known by geologists as the *Great Oxygenation Event*. This event marked the end of the Archean eon and the beginning of the Proterozoic eon in the geologic timescale.

The Proterozoic is marked by the first appearance of "continental red beds" comprised of sediments deposited on land coated with iron oxide. These coatings must have formed during and/or immediately after their deposition which means that there had to be oxygen present in the atmosphere and in ground water.[9]

Let's put on our space suits again and go back to stand on that ancient shore and watch the ending of the Archean. The time is two and a half billion years ago. The view has changed quite a lot since the start of the Archean. There is a slight greenish tinge to the ocean today caused by all the plankton suspended in the water. The ocean tide has reduced to a more comfortable 3 m (10 feet) amplitude, so we can stand a bit closer to admire the surf, crashing on the beach. There is quartz sand on this beach made possible by the creation of granitic continents (more on that later) and a day now lasts 20 hours. Our young sun looks weak and pale compared with our sun today. That's because two and a half billion years ago, the sun's radiation was actually about 20% less intense than it is today. And there does seem to be a bit of a chill in the air; why is that?

The Earth's early atmosphere contained a lot of methane ($CH_4$) which is an incredibly powerful greenhouse gas, around 30 times stronger at trapping heat than carbon dioxide ($CO_2$). In the modern atmosphere, methane is quickly destroyed by free oxygen, so the methane level in our atmosphere today is very small, around one part per million (1 ppm). But since there was no free oxygen in the early atmosphere, methane was able to accumulate to very high levels, thereby warming the Earth and giving us liquid water and oceans while also turning the sky orange.

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[8] Blamey et al. (2016).

[9] Walker (1979).

Recent chemical modelling of the Earth's early atmosphere suggests that methane levels were probably around 10 ppm.[10] By two and a half billion years ago, free oxygen was sucking methane out of the atmosphere at a tremendous rate. The reaction of oxygen and methane produces carbon dioxide and hydrogen. But since hydrogen gas ($H_2$) is light enough to escape Earth's gravity, only carbon dioxide, oxygen, and essentially inert nitrogen gas that dominate our atmosphere today were left behind (today's atmosphere is 78% nitrogen and 21% oxygen).

One visible sign of this change in atmospheric chemistry would be a familiar blue sky. But the oxygen levels are still too low for you to breathe, so you'll still need that space suit to survive on Earth.

On Earth two and a half billion years ago, the greenhouse gas levels (especially methane) began to rapidly decline, as the newly available free oxygen destroyed the methane gas. It is also possible that a lull in volcanic activity caused the levels of $CO_2$ to drastically reduce, further cooling the planet. At around 3 billion years ago, the atmosphere was probably only about half the thickness that it is at present,[11] and thinner air is colder (think of what happens when you climb a mountain to a higher altitude – where the atmospheric pressure is lower it gets colder!). But these are not the only factors causing a chill in the air. There is also the albedo effect.

The Earth's albedo (amount of sunlight that is reflected) is controlled to a large extent by how much ocean there is compared to the amount of land. Ocean has a very low albedo (absorbs heat from the sun) compared with a higher albedo on land (reflects more heat). Ocean near the equator absorbs the most heat, and land at the equator absorbs less (reflects more heat back into space). At times when the oceans covered more (or all) of the Earth, especially near the equator, then this would have a global warming effect. But when there is land along the equator, the Earth is cooled. The circumference of the Earth at the equator is 40,075 km (24,901 miles), and with the current (warm Earth) configuration of continents, 78.7% lies across water, and only 21.3% of the equator lies over land.

Another important factor controlling the Earth's albedo is cloud cover. White clouds reflect sunlight back into space cooling the planet by about 12 °C (22 °F). However, the water vapor comprising clouds is also a powerful greenhouse gas that traps heat and warms the planet by about 7 °C (13 °F). That is why cloudy nights are often warmer than clear nights. Think of the heat that comes off the pavement on a sunny day. After the sun goes down, you can still feel heat coming off the pavement – that's the longwave (invisible) radiation that clouds trap. The net result of cloud cover – cooling from albedo or warming from greenhouse – is a net cooling of about 5 °C (9 °F). The type of cloud (low versus high clouds and cloud density) also makes a big difference on both albedo and radiation trapping efficiency.

A combination of factors two and a half billion years ago favored a much cooler climate and the cooler climate allowed sea ice to form at the poles and ice sheets to cover the land at high latitudes. As the ice crept ever further south, year by year, the white albedo of snow and ice reflected the solar radiation back into space, cooling

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[10] Olson et al. (2016).

[11] Som et al. (2016).

the Earth even more. And so, as the ice caps expanded, the Earth got colder and colder. The downward spiral toward an ever-colder climate led to a transformation of our planet.

Welcome to snowball Earth!

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Once the polar ice caps expanded beyond a certain *tipping point* around 2.4 billion years ago, the Earth's climate became locked into a global ice age from which escape was (nearly) impossible. The concept of tipping points applies to economics, communications (when a tweet goes viral), the spread of infectious diseases, and climate and other natural cycles, including the population of species. Once a natural system has exceeded its tipping point, it can be very difficult to break the pattern and revert to a more balanced condition. It can also drive the system toward extreme conditions.

What extreme conditions occurred on snowball Earth? Did the oceans freeze throughout their depth with ice extending to the deepest parts of the seafloor? Were the oceans made of solid ice? How did Earth ever escape from this frigid situation?

We know from the rock record that glacial till was deposited on land located at tropical latitudes from between 2.4 and 2.1 billion years ago. This was the first global glaciation event, known as the *Huronian* glaciation, and it lasted for 300 million years.

Scientists now understand how finely balanced the Earth's climate actually is. A slight increase in solar radiation or greenhouse gas content in the atmosphere can tip the balance causing the climate to drastically change from greenhouse Earth to snowball Earth. There are many factors that exert control over the climate. Some climate change factors are very subtle like small changes in the Earth's orbit so that the sun is either closer or farther away. We have already discussed some others: changes in concentrations of trace gasses in the atmosphere, the Earth's albedo, and volcanic eruptions. Combinations of these factors can abruptly tip the climate balance from greenhouse Earth to snowball Earth, or vice versa.

How did Earth's climate recover from such extreme, snowball conditions? There may have been a different combination of the same factors, or perhaps other processes played a part. For example, we can assume that primary production must have slowed when the ocean was covered in ice. Sea ice blocks out the sun, and where the oceans were covered by year-round ice, primary production would be greatly reduced. In the seasonally melting sea ice zone at the poles, only specialized species of diatoms survive today. Since there was less primary production (there were no plants growing on land at this time), there was also less oxygen produced which, in turn, allowed greenhouse gasses like methane to slowly accumulate in the atmosphere once again.

Perhaps there was an episode of more intense volcanic activity, pumping more $CO_2$ into the atmosphere. And anyway, we don't really know how cold the Earth had become in the first place. The geologic evidence indicates that there may have been glaciers on land at tropical latitudes, just as there are glaciers today on the mountains of Papua New Guinea (in tropical latitudes). Perhaps “snowball” Earth looked more or less as it did at the peak of the last ice age, 20,000 years ago? We don’t really know for certain.

Over the next 2 billion years, during the eon known as the Proterozoic, there is evidence that Earth experienced a global glaciation (snowball Earth) three or perhaps four more times. The exact causes of these glaciations, as well as the means of escape from snowball conditions, are unknown. However, we have a fairly good grasp on the basic principles that can drive the climate into snowball-Earth or greenhouse-Earth conditions. One factor we haven’t discussed yet is the effect of continents on the oceans and on Earth’s climate.

As noted already, continents have a higher albedo than the ocean, so when there is more land near the equator, there is more heat reflected and less heat absorbed by the oceans (and vice versa when there is less land and more ocean at the equator). Also, the continents play an important role in deflecting warm ocean currents toward the polar seas which can influence regional climates (like the Gulf Stream’s effect on the climate of Norway). The continents wandered around the globe over the 300 million years of the Huronian glaciation, so it is possible that a continental configuration favorable to snowball Earth at 2.4 billion years changed to a less favorable configuration by 2.1 billion years ago. It is clear that we cannot tell the story of the oceans without also referring to the continents.

By the time of the Great Oxygen Event at the start of the Proterozoic, geologists estimate that Earth had accumulated about 40% of its continental area. Our planet was then 85% ocean and only 15% land. How was this land configured? Where did the continents come from in the first place? How did they grow bigger? How do we know that the continents have moved? The answer to these questions is provided by what is perhaps the most remarkable scientific discovery of the twentieth century.

The theory of plate tectonics.

# Chapter 2
# Oceans Created: Oceans Destroyed

> *"During the 1960s we found ourselves discarding most of our philosophy of the orderly development of the planet, and taking up what first seemed a prophetic dream of continents splitting apart and new oceans forming. Suddenly many puzzles of geological history began to make sense…"*
> *Francis P. Shepard*
> *Geological Oceanography, 1977.*

**Abstract** Oceans have been created, and oceans have been destroyed many times in the Earth's history by plate tectonics. In this chapter we shall meet Alfred Wegner and learn about his early theory of continental drift and its problems. Rivals to Wegner's theory were the shrinking Earth theory and the expanding Earth theory, but they had problems of their own. We will meet Marie Tharp and her discovery of the great rift valley that encircles the globe. The "Rosetta Stone" for plate tectonic theory was the discovery of magnetic "stripes" on the ocean floor created by episodic reversals of the Earth's magnetic field. The disintegration of Pangea 170 million years ago and the rise and fall of the Tethys Ocean 6 million years ago are merely brief stages of the cycle of the birth and death of oceans.

**Keywords** Alfred Wegener · Pangea · Continental drift · Plate tectonics · Marie Tharp · Bruce Heezen · Harry Hess · Seafloor spreading · Paleomagnetism · Magnetic north pole · Panthalassa Ocean · Tethys Ocean

We are all standing on unsteady ground, for the continents are moving beneath our feet, driven by giant convection cells in the Earth's mantle. The continents float at the mercy of random upwellings and downwellings of molten rock, like the scum of milk floating on the surface of a cup of hot tea.

The discovery of plate tectonic theory involved many individuals who each contributed small pieces of knowledge that, once assembled, allowed the theory to develop over almost a century of scientific debate and exploration. No single person

P. T. Harris, *Mysterious Ocean*, https://doi.org/10.1007/978-3-030-15632-9_2

can take the credit for its discovery; there has never been a Nobel Prize awarded for the discovery of the plate tectonic theory. However, there have been a few individuals who have made exceptional contributions to developing the theory. One of them was Alfred Lothar Wegener (1880–1930).

Wegener was born in Berlin, Germany, and graduated from Friedrich Wilhelm University, completing his PhD in 1904 in the field of astronomy. Earlier workers had already noticed that the continents could be fitted together like pieces of a jigsaw puzzle; the west coast of Africa fits (almost) exactly into the east coast of South America, and the south coast of Australia fits into the coast of east Antarctica, etc. Geologists showed that, if the continents were assembled in a certain way, geological formations could be traced between them that contained fossils from the same geological era.

Wegener assembled vast amounts of data to develop and support his theory of "continental drift" which he later described in more detail in his book "The origins of continents and oceans" published in 1912. He did not stop there. He continued adding more and more information such that his book grew in size from 94 pages in its first (1912) edition to 234 pages in the fourth (1929); a sixth edition of the book was published in 1966 and it was translated into seven languages.

The meticulous gathering together of factual evidence that the continents had once been joined together in a giant supercontinent (named *Pangea* by Wegener) is undoubtedly one of Wegener's greatest contributions to the development of plate tectonic theory. That part of Pangea located at polar latitudes explained the occurrence of glacial deposits found today at sites near the equator; coal deposits that must have formed in humid tropical latitudes are today found in temperate and polar regions. Continental drift explained these observations. But Wegener's deductions went even further than this. He reasoned that mountain ranges must have formed where continents collided, and he gave the example of the Himalayas as an example (which is correct).

The influence of Wegener's theory was so large that two international conferences were organized, in 1923 (London) and 1926 (New York), although neither of the conferences was attended by Wegener himself. His PhD was in astronomy, not geology, a fact which detractors of the continental drift theory regularly pointed out. Wegner probably did not attend these conferences to avoid being ridiculed by his scientific rivals.

The prevailing, alternative theory, at the time Wegener published his continental drift theory, was that the Earth was shrinking and contracting due to cooling. Mountain ranges supposedly formed as the crust wrinkled, like the skin of a desiccated apple. The shrinking Earth concept had its own problems; for example, the shortening needed to raise all of the various mountain ranges required the volume of the Earth to have reduced by an amount much greater than could be explained by cooling and contraction of the crust and mantle. The shrinking Earth theory kept the continents fixed in their places, and this was the dogma of the scientific community well into the 1950s.

Wegener was convinced that the continents had once been joined in the geologic past but that they had "drifted" apart; the problem was that there was no logical explanation as to what force had caused the continents to "drift." Wegener never