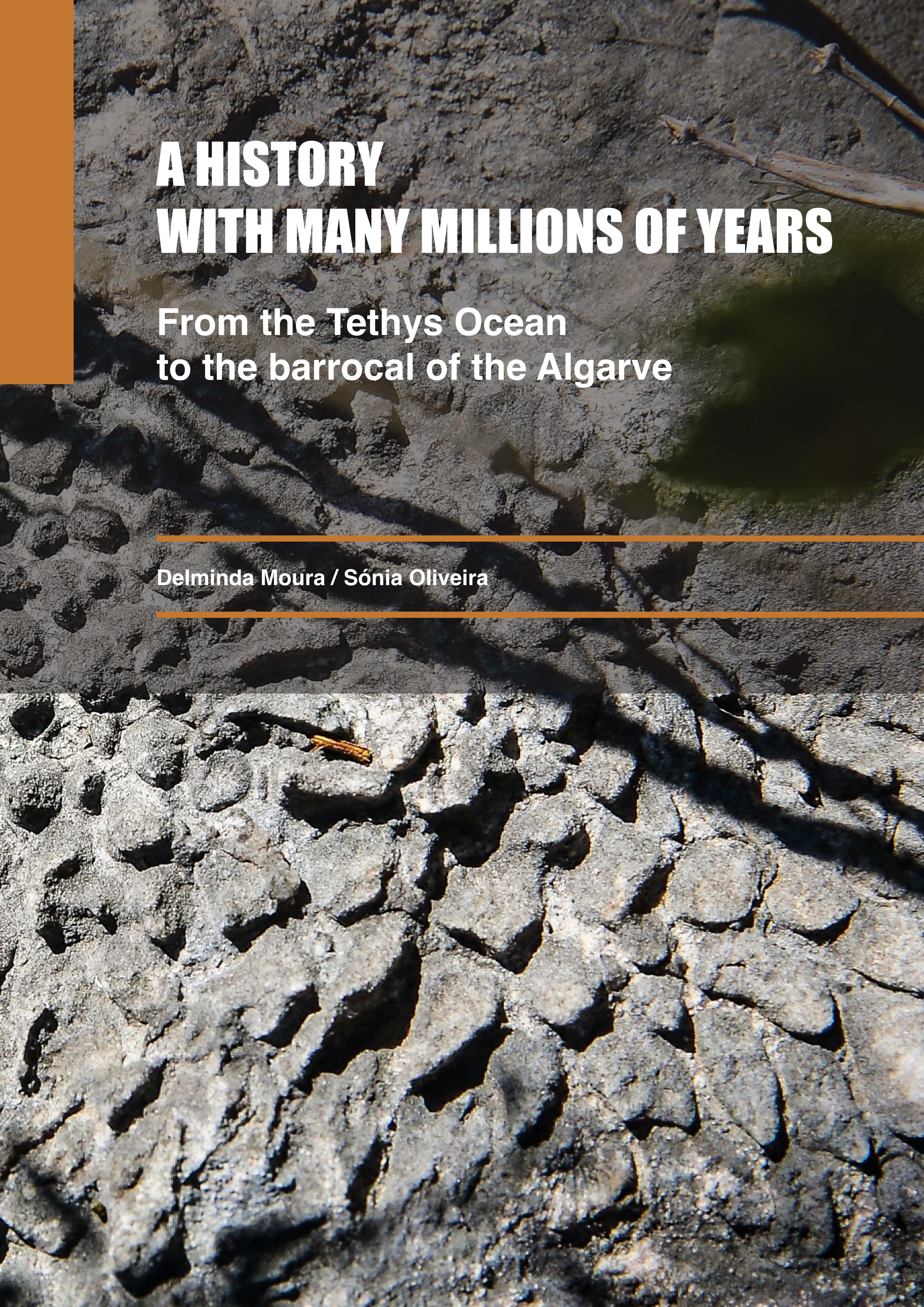

A HISTORY WITH MANY MILLIONS OF YEARS

From the Tethys Ocean to the barrocal of the Algarve

Delminda Moura / Sónia Oliveira

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A History with many millions of years
From the Tethys Ocean to the barrocal of the Algarve

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Delminda Moura / Sónia Oliveira

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CONTENTS

CHAPTER 5

CHAPTER 6

CHAPTER 7

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After a brief period in 1995 working in the private hotel sector, the following year he embarked on a technical career in tourism at the Municipality of Albufeira. He worked there until 2008, when he obtained a municipal license to assume functions as Marketing Manager at the Agency for the Promotion of Albufeira. In 2012, he became General Coordinator of that Agency. He returned to the Municipality of Albufeira in April 2019 as a Senior Technician assigned to the Mayor's Support Services. Since then, he has assumed the Coordination by the Municipality of Albufeira of the candidacy of the Geopark Algarvensis Loulé-Silves-Albufeira to the UNESCO Global Geoparks Network.

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AKNOWLEDGEMENTS

The enthusiasm of all those involved contributed to this book, from the proponent, the Mayor of the City Council of Albufeira, José Carlos Rolo, to the person responsible in this municipality for coordinating the candidacy of the aspiring Geopark Algarvensis to the UNESCO World Global Geoparks, Luís Pereira, and to Professors Nuno Pimentel and Cristina Veiga-Pires, for reviewing the manuscript and providing valuable criticism. Without exception, all these players were in the field where everything happens.
We thank them all for their commitment and contributions.

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RETURN POWER TO EARTH

This is a daring project. We are aware that the power of Geology is a precondition for economic revival.

And our Escarpão Plateau, which well deserves this commendable study, is a unique area of inestimable interest for understanding the evolution of Planet Earth. And this is to give back power to the mountain, to the stones, to the long back of limestone that rises into view when we turn our backs to the sea to watch the plateau's past in the present. We find no traces of its beginning, but we also see no prospect of its end, as James Hutton, the father of modern geology, would say.

This knowledge is decisive for the future. It's no secret: to scientific knowledge, we also intend to add a sustainable economy and to encourage geotourism, with cultural knowledge in the mix.

The aspiring UNESCO Global Algarvensis Loulé-Silves-Albufeira is the result of a new administrative look. This strategic look aims to enhance the unique marks of the earth's crust in a given region, to make this natural phenomenon a distinct sign of differentiation and power, under a common commitment of communities, institutions, schools and companies.

One way of kicking off this commitment to our basic territory is to pick up this book and learn from someone who has done a lot of research. We are all ambassadors of this heritage, rich in diversity, history and promise for the future.
To the authors, my admiration and gratitude.
To the readers, the best wishes for a new and noble path.

José Carlos Rolo,
Mayor of the City Council of Albufeira

FOREWORD

Each place contains within itself the history of the time that preceded it and that of the world it involved. The authors of this book adopted that idea as the starting point for this glance over the Escarpão Plateau. They chose a place where the rocks tell us about more than 150 million years of geological events and where the world of plate tectonics dictated the rules and left its traces. On a journey through time and space, this work explains how this plateau was formed, from the rocks we find there to the valleys that fit into them.

This is an unusual work, as it seeks to tell the long geological history of a specific place following an approach that is both scientific and intended for dissemination. Scientific rigor is always present, in every detail about the organisms, paleoenvironments, ages or structures. But we can also feel a broader view, which seeks to talk about the geological "rules of the game", its processes and the resulting materials.

To "open the ball", the authors tell us of the geological time, that inhuman immensity of geological time, which our minds can hardly comprehend. But we must board this ship to understand the magnitude of the slow geological processes. In particular, we need to understand geological time to embark on the story of the birth and growth of the Atlantic Ocean, the ocean in which the rocks of the Escarpão were formed. We are then taken to dive in that ocean, to understand what its tropical shores were like, where corals and other organisms (to us, exotic) proliferated at the time. And so we were given a bridge between the past and the present, a past inscribed in the rocks of the Escarpão and of which we have glimpses when we look (our eyes have now a wider understanding) at the rocks and the fossils they contain.

We are now entering the Escarpão, layer by layer and unit by unit, on a journey through time and the seabed. The authors take us up there, in stratigraphy and paleobathymetry, from the pelagic depths to the surface exposed to the tropical sun. We travel with them, so let's let ourselves be carried away by geology and our imagination, now spurred on by the information we presently have.

With our minds already fuelled by such a long plot, the authors offer us the description of the scenario where everything happened, the geodynamic scenario where the tectonic plates moved, promoting subsidence and sedimentation in basins as well as collisions and the alpine uplift that exposed them.

We thus arrive at the "end of the dance", with all the participants already exhausted from so much commotion, crashed in their resting places, but with the lights still on. Lights of recent times, of times when there is still a breeze stirring the props and costumes of this ball. This is the time of the current landscape, of the exogenous processes that shaped and sculpted the valleys, the slopes and the plateau. The time of rain and wind, of the slow struggle of each drop against each rock, of each creek along each slope. It's the end of a long journey. We now know that nothing that is here now is like it was before. That geological time is immense and surprising. That where today we see rocks and valleys, in other times we had tropical seas, reefs and colorful marine life. That plate tectonics is not something that only happens far away where there are volcanoes and earthquakes, but it also happens right here on our doorstep, since forever and until today. And that each place can be a place of inspiration, if we know how to listen carefully to it and read what it has to tell us. I hope we know how to listen, and the authors give us the tools to do that.

Like a record that is there intact, but without music, this work is the record, or CD or MP4, player that allows us to listen to that music. A song far away in time, but which makes us think of balls with tropical extras, muscular security guards and meticulous cleaners. Let's accept the invitation and embark on the journey!

Nuno Pimentel, 7 February 2022

INTRODUCTION

This book resulted from a challenge by the Mayor of the City Council of Albufeira, José Carlos Rolo, to produce a scientific-pedagogical document that would reveal the mysteries of the Escarpão Plateau and surrounding region to a diverse audience. Luís Pereira, from the Mayor's support office, a tireless apprentice of geology with unshakable enthusiasm, traveled with us along all the paths of the Plateau and adjacent lands. Together we have experienced fantastic adventures! There was no shortage of moments of conviviality, whether in more conventional lunches or in picnics.

At one of our picnics, we were so fascinated by the landscape that we hurriedly ate our lunch while standing up. Truth be told, in a karst terrain where the rocks are sharp and the bush is thorny, the invitation to sit down is not very appealing. But let the authors of this book tell you how, on a day when we ventured without Luís through the valley of Quarteira stream, we became trapped in the middle of dense vegetation, all full of thorns, from the creepers to the undergrowth, next to a fast flowing river with rapids. This truly happened! The Quarteira stream, in which the water quickly disappears after the rains, as it happens in its subsidiary streams, was full that day. With the valley getting darker and darker, we felt that we were doing our military training, crawling under the bush and crossing the rapids of the stream. We were saved by our colleague and friend Ana Gomes, who picked us up, with water canteens and towels, close to the Castle of Paderne, 13 kilometers away from the place where, early that the morning, we had parked our car. But at no point did we regret having said yes to the challenge.

So, we agreed to write a book in which the Escarpão Plateau is the main actor, and here is the product in the form of seven chapters with illustrative diagrams and field photographs. Although the Escarpão Plateau is the dominant physiographic entity, both because of the area it occupies and because of its importance to the paleogeographic interpretation of the Late Jurassic, the book carries over into the surrounding regions, dotted with hills with wonderful views over the Barrocal and stretching to the ocean. In the Algarve, we are never too far from the sea. To appreciate and understand the landscape that we can enjoy from the hills, just visit them, as they are equipped with interpretive panels.
The chronostratigraphic table (geological time table) was deliberately included in one of the first pages of the book, instead of having it entered as an annex. The reader will find the names of the geological divisions (Eras, Periods and Epochs) throughout all chapters. For this reason, we recommend that you consult the referred table, to first get familiar with the names before getting involved in the reading.

Chapter one aims to inform those less familiar with this subject about the organisation of geological time and explain the phenomena that are at the basis of its division.

Chapter two is devoted to the birth of an oceanic basin: the Atlantic Ocean and its predecessor, the Tethys Ocean. This excursion is essential, since the Tethysian domain is invoked several times in relation to the ecology of the fossil organisms that were found.

Chapter three closes the set of general information chapters that allow you to understand the Escarpão Plateau, to which chapters four, five and six are dedicated. In chapter three, we talk about life in the Jurassic ocean and the ocean provinces. In this way, when in chapter four we describe and interpret each of the stratigraphic units that are the physical support of the Plateau, the text can now run freely without interruptions for additional explanations.

Chapter five is dedicated to the paleoenvironmental evolution of the geological formations that appear in vertical succession on the Escarpão Plateau and surrounding area. The proposal made for the evolution of the formations is based on the interpretation of the sedimentary facies described in chapter four.

Chapter six is devoted to the geodynamic evolution of the region, from the Late Jurassic to the Miocene, based on the diverse scientific literature already published.

Finally, chapter seven deals with the most recent development of the landscape, its last aspects being the result of the interaction between the geomorphic and anthropogenic processes that occurred throughout the Quaternary.

Explanations and the meaning of less common terms are given in the text when they do not cause interruptions that hinder understanding. Otherwise, the explanations were moved to the glossary.

The bibliography used and possible additional readings for those who want to deepen their knowledge are provided at the end of the book, divided by the chapters for which they are more relevant. Likewise, figure credits are also arranged under the chapters in which they appear.

Finally, we would like to pay a special tribute to our colleague Miguel Ramalho, a major figure in the Portuguese geological spectrum and a scholar of microfossils from Late Jurassic formations, in particular those that emerge on the Escarpão Plateau. The specimens that we name in chapter four were identified by him. The description of their ecology and the environmental interpretation were made by the authors of this book based on the consulted bibliography which, as mentioned, is listed in the section “Bibliography used and further reading”.

Delminda Moura & Sónia Oliveira

CHAPTER 1
THE GEOLOGIC TIME

1.1 The age of the Earth

Geologic time is synonymous with the age of the Earth. The term “geologic time” evokes dynamism and is not an abstract concept. It is inseparable from the set of processes that contributed to the evolution of our planet over millions of years.

A geological time scale was created (Figure 1.1) to allow temporal organisation of these processes. It has undergone several changes as the methods used to date the rocks became more sophisticated. The increase in knowledge about the evolutionary relation between groups of organisms (phylogeny) has also contributed to a more precise temporal organisation of events. Having a temporal and geographic framework is fundamental to talk about the complex, dynamic and fascinating history of our planet, just like any other well-told story. When starting studies in Geology, the magnitude of the geological time and its organisation may be concepts difficult to understand.

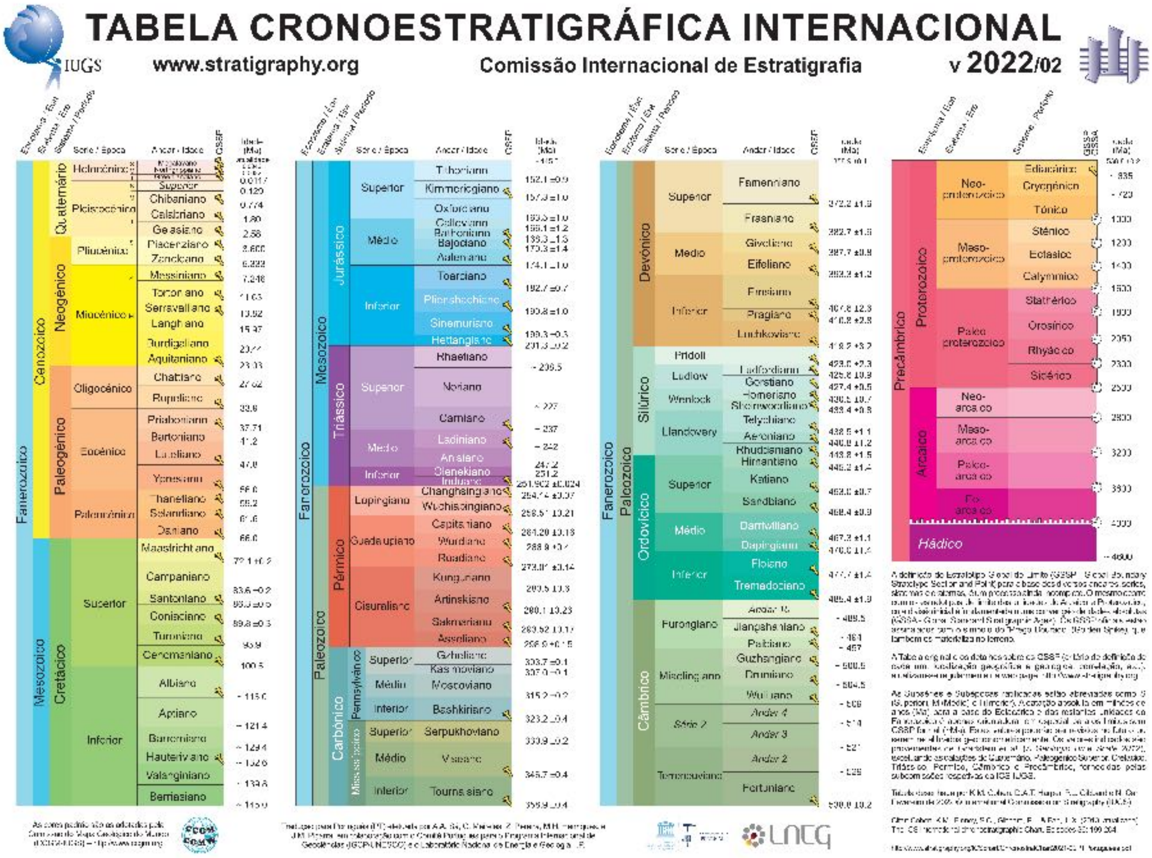


Figure 1.1. Chronostratigraphic table (relationship between rock strata and time of formation)

The calendar system that regulates human activities has itself come a long way and has caused one of the first splits between the Eastern Orthodox Church and the Roman Church. The cause of this disagreement was the temporal setting of Easter, which is governed by lunar cycles, but was sought to be always celebrated on a Sunday. Only in the 16th century did Pope Gregory XIII organize the calendar that currently guides the Western world. In different civilizations, the week, an arbitrary temporal division, was established in various ways according to the religious orientation and the needs for rest and participation in markets. If the organisation of the calendar that governs human activities was the object of numerous adjustments and disagreements, then how can we structure such a vast amount time as is the Earth's age? Lunar and solar cycles are inadequate for the long period of time our planet has existed. But there is a prior question that had to be resolved before making any attempt to divide geological time: how old is the Earth?

The age of the Earth is estimated at 4,540,000,000 years, with a degree of uncertainty of less than 1%. If a cake layer 5 centimeters thick is equal to one millennium, it will be necessary to make a cake 227 kilometers high to represent the totality of geological time. However, there are no traces of rocks as old as the age estimated for the Earth. They were destroyed either in the subduction zones, where the denser oceanic crust plunges under the less dense continental crust, or on the Earth's surface by the action of processes of alteration and erosion. The oldest known rocks are 3,600,000,000 years old. However, some zircons found in sediments in Australia were determined to be 4,300,000,000 years old, so this must be the minimum age of the Earth. Zircon is a very resistant mineral and can survive several cycles of erosion-sedimentation. The zircons eroded from the rocks of which they were originally part were later incorporated into younger rocks, such as those from the Jack Hills mountains, located in a very arid region, which favors the preservation of outcrops (Figure 1.2).

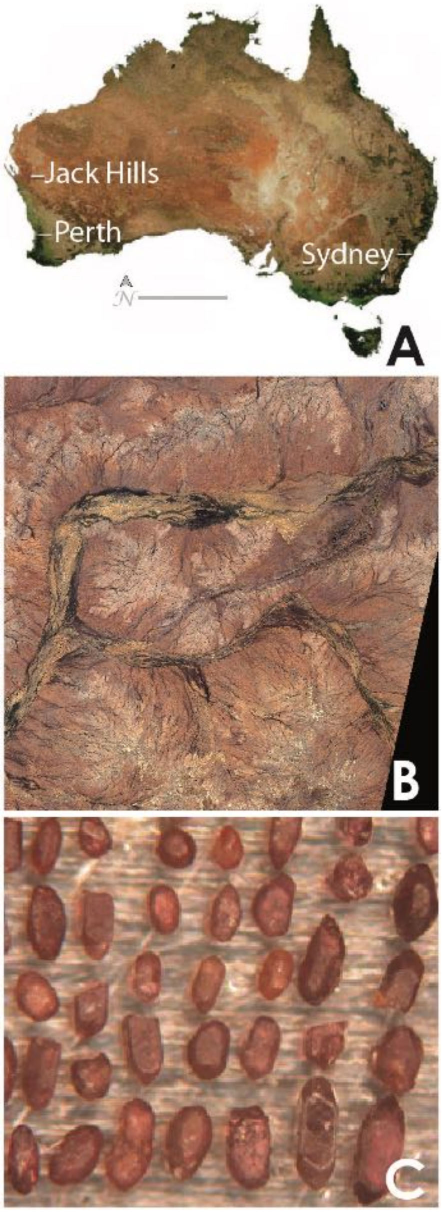


Figure 1.2. A: Location of the Jack Hills outcrops in Australia. Jack Hills zircons are the oldest materials found on Earth so far; B: Satellite image of the Jack Hills Mountains; C: Grains of Jack Hills zircon (average dimension: 0.4 millimeters).

The probable age of the Earth, of 4,540,000,000 years, was obtained from lunar rocks collected during the *Apollo* and *Luna* missions, considering that both planets Earth and the Moon have identical ages in the context of the formation of the Solar System. This impressive number is far from what was proposed in the 17th century by Archbishop Ussher. In 1650, the Irish Archbishop James Ussher (Figure 1.3 A) estimated the age of the Earth based on the Bible (on the family trees of the Old Testament). According to his calculations, the Earth would have been created on the 23rd of October of the year 4004 Before Christ and, just six days later, Man was created (based on the Genesis text).

If we accept this temporal perspective, the only way to explain the genesis of mountains, valleys, rivers and seas would have to be in the light of catastrophism (theory that defended an evolution of our planet based on extreme events). In 1749, Georges-Louis Leclerc, Count of Buffon (Figure 1.3 B), put forward an age for the Earth of 75,000 years, estimating the time that was necessary for fusion materials on the planet to cool down. This calculation was based on his experiments with heated cannonballs. However, he recognized that this age was not long enough to frame all the great natural work.

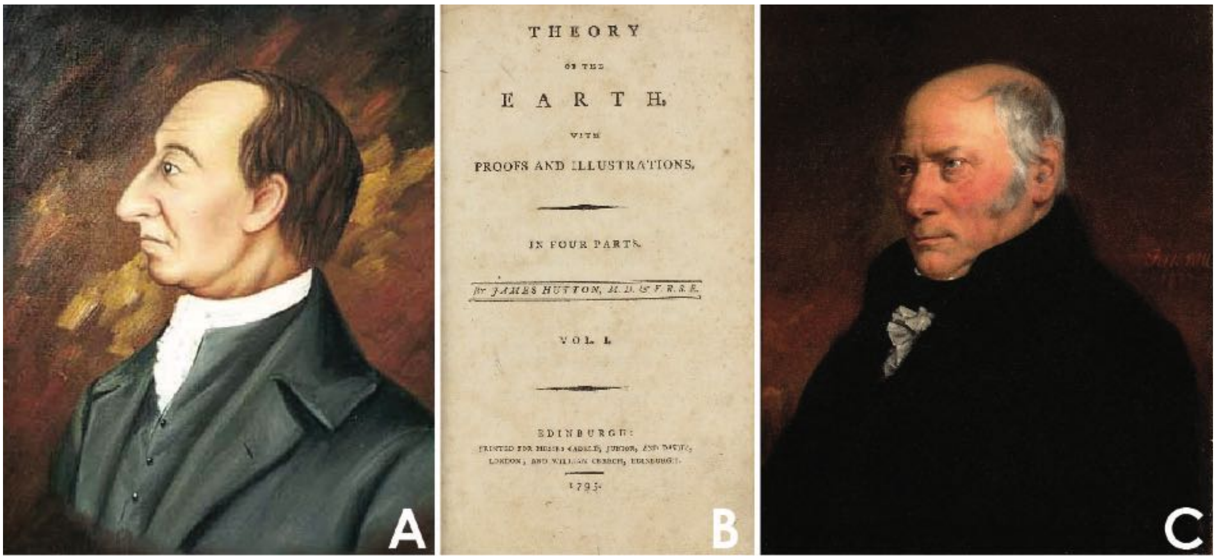
Also taking as a reference the time required for the cooling and petrification of the planet, Lord Kelvin (William Thomson, Figure 1.3 C), a physicist and mathematician born in Belfast, estimated the age of the Earth at 40 million years.

Figure 1.3. Portraits of: A: Archbishop Ussher; B: Georges-Louis Leclerc, Count of Buffon, C: Lord Kelvin (William Thomson).

Charles Darwin, British naturalist born in 1809, felt uneasy about the estimates for the age of the Earth. According to his observations on the evolution of species, the Earth would necessarily have to be much older. A clash of ideas then began between Darwin and Kelvin. In 1893, the latter confronted Darwin with a new estimate for the age of the Earth: only 24 million years. With Darwin already dead, in 1904 Rutherford discovered that some constituent elements of the Earth release substantial amounts of heat by radioactivity. That demonstrated that the age of the Earth had been underestimated in Lord Kelvin's calculations because he did not account for that important fact. Lord Kelvin was unaware that there is an internal source of heat that counteracts the progressive and irreversible cooling of planet Earth over time.

1.2. Organisation of the geologic time

Understanding the age of the Earth and the magnitude and rhythm of occurrence of geological phenomena, whether internal or superficial, is the first barrier we have to overcome when we first approach Geology. Once the age of the Earth is known with an astonishing degree of precision, a no less complicated issue arises: How to divide the immense geologic time on a functional way? In order to create divisions, there are several events that allow us to establish milestones in the course of the existence of our planet. These milestones may correspond to phases of great instability on the Planet, associated with the genesis of mountain ranges (orogeny), or to mass extinctions. James Hutton (1726-1797), a Scottish geologist and naturalist, and William Smith (1769-1839), a British geologist (Figure 1.4), organised the first relative chronology table (without figures for age) for geological time based on the succession of strata (stratigraphy).



THEORY
OF THE
EARTH,
WITH
PROOFS AND ILLUSTRATIONS.
IN FOUR PARTS.
By JAMES HUTTON, M. D. & F. R. S. E.
VOL. I.
EDINBURGH:
1795.

Figure 1.4. A: Portrait of James Hutton; B: Cover of the book New Theory of the Earth by James Hutton; C: Portrait of William Smith.

Stratigraphy is the branch of Geology that studies the succession of layers (strata) of rocks. Each layer was deposited in a particular environment and its vertical succession (stratification) (Figure 1.5) is equivalent to a given geological time interval. With a few exceptions, related to tectonics and river dynamics, the most recent layers overlap the oldest ones. Plutonic rocks, that is, rocks consolidated deep inside the Earth, such as granite and syenite, are not stratified (Figure 1.5).

In addition to estimating the age of rocks based on their stratigraphic relationships (relative age), there are absolute dating methods that allow to directly determine the age of geological materials in years: i) isotopic methods, based on the radioactive decay of unstable chemical elements, ii) radiogenic methods, based on radiation emission, and iii) incremental methods, based on the biological activity or sediment accumulation.

The Eons are the major divisions of geologic time (see Figure 1.1) and their names are derived from the Greek: Hadean (under the Earth), between 4560 and 3900 million years; Archean (ancient), between 3900 and 2500 million years ago; Proterozoic (first life), between 2500 and 545 million years ago; Phanerozoic (visible life), from 545 million years ago to the present. The Eons are divided into smaller temporal intervals, called Eras, separated by important alterations in fauna and flora: Paleozoic (ancient life), Mesozoic (middle life), and Cenozoic (recent life). The Precambrian (Proterozoic) divisions are based on the evolution of stromatoporoids (Figure 1.6). Although there are still doubts as to their taxon (scientific classification), the stromatoporoids constitute the oldest evidence of life on Earth. The first known stromatoporoid fossils date from the Archean. Some fossils are indicators of the Era or Period in which organisms lived. Thus, the concept of

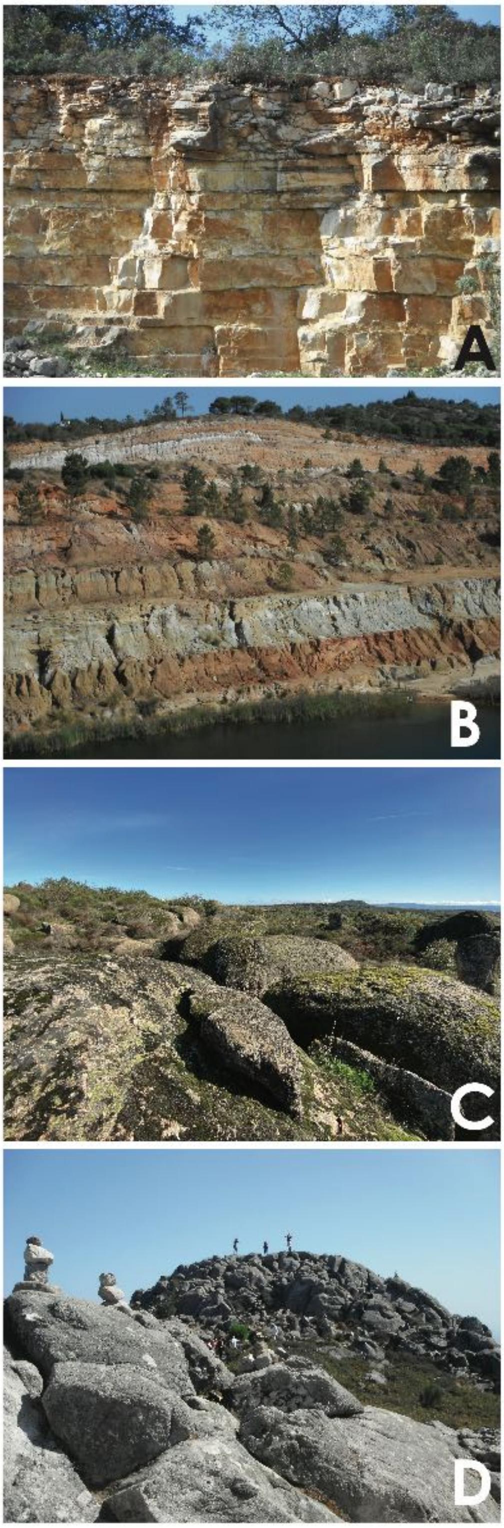


Figure 1.5. A: Marly limestone strata from the Peral Formation. Quarry in Agostos (Santa Bárbara of Nexe); B: Cretaceous marl stratification in a ceramics exploitation front belonging to Fábrica de Cerâmica do Algarve (FACEAL), Mem Moniz; C: Granite outcrop in the region of Castelo Branco; D: Nepheline syenite outcrop in Fóia, Serra de Monchique.

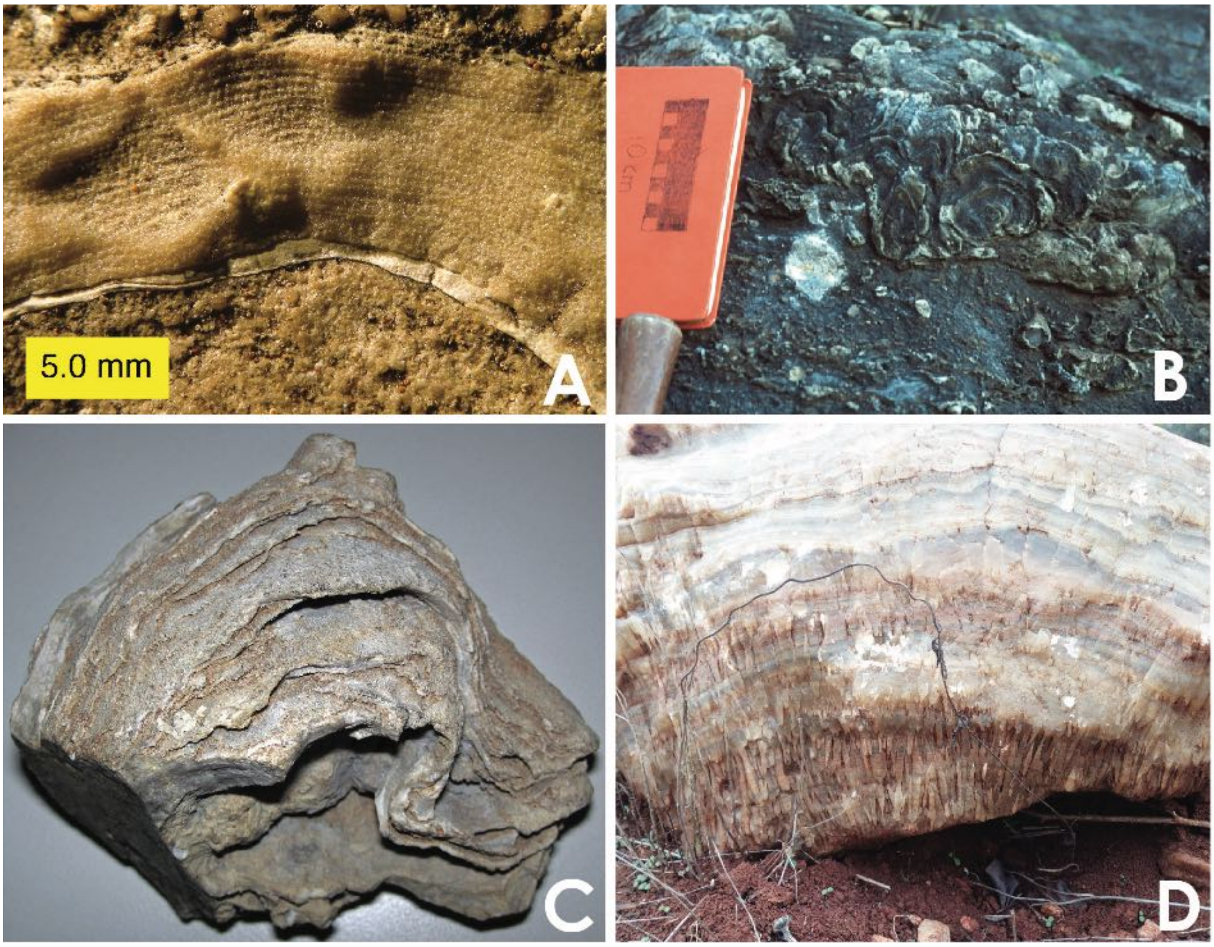


Figure 1.6. A: Devonian stromatoporoid, Ohio; B: Silurian stromatoporoid, Keyser Formation, Pennsylvania; C: Devonian stromatoporoid, Ohio; D: Stromatoporoid with structure replaced by calcite due to diagenesis, although the original lamination is maintained. At the base, elongated irregular crystals typical of the diagenesis of stromatoporoids - Limestone from the Escarpão Formation, Escarpão Plateau.

index fossil (or age fossil) came into being as the record of a species with wide geographical distribution and existence on the planet during a short period of time (Table 1.1). For example, the ammonite and belemnite cephalopods (Figure 1.7 A and B) were abundant during Jurassic but became extinct at the end of the Cretaceous, along with the dinosaurs, in a mass extinction event referred to as the “K-T event” (Figure 1.7 C).

Table 1.1. Geologic Eras and some of the age fossils of Periods. See Figure 1.1 for a better time frame.

ERA	PERIOD	ORIGIN OF THE NAME	INDEX FOSSILS
CENOZOIC	Quaternary	The Eras were initially named as Primary, Secondary and Tertiary. These names for Eras have fallen into disuse but the names Tertiary and Quaternary for the Periods of the Cenozoic Era remain.	*Pecten gibbus* (Bivalve) *Neptunea tabularis* (Gastropod)
	Terciary		*Calyptraphorus veiatus* (Gastropod) *Venericardia planicosta* (Bivalve)
MESOZOIC	Cretacious	From the Latin “*creta*”, meaning “chalk”, a rock that constitutes the cliffs along the English Channel	*Scaphites hippocrepia* (Cephalopod) *Inoceramus labiatus* (Bivalve)
	Jurassic	From the Jura Mountains (between France and Switzerland)	*Prisphinctea tiziani* (Cephalopod – Ammonite) *Nerinea trinodosa* (Gastropod)
	Triassic	From “Trias”, in recognition of the 3 generations of folds in European rocks	*Trophites subbullatua* (Cephalopod – Ammonite)
PALEOZOIC	Permian	From the province of Perm, in Russia	*Leptodus americanus* (Brachiopod) *Parafusulina bosei* (Foraminifera)
	Carboniferous	Coal deposits	*Cactocrinus multibrachiatus* (Crinoid) *Lophophyllidium proliferum* (Coral)
	Devonian	From the county of Devon, in England	*Mucrospirifer mucronatus* (Brachiopod)
	Silurian	From the Celtic Siluros tribe, from Wales	*Cystiphyllum niagarense* (Rudist)
	Ordovician	From the Celtic Ordovices tribe, from Wales	*Bathyurus extans* (Trilobite) *Tetragraptus fructicosos* (Graptolite)
	Cambrian	From “Cambria”, the roman name for North Wales	*Paradoxides pinus* (Trilobite) *Billingsella corrugata* (Brachiopod)

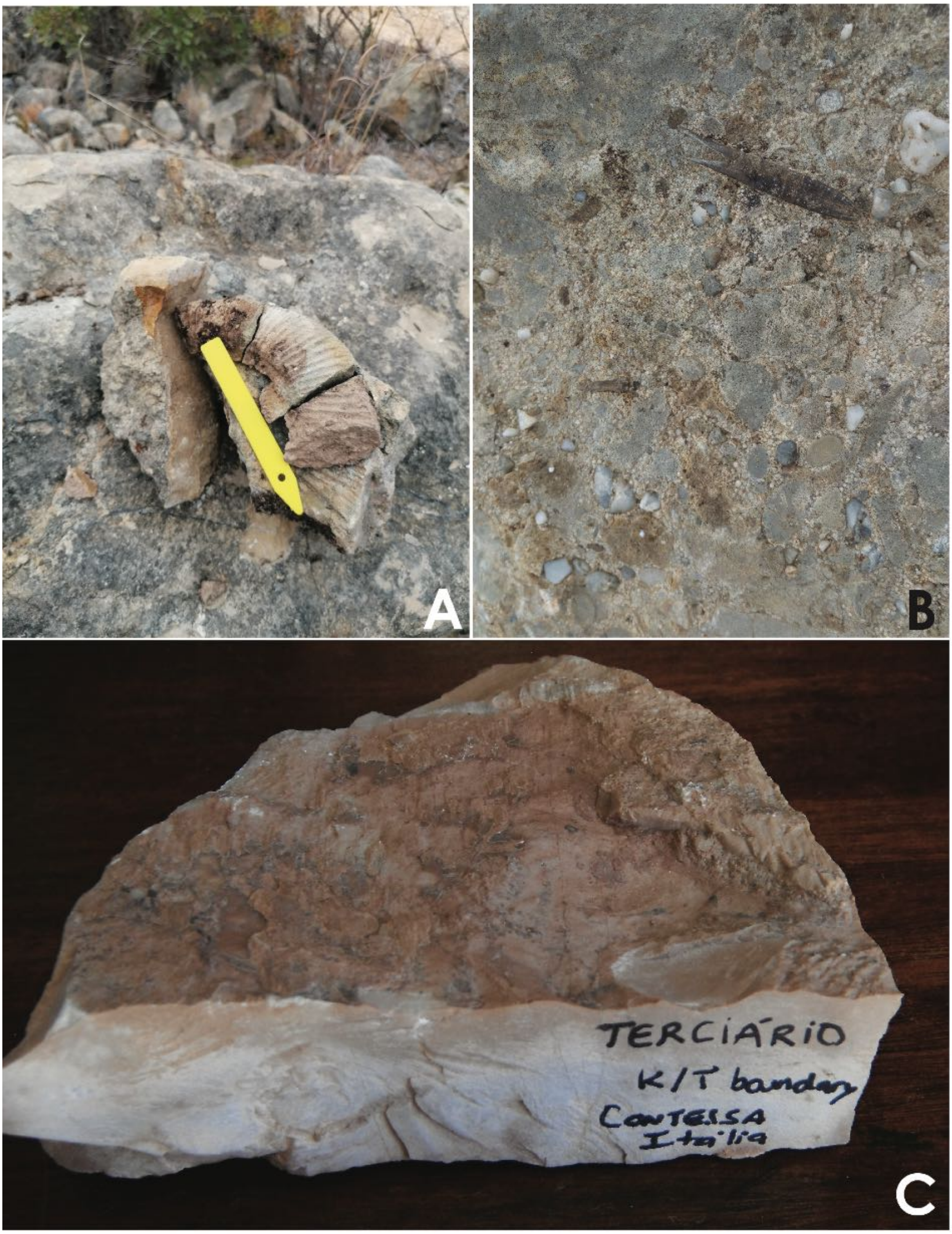


Figure 1.7. A: Ammonite internal mold from the Peral Formation, Escarpão Plateau. It is fractured, because larger fossils tend to break easily in this marly matrix (yellow bar is 10.5 centimeters long); B: Belemnite rostrum from the Peral Formation, Escarpão Plateau; C: Sample of the layer at the K-T boundary (see text), formed by claystone and iridium.

CHAPTER 2
AN OCEAN IS BORN

2.1. Atlantic Ocean

It was in the Mesozoic Era, between approximately 251 and 66 million years ago, in a young and changing ocean, that the sediments later transformed into the rocks that constitute the *Barrocal* of the Algarve were deposited. The ocean we know today as the Atlantic Ocean, which bathes the entire Portuguese coast, is the result of a long evolution.

The name "Atlantic" derives from Atlas, which in Greek means the one who supports the world on his back. During the Middle Ages, the name "Atlantic" fell into disuse, being replaced by "North Sea" and "West Sea". Gerhard Mercator (1512-1594), geographer, cartographer and mathematician born in Flanders, author of the first flat map of the Earth (World Map – Figure 2.1), rehabilitated the name "Atlantic Ocean".

The Atlantic Ocean, so important to man today, did not exist in the Paleozoic Era. The first scientist to hypothesize that the continents moved (continental drift) were the French geologist Antonio Snider-Pellegrine, in 1858, and Alfred Wegener, a German meteorologist and geophysicist (Figure 2.2), later in 1929. This hypothesis was based on the similarity between the physiography and the geological structures on both sides of the Atlantic Ocean – South America and Africa. Another argument used by Alfred Wegener was that there were similarities between the fossils on both sides of the different oceans.

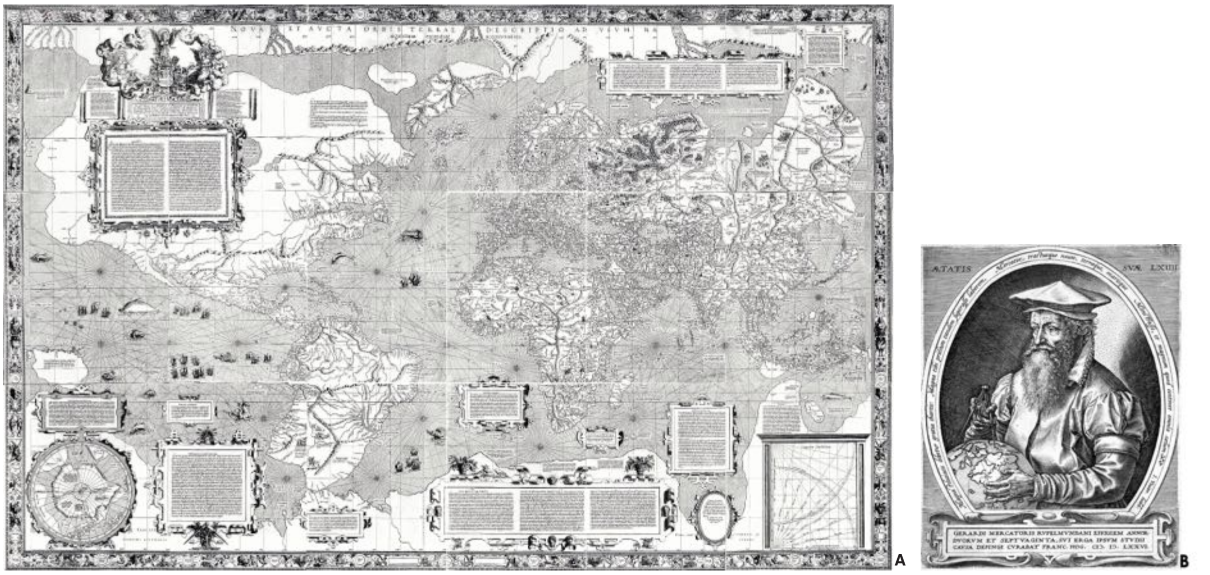


Figure 2.1. A: Map of the world by Gerhard Mercator (1569); B: Portrait of Gerhard Mercator painted by Franz Hogenberg in 1574.

Fossils of the early aquatic reptile *Mesosaurus*, as well as fossils of *Lystrosaurus* (Figure 2.2), have been found on presently separated continental margins (Africa and South America in the first case, Africa, India and Antarctica in the second). For Wegener, these facts could only mean that the continents had once been together. However, in 1929 this hypothesis was too eccentric to be accepted by scientists as a whole.

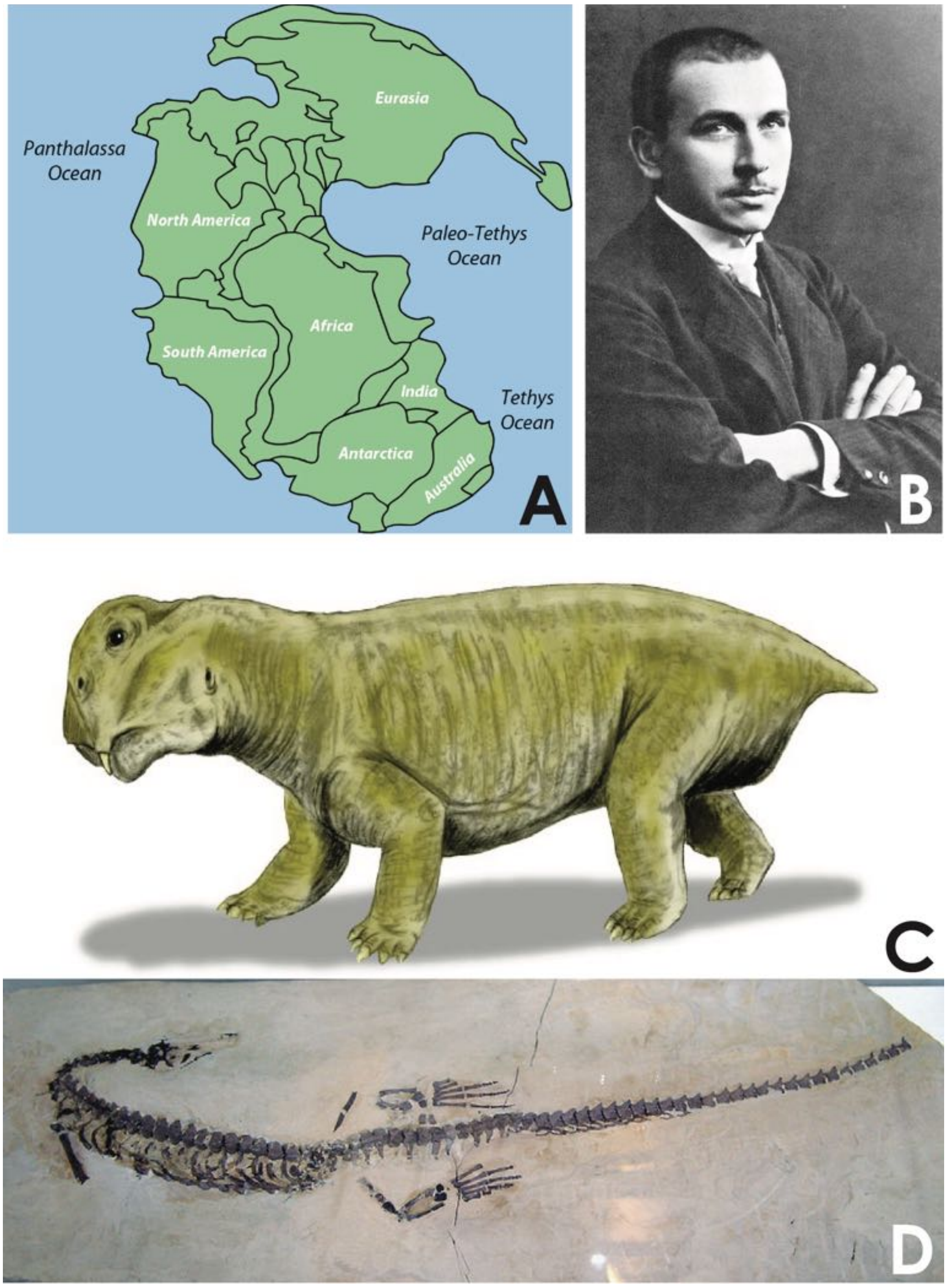


Figure 2.2. A: The supercontinent Pangea in the Paleozoic Era, between 541-252 million years ago (see Figure 1.1). The ocean surrounding Pangea is called Panthalassa; B: Portrait of Alfred Wegener (unknown author, 1910); C: Drawing of a *Lystrosaurus murrayi* from the beginning of Triassic (ca. 250 million years ago) found in South Africa; D: *Mesosaurus* (aquatic reptile from the Paleozoic Era), whose fossils are found in both the South America and Africa continents.

The opponents of the hypothesis of continental drift countered that there would have been land bridges that allowed certain animals to cross continents. That way, the presence on both ocean shores of fossils of identical organisms that were already extinct was justified. However, explaining the glacier deposits in South Africa, India, Australia and Arabia attributed to the Permo-Carboniferous glaciation was difficult without admitting that these regions had been positioned at latitudes different from the current ones. Nonetheless, it was equally difficult for the scientific community to explain the mechanism that could have made the continents move. The theory of plate tectonics only emerged in the 1960s, 30 years after Wegener's death. It was supported by geophysical studies of the ocean floor, which demonstrated that new oceanic crust is formed in rift zones and old crust is destroyed in subduction zones.

In rifts, the newly created oceanic crust moves from one side to the other, similar to moving walkways, while in subduction zones, because the crust is denser, it sinks beneath the less dense continental crust (Figure 2.3).

The rate of formation of oceanic crust has not been constant over time. In the first half of the Cenozoic Era, the overall speed of the "walkways" (seafloor spreading) was 20% higher than before, to then decrease by 12% in the second half of that same Era. At present, the seafloor spreading rates are highly variable, ranging from less than 2.5 centimeters per year on the Arctic Ridge to more than 15 centimeters per year on the Eastern Pacific Ridge, near the Isle of Easter (about 3400 kilometers west of the coast of Chile).

The rift valley and the Mid-Atlantic Ridge are extraordinary morphological features that run longitudinally along the Atlantic Ocean, over a length of about 1600 kilometers, from Iceland to 58° south latitude (Figure 2.4). The water column over this submerged mountain does not exceed 2700 meters and the mountain top emerges in some areas, as is the case of the Azores archipelago. On the contrary, the British and the Falkland Islands are examples of islands that are rooted in the continental shelves of the Atlantic Ocean.

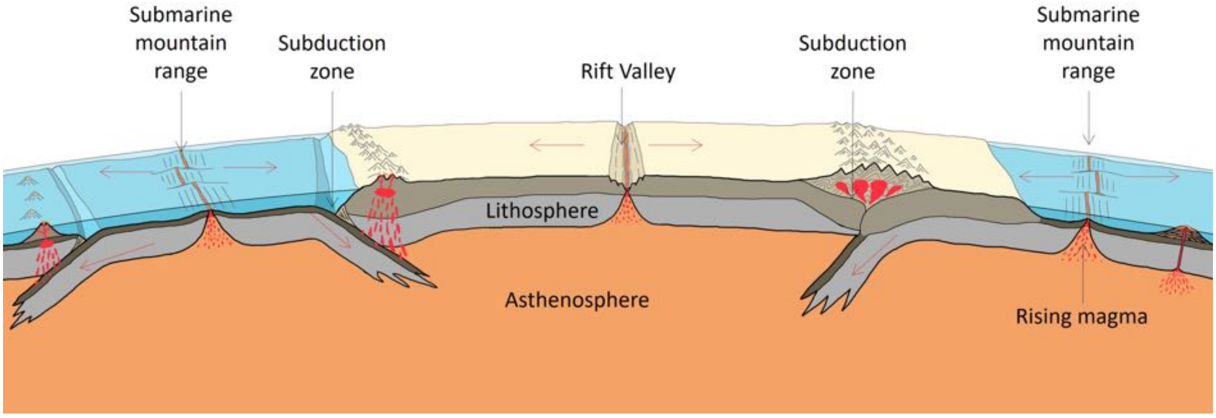


Figure 2.3. Schema of the processes involved in the continental drift - plate tectonics. The lithosphere is the outermost solid layer of the Earth; its thickness varies, being thicker under mountain ranges; the asthenosphere is the zone of the Earth's mantle; less rigid than the lithosphere, it lies from about 80 to 200 kilometers below the Earth's surface.

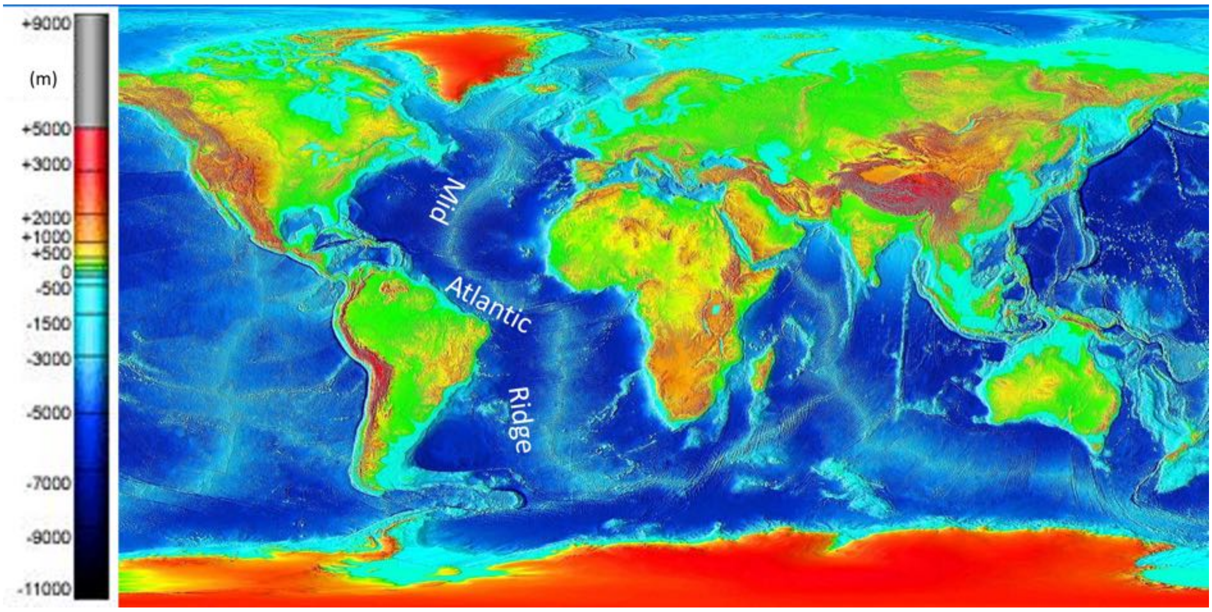


Figure 2.4. Global topographic and bathymetric chart (represents the continental relief and also that of marine basins). The zones in light blue, on the margins of the continents, correspond to the continental shelves.

At present, the Atlantic Ocean extends from the North Pole to the South Pole and, therefore, the physico-chemical characteristics of its waters are very dependent on the climatic conditions in the polar domains. But it was not always like that. In the Triassic, when the Metoposaurus algarvensis (a large amphibian) fed on the flooded banks of rivers and lakes in the (paleo) Algarve, the Paleozoic supercontinent Pangea, bathed by the Panthalassa Ocean, began to break up (Figure 2.5). The drift of the continental masses Gondwana and Laurasia resulted in the formation of the Tethys Ocean, which later evolved into the Central Atlantic Ocean. From the Late Jurassic (Tithonian: 140 million years ago) to the middle Cretaceous (Aptian: 125 million years ago), the Paleo-Tethys Ocean was a circum-equatorial ocean, allowing the circulation of warm surface water around the globe (Figure 2.5). The warm current, established at the beginning of the Late Jurassic, resulted from the opening of a connection between the Pacific and the Tethys oceans, through the Gulf of Mexico. This connection closed much later, around 10 million years ago (Upper Miocene), at the same time that the Iberian Peninsula got closer to the African continent. The warm surface current that circled the Earth in an equatorial voyage was thus interrupted. All this movement of continental masses, the opening and the closing of connections between oceans, had strong consequences on ocean circulation and, therefore, on climate.

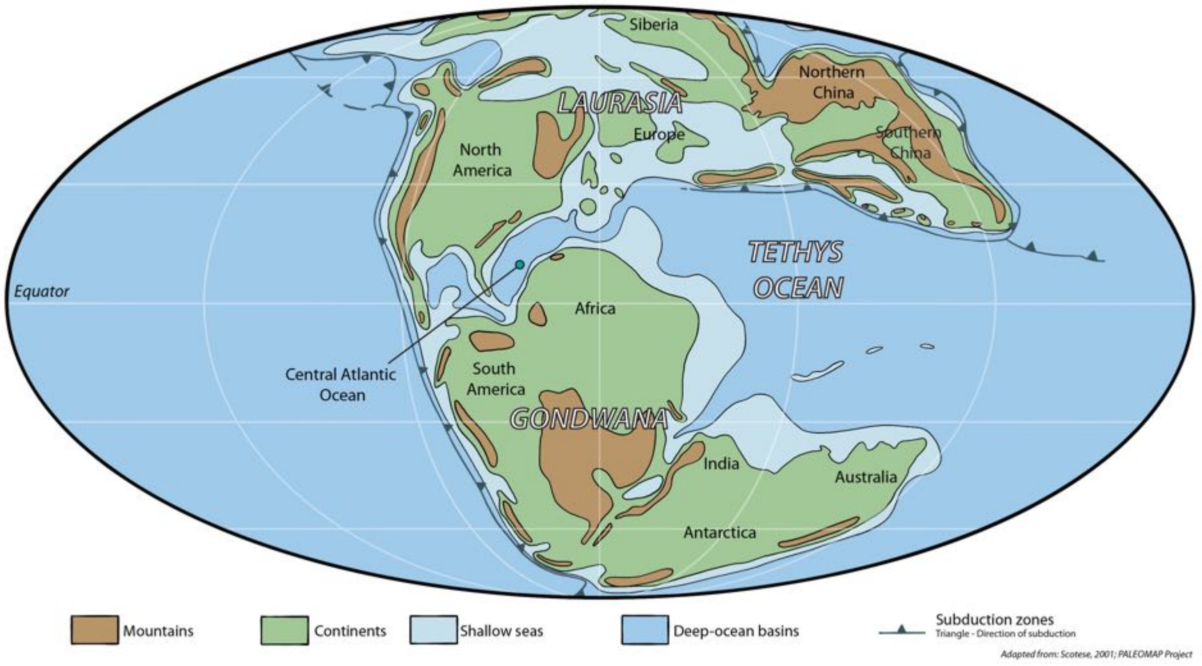


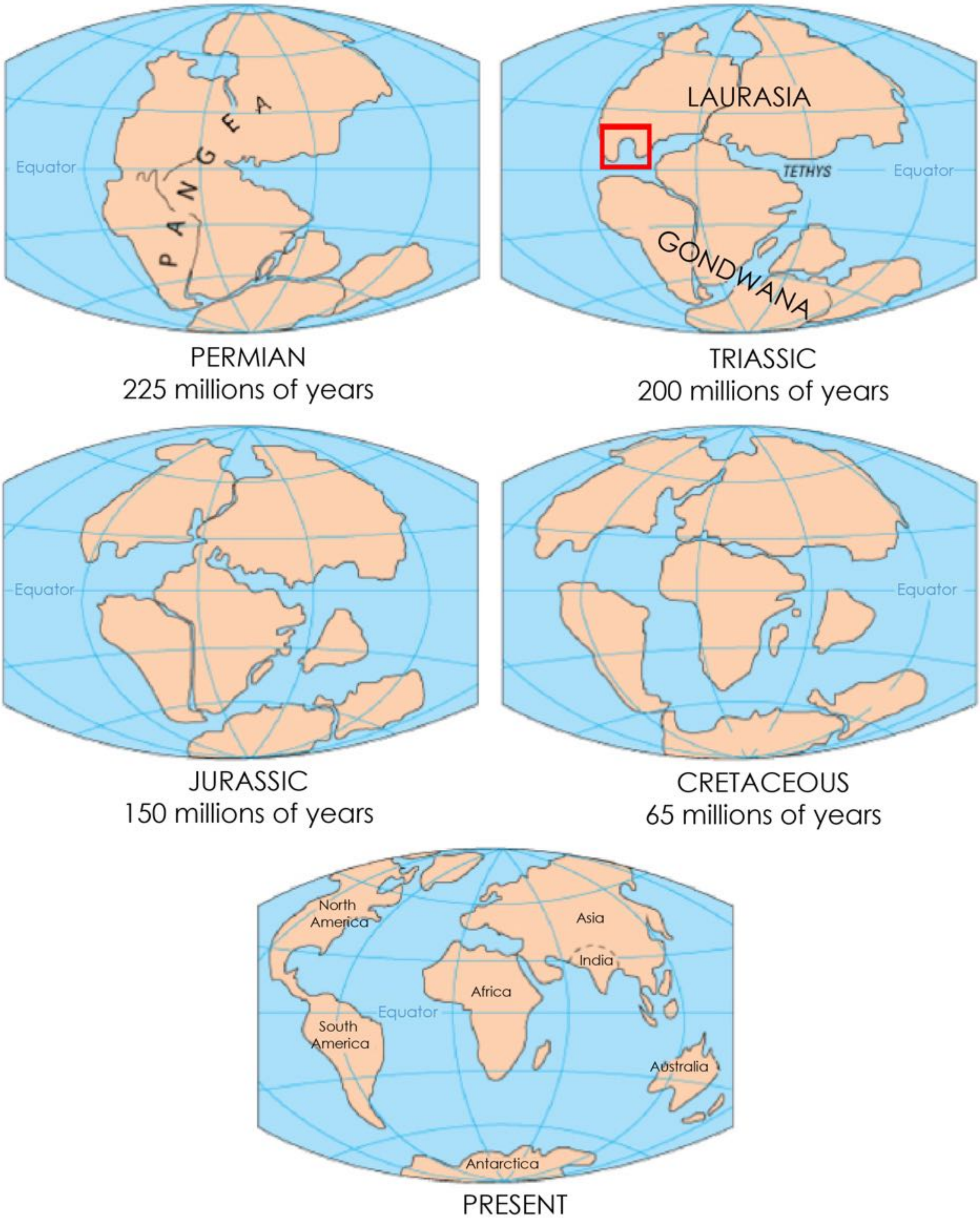
Figure 2.5. Late Jurassic Paleogeography.

2.2. Consequences of continental drift on climate

During much of the Mesozoic Era, the hot and humid climate, quite uniform across the planet, favored the development of the lush fern forests where some dinosaurs lived. Ammonites and belemnites, among many other marine beings, swam in the warm waters of the ocean, and reef buildups settled in the continental shelves (see Chapter 3).

It was approximately 65 million years ago (end of the Cretaceous) that the Earth's climate became gradually colder in relation to the Paleocene-Eocene maximum high (see Figure 1.1), when the Antarctic continent and Greenland were not yet covered by ice. In the Late Eocene, around 40 million years ago, the passage between South America and Antarctica became wider due to migration from South America to the North.

This event favored the emergence of a circumpolar surface current that isolated the Antarctic continent from the influence of warm currents coming from the equatorial zones. About 35 million years ago, in the Oligocene, glaciers began to form on that continent. The northward migration of South America closed the water flow between this continent and North America, at the Isthmus of Panama, further restricting the free circulation of the warm circum-equatorial current (Figure 2.6). With the loss of this current and the Antarctic circumpolar current active, the Earth's climate began to cool down in successive stages. However, it was only during the Pliocene, about 5 million years ago, that the northern hemisphere recorded glacial conditions (Table 2.1).



PERMIAN
225 millions of years

TRIASSIC
200 millions of years

JURASSIC
150 millions of years

CRETACEOUS
65 millions of years

PRESENT

Figure 2.6. Paleogeographic evolution of the continents from 225 million years ago to the present. The red square indicates the position of the Gulf of Mexico in the Triassic.

Table 2.1. Continental drift and global climate interconnected events, from the Late Jurassic to the base of the Pliocene. For a better time frame, see Figure 1.1.

ERA	PERIOD/EPOCHS	PALEOGEOGRAPHY	PALEOCLIMATE
Cenozoic	Pliocene	Position of the continents similar to the current one.	Ice began to accumulate on the northern hemisphere continents.
	Late Miocene	Approximation between the Iberian Peninsula and the African continent by counter clockwise rotation of the Peninsula.	Global cooling began
	Oligocene	Northward migration of South America. Closure of the Isthmus of Panama and consequent inhibition of the warm circum-equatorial current.	
	Late Eocene	Widening of the passage between South America and Antarctica. Creation of an Antarctic circumpolar current, isolating this continent from the influence of the warm Pacific, Atlantic and Indian currents.	
	Early Eocene	The Antarctic continent and Greenland remained free of ice.	Warm weather
	Paleocene		
Mesozoic	Late Jurassic (Tithonian) to middle Cretaceous (Aptian)	A connection between the Pacific and Atlantic oceans was established at the Gulf of Mexico. A warm circum-equatorial current was formed in the central region of the North Atlantic, with an east-west trend.	

CHAPTER 3
LIFE IN THE JURASSIC OCEAN
THE OCEAN PROVINCES

3.1. The marine sediments

The alteration of exposed rocks on the surface of the continents gives rise to sediments that are transported by wind, glaciers and rivers to marine basins, where they are deposited and mixed with the remains of organisms, such as shells, scales and various other skeletal parts. Cosmic dust and ash from volcanoes are also a source of sediments for marine basins (Figure 3.1). A sediment is called lithogenic, terrigenous or clastic when it is composed of minerals and rock fragments. In contrast, when the main component of a sediment is skeletal parts of organisms, it is called biogenic or bioclastic. The sediment is said to be chemical if it is composed of minerals precipitated from a solution. The depressed areas of the Earth where the sediments are deposited are the sedimentation basins. The most important sedimentation basin is the seabed.

The global ocean is subdivided into several marine basins, based on aspects of the underwater morphology. About 73% of the world's sediments accumulate on the continental margins, constituted by the continental shelf, the slope and the continental rise (Figures 3.2 and 3.3).

The sediments are called neritic, hemipelagic and pelagic according to where they are deposited in

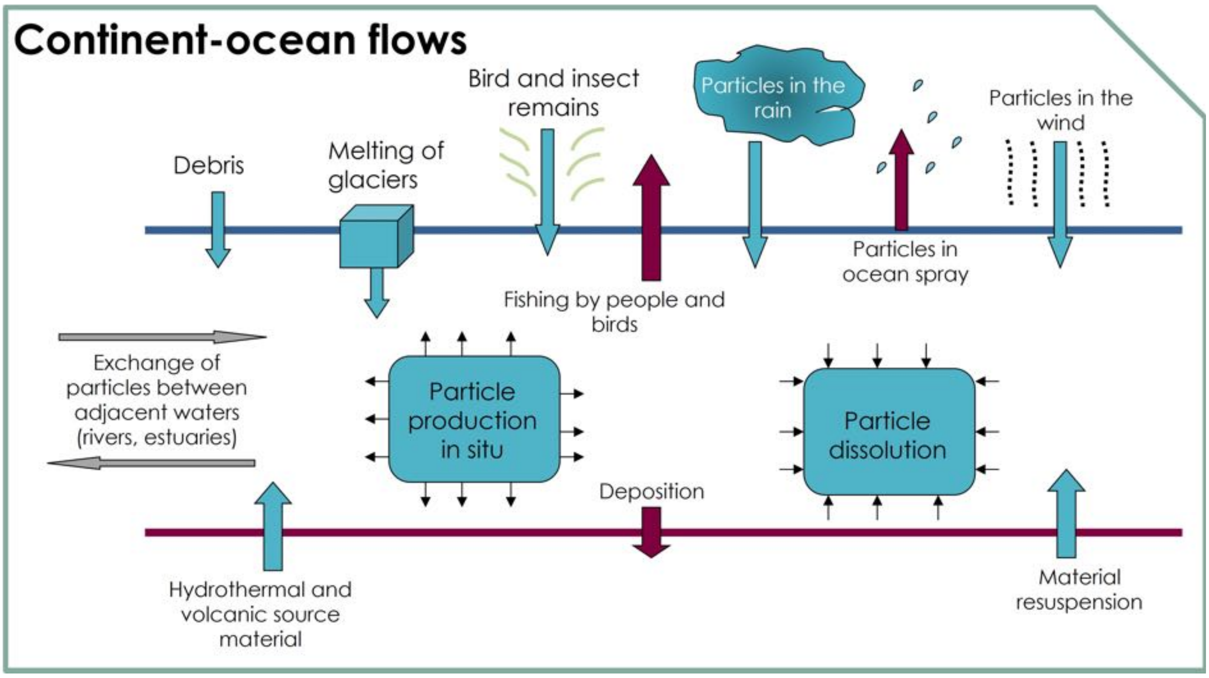


Figure 3.1. Balance of particle flows in the ocean.

marine basins. Neritic sediments are deposited on the continental shelf, in shallow waters, and suffer terrigenous influence (minerals and rock fragments) from the adjacent continental masses (Figure 3.4). Pelagic sediments are those that are deposited far enough from the coast not to be influenced by terrigenous sediments. They are, therefore, mainly biogenic or chemiogenic.

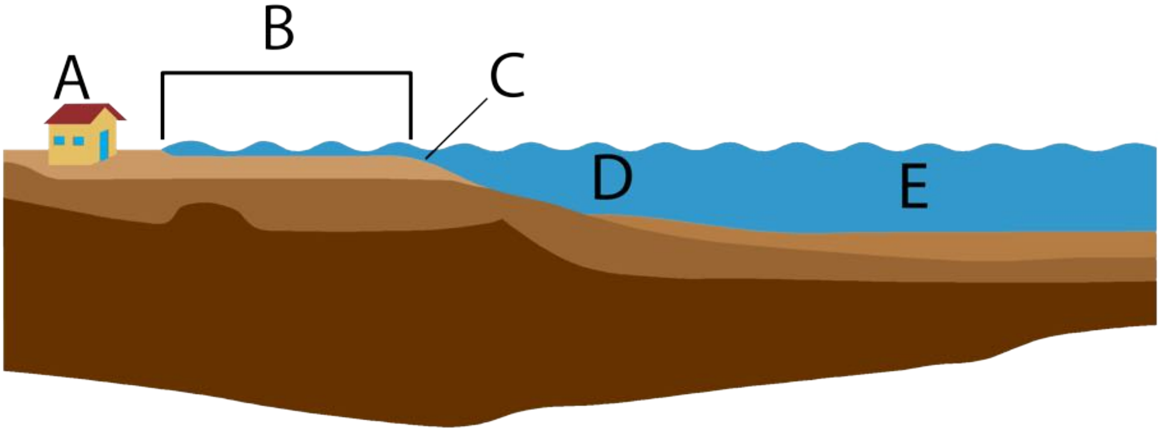


Figure 3.2. Schema of a continental margin, composed of continental shelf (B), continental slope (C) and continental rise (D), between the coastal (A) and deep marine (E) domains with which it exchanges mass and energy. See section 3.2 for further explanation.

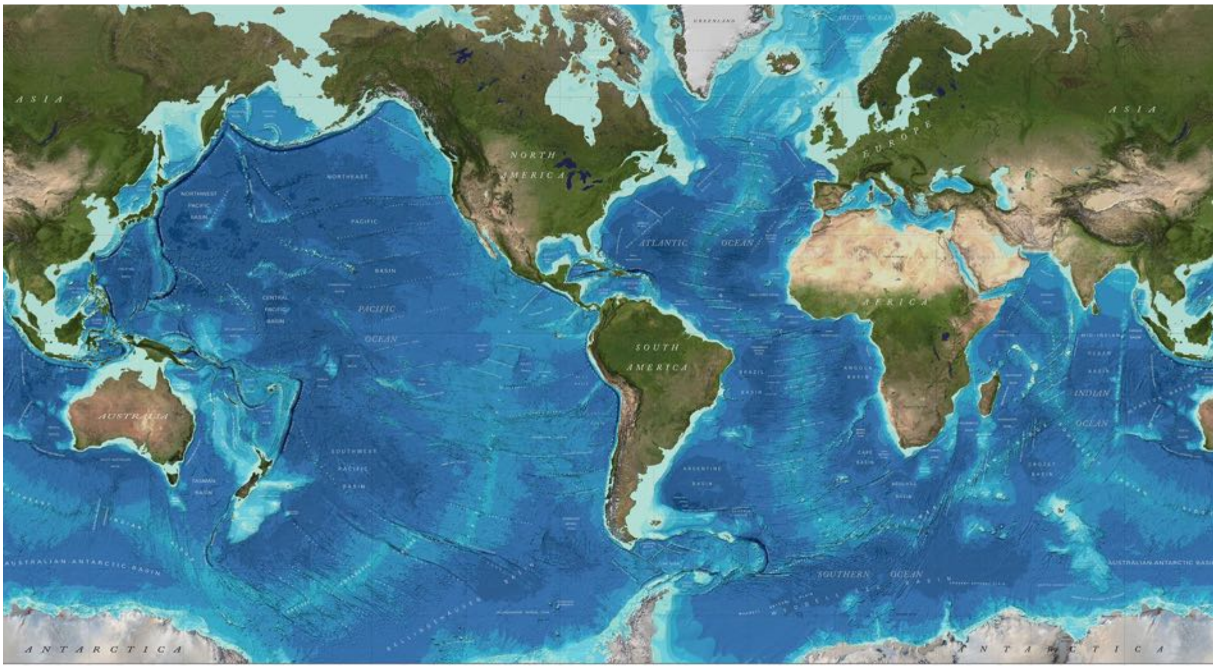


Figure 3.3. Worldwide distribution of continental shelves: lighter blue next to continents. In the Last Glacial Maximum (LGM), around 18,000 years ago, the average sea level dropped 120 – 140 meters; as a result, the continental shelves became exposed. During the LGM, Europe was 40% larger than it is today.

Hemipelagic sediments, as the name indicates, are deposited at intermediate depths between the neritic and pelagic sediments and, therefore, contain elements from both domains. They are mainly clays with varying percentages of sand and pelagic organisms. This domain includes clays with a significant quantity of calcium carbonate ($CaCO_3$) that give rise to marls (having up to two thirds of $CaCO_3$ of total mass) and marly limestones.

Pelagic sediments accumulate very slowly, typically at a rate of ten centimeters every thousand years. If a person's hair grew at a similar rate, it would have grown only seven millimeters after seventy years. Individually, each particle can take thousands of years to go down the oceanic water column before reaching the bottom. However, this journey is accelerated if the particles are integrated into larger particles, such as fecal pellets (excrement of organisms).

When sediments are deposited above the calcite compensation level, which is the depth below which calcite dissolves, carbonate skeletons predominate (e.g., tests of foraminifera and coccolithophores – Figures 3.5 A, B and C) and are called carbonate oozes. Below the calcite compensation level, skeletal parts are mostly siliceous: siliceous oozes (e.g., diatom and radiolarian frustules – Figure 3.5 D, E, and F). In zones of low biological productivity, the sediment that covers the ocean floor is known as pelagic red clay (see Figure 3.4). This clay has two origins: (i) allochthonous – transported from the continents, sometimes from long distances, and (ii) autochthonous – residual sediment resulting from the dissolution of carbonates, which has the lowest accumulation rate on the planet, between about 1.1 to 1.2 grams per square centimeter each millennium.

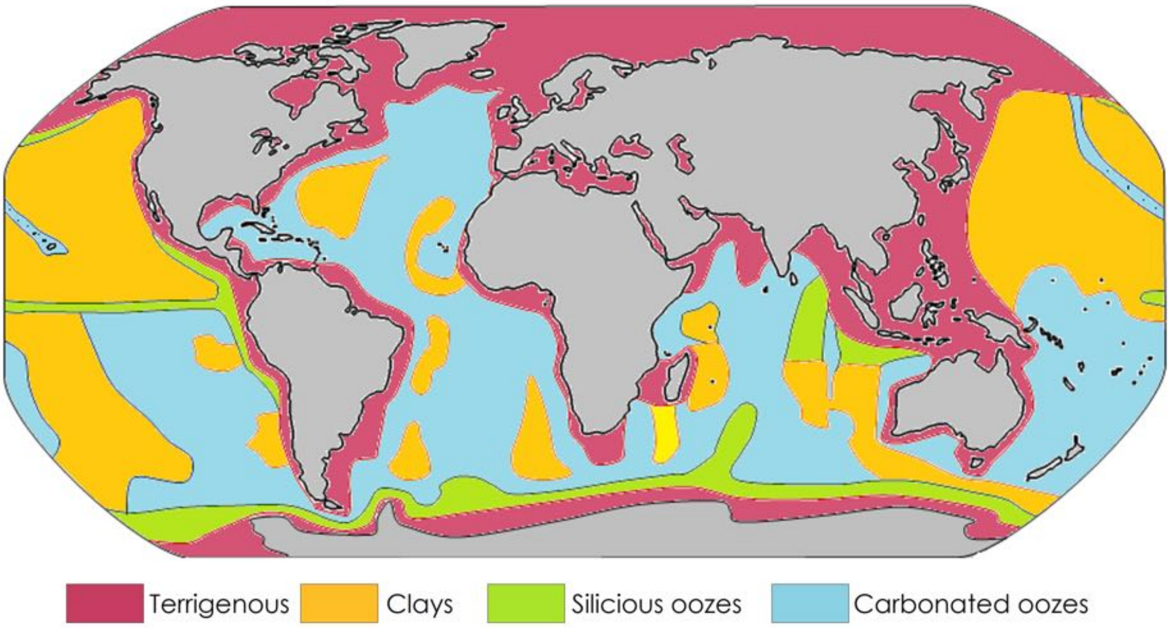


Figure 3.4. Distribution of sediments in marine basins according to the depths at which they are deposited. Note that terrigenous sediments occur near the edges of continents. The clays shown on the map are clays from the great depths.

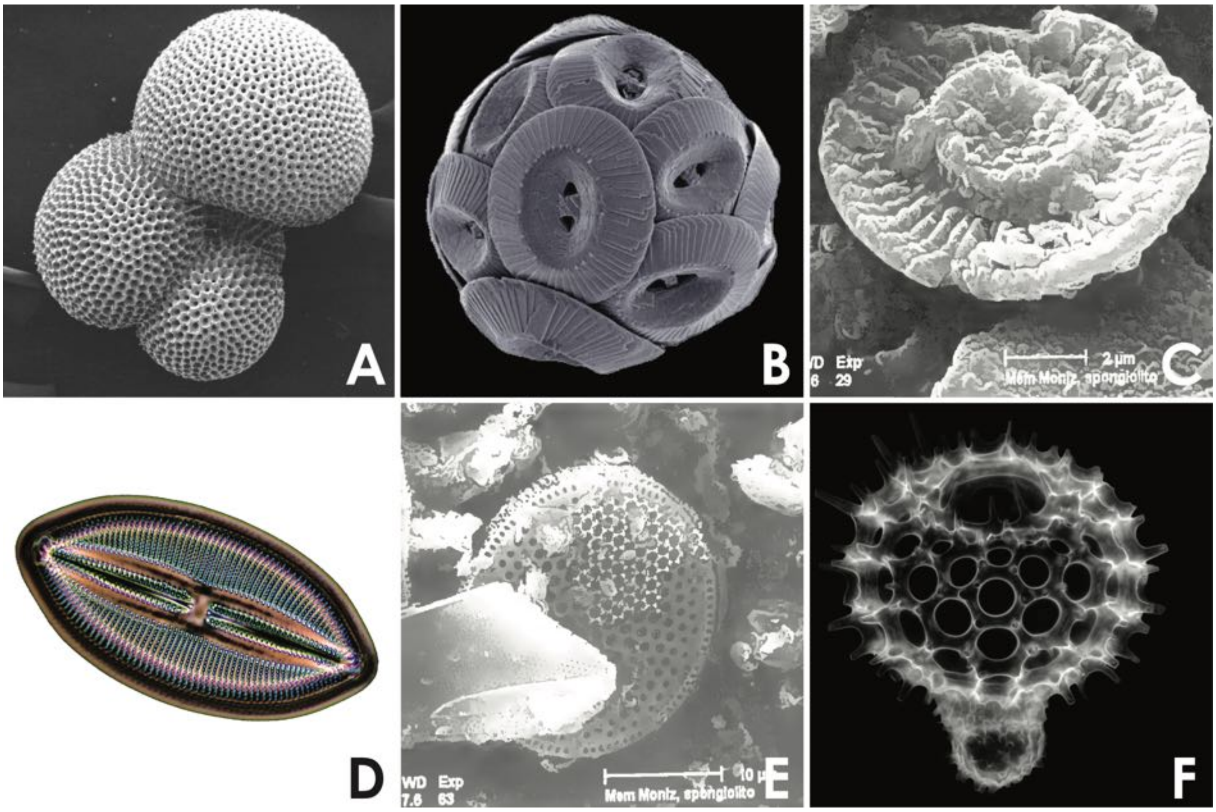


Figure 3.5. Examples of microorganisms that are part of ocean oozes. Carbonate oozes: A: Foraminifera *Globigerin*; B: Coccolithophorid, *Coccolithus pelagicus*; C: *Coccolithus miopelagicu*s from the Mem Moniz Spongoliths Formation. Siliceous oozes: D: *Lyrella hennedy* diatom (1500 magnification); E: Diatom from the Mem Moniz Formation; F: *Calocycloma* sp. radiolarian

3.2. Continental Shelves

The continental shelves are the shallowest areas of marine basins. They extend from the line reached by the equinoctial low tide to the shelf break towards the continental slope (see Figure 3.2), which typically occurs at a depth of 140–200 meters. The world average width of continental shelves is 75 kilometers. However, there are deviations from these average dimensions. For example, in the Antartic continental shelf, the shelf break towards the continental slope occurs at 300 – 400 meters, due to the load exerted by the ice cap.

According to the dominant type of sediment covering the continental shelf, it is called siliciclastic or carbonate. The predominant sedimentation in a siliciclastic continental shelf is terrigenous (minerals and rock fragments), while in a carbonate continental shelf it is carbonate (calcium carbonate).

The continental shelves can alternately be siliciclastic and carbonate, depending on climatic conditions. They are siliciclastic when the climate is humid enough to cause changes and erosion on the continental areas. The solid load of the river that reaches the coast during the humid phases is higher than during the dry climatic periods. The abundance of terrigenous sediments inhibits biological productivity and, therefore, the formation of carbonates.

The thickness of the sediments on the continental shelves depends on their morphology, the amount of sediments available, the energy of the waves and currents that disperse the sediments, and the tectonic context.

Tectonics controls the space available to accomodate the sediments. The space in a given location may increase due to subsidence or, on the contrary, reduce due to uplift. These processes are local and generate sedimentation sub-basins, as happened during the Jurassic in the Algarve Basin, where two sub-basins were formed, one to the west and the other to the east, separated by the structural high of Budens-Lagoa/Algoz. The eastern subbasin, between Lagoa and Tavira, was markedly subsident throughout the Jurassic, generating sedimentary sequences hundreds of meters thick.

It is thanks to subsidence that the thickness of the sediments accumulated on a continental shelf can exceed the depth of the water column, without the basin becoming extinct. Since the depth of water over the shelf varies on average from 140 to 200 meters, only the sinking of the seabed (subsidence) can justify that sediments continue to accumulate and reach several hundred meters in high in a relatively constant environment, as demonstrated by the paleoecology of fossil organisms.

The energy of waves and currents is also one of the parameters that influence the thickness of the sedimentary cover on the continental shelves. At present, to the north of the Nazaré Canyon, the Portuguese continental shelf receives the contribution of numerous rivers. However, since the energy of the waves and currents is high and the dispersion of sediments exceeds the supply, the sediment cover is not very thick. By contrast, despite having little fluvial contribution, the less energetic continental shelf of the Algarve maintains a thick sedimentary cover.

Once deposited, the sediments suffer a series of physical and chemical transformations (diagenesis) and are transformed into sedimentary rocks. Similar to the classification of the sediments, the sedimentary rocks that resulted from them are called terrigenous or clastic, bioclastic and chemical.

Limestones are the most common chemical rocks in the world. They are formed by precipitation of calcium carbonate (calcite-$CaCO_3$) from sea water. Magnesium (Mg) sometimes replaces the calcium (Ca) in calcite crystals to form the dolomite mineral, which is a double carbonate of calcium and magnesium, [$CaMg(CO_3)_2$]. The genesis of limestone constitutes the biggest carbon sink, playing a fundamental role in the carbon cycle and, therefore, in the climate. The precipitation of calcite from water may be inorganic, but it is mainly the result of biological activity. More than 90% of the world's limestone is of biochemical origin, that is, it resulted from calcite precipitation mediated by metabolic processes. That is why limestones can be classified as biochemical rocks.
The sedimentary rocks generated in the ocean usually have abundant fossils (macro and micro), which are used as paleo-environmental indicators, that is, they allow inferences to be made about past ecosystems. This paleoecological reconstruction is based on the “Principle of Uniformitarianism” or “Actual Causes”, a theory according to which the present is the key to the past. This theory was formulated by James Hutton (1726 - 1797), often referred to as the “founder of modern geology”. James Hutton (see Figure 1.4), a Scottish farmer and naturalist, was a keen observer of rocks, their structures and

the processes that shape the landscape. For example, he explained that the crabs that prey on bivalves and gastropods from the Indo-Pacific have more robust pincers than their Atlantic relatives because their prey also have more robust shells since the precipitation of calcium carbonate in hot water is facilitated. This knowledge of current ecology is transposed to paleoecology, by assuming that there is a direct causal relationship between the characteristics of preys and that of predators, as it happens today.

3.2.1 Siliciclastic continental shelves

On the siliciclastic continental shelves, which are greatly influenced by sediments coming from adjacent continental masses, minerals and rock fragments accumulate. The rock fragments came from the erosion of rock formations exposed to the action of transforming agents on the Earth's surface: rain, ice, wind, temperature and living beings. The terrigenous sediments are mixed with the remains of organisms, are then dispersed by waves and currents, and can even be transferred to greater depths by sliding along the continental slope (see Figure 3.2). As the name indicates, sediments composed of silica, such as quartz, predominate in siliciclastic shelves.

Quartz (Figure 3.6 F), which is a silicate (SiO_2), is a ubiquitous mineral that occurs in almost all rocks in the Earth's crust, with the exception of ultra basic rocks, which are very rich in iron (Fe) and magnesium (Mg) and have less than 45% SiO2. As an example, peridotite (Figure 3.6 B) is an ultra basic rock, being in some cases composed solely of olivine, which is a ferromagnesian mineral (Figure 3.6 A). Monchique The nepheline syenite from Monchique (Figure 3.6 C) is a basic rock in which quartz is absent.

Quartz is a very resistant mineral, and that, together with its abundance, makes it the most common mineral on beaches and siliciclastic shelves around the world (Figure 3.6 D). The feldspars, a group of minerals also very abundant in the rocks of the Earth's crust, are, however, very vulnerable and hardly resist being dissolved. The fact that we refer to feldspars in the plural form, instead of the singular form used for quartz, means that they form a group whose composition varies (within certain limits), although they do not lose their common characteristics of composition and structure. For example, we speak about potassium feldspar, sodium feldspar and calcium feldspar. Many other minerals (Figure 3.6 G, H and I), more or less resistant, contribute to the sedimentary cover of siliciclastic shelves, but it is quartz that predominates. The presence of mineral grains less resistant to alteration, such as olivine, garnet, mica and pyroxene, depends on the occurrence of parent rocks nearby. The volcanic rock cliffs of the Azores throw onto the beaches these minerals on a daily basis (Figure 3.6 E). Since these minerals were originated in hot and high pressure environments inside the Earth, very different from surface conditions, they are very vulnerable to chemical weathering. However, that does not mean that they are soft minerals.

Figure 3.6. A: Olivine crystal; B: Peridotite. The green color results from the high amount of olivine; C: Syenite nepheline from Monchique, a basic rock of peculiar composition, unique in the world; D: Praia da Galé, Algarve, where the predominant mineral is quartz; E: Praia de Monte Velho, Azores. Left in the background, a cliff carved in basalt, a volcanic rock; F: Crystals of several varieties of quartz; G: Ferromagnesian minerals from the volcanic island of Fogo, Cape Verde; H: Sand from Búzios, Brazil, photographed under a microscope. The pink minerals are garnets; I: Sand from the Reunion Island photographed under a microscope. The green minerals are olivine.

3.2.2 Carbonate continental shelves

On carbonate continental shelves, the sediments are mostly biogenic (of biological origin), resulting from the accumulation of skeletal parts of organisms, such as shells of bivalves and gastropods, sponge spicules, spicules and fragments of shell of sea urchins, foraminifera tests and coral fragments, among many other elements of a biological nature. Carbonate platforms occur in regions of the globe where the environmental parameters favor the precipitation of calcium carbonate.

An example of carbonate shelves are those where reef buildups settled in. These buildups are composed of different species of coral and other sessile organisms that build carbonate external skeletons, such as crinoids (sea lilies), sponges, rudists and even microorganisms. These are extraordinary and complex ecosystems whose development is limited by factors like the turbidity (transparency), the temperature and the acidity of the water.

Examples of modern carbonate shelves are the Great Barrier Reef of Australia, the atoll of Belize (Central America), the coral banks of the Bahamas (Central America), and the reefs of Papua New Guinea (Figure 3.7).

All these regions have something in common: they are on the western margins of the oceans, do not receive important sedimentary input from rivers, and are located on the tropical zone of warm surface waters (Figure 3.8). Its location on the western part of the oceans is due to the oceanic circulation on the surface, which transports warm water from east to west. To compensate for the water that traveled west pushed by the wind, the cold water from the deeper layers of the ocean (upwelling currents or coastal outcrops) rises. The areas with coastal outcrops are of high biological productivity, because the cold water coming from the deep ocean is very rich in nutrients, namely silica, nitrates and phosphates.

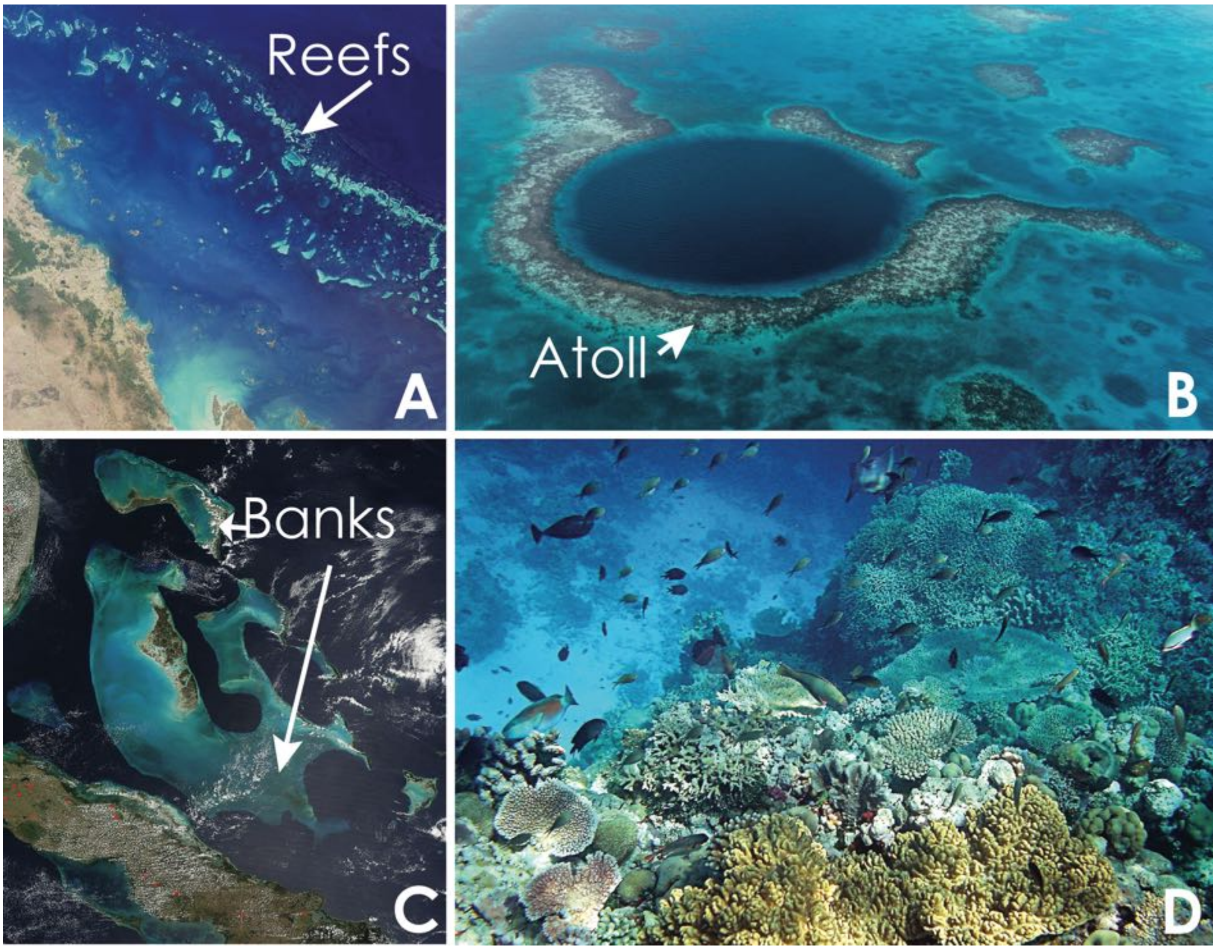


Figure 3.7. A: Australian Great Barrier Reef; B: Belize atoll; C: Bahamas coral reef banks; D: coral reef in Papua New Guinea.

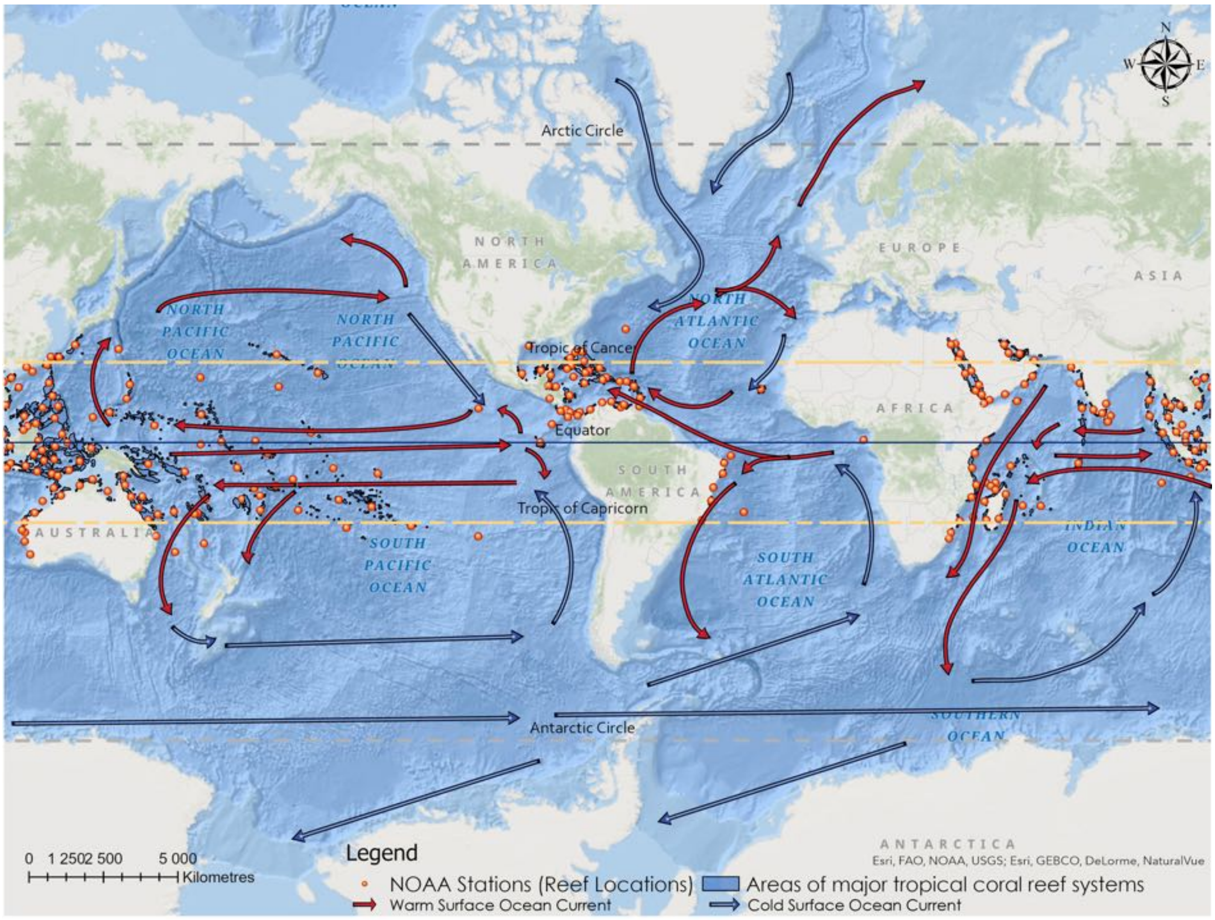


Figure 3.8. A: Australian Great Barrier Reef; B: Belize atoll; C: Bahamas coral banks; D: Papua New Guinea coral reef.

These regions provide more than 20% to the world's marine fish catch. However, they are not regions that favor the precipitation of calcium carbonate, due to the low temperature and the high turbidity.

Ocean water contains sixty times more carbon dioxide (CO_2) than the atmosphere, and this gas dissolves more easily in cold water than in hot water. Since it has more CO_2 dissolved, the cold water is more acidic than hot water and, consequently, is able to dissolve calcium carbonate better. On the contrary, precipitation of this compound from sea water is favored in warm water. It is for this reason that the shells of bivalves and gastropods from warm waters are more exuberantly ornate than the specimens from cold waters (Figure 3.9).

Another factor that limits the distribution of reef formations is the transparency of the water. Corals live in symbiosis with photosynthetic algae (Zooxantellae), which require transparent water for the sunlight to penetrate. These algae live in the tissues of animals and capture the carbon dioxide dissolved in the water to produce photosynthesis. The result is that the water becomes less acidic and favors the precipitation of calcium carbonate. That is why reefs do not form on continental platforms into which rivers laden with sediments flow turning the water very turbid. That is the case, even if they are located in

Figure 3.9. Well ornate and colorful shells characteristic of warm waters (left) and coral fragment (right).

the tropical zone, like the oceanic area adjacent to the estuary of the Amazon River.

Hermatypic corals, that is, corals that build large reef formations, are colonial organisms that live within the photic zone of clear waters with temperatures that do not fall below 20°C. But only about half of the reef formation is solid matter. The other half is composed of water-filled pores, various organisms such as algae and sponges, and fragments of the skeletons of all inhabitants of the reef, including the corals themselves. Many of these fragments result from the predatory activity of fish, crustaceans and sponges. They disintegrate into increasingly finer particles until reaching a size of less than or equal to four micrometers (a micrometer is equal to one thousandth of a millimeter). This very fine carbonate sediment is called "micritic mud". The bioclasts (fragments of biological origin – Figure 3.10 A, B, C and B), resulting from the breakdown of the reef (bioherm) accumulate on its periphery and their set is called "biostroma"

One thing that is a surprise on the Escarpão Plateau is the vast area covered by fragments of reef buildup forming real reef breccia (Figure 3.10 E, F and G), when compared with the scarce amount of bioherms (not yet identified as such).

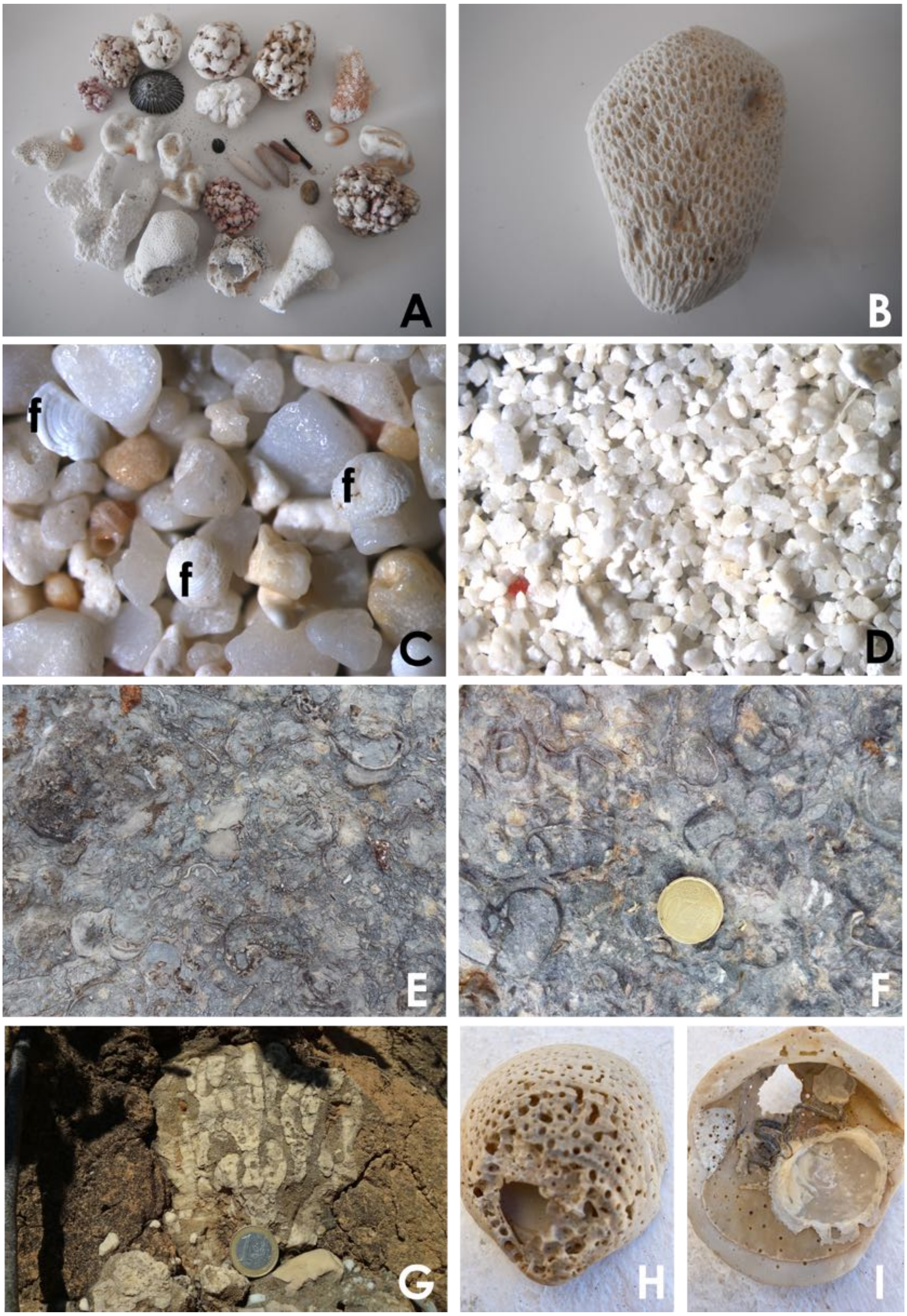


Figure 3.10. A: Gastropods and sea urchin spicules; B: Coral fragment; C: Sand from a Cuban beach, consisting of quartz grains and bioclasts (foraminifera); D: Sand from a beach in the Maldives, entirely bioclastic; E and F: Reef breccia, with fragments of stromatoporoids, sponges and rudists (Escarpão Formation); G: Coral fossil (Escarpão Formation); H: Shell of present-day bivalve with intense bioperforation, an indication it will break easy; I: Ventral face of the same H shell, showing that it served as substrate for the attachment of other organisms. For this reason, identification of fossils is not always easy.

3.3. Morphology of carbonate shelves

In sections 3.2.1 and 3.2.2, the continental shelves were distinguished according to the type of sediment they are covered with. In this section, the carbonate shelves are described in terms of their morphology (shape) and hydrodynamics (waves, tides and currents). We will pay special attention to these type of shelves, because, as a whole, the Escarpão Plateau is a carbonate paleoshelf from the Late Jurassic.

3.3.1 Neritic domain

Depending on the morphology, carbonate shelves can be classified as ramps, rimmed, epeiric, isolated and drowned. In the case of ramps, the gradient of the slope is low, less than 0.1º, and the processes are similar to those of an open continental shelf. They include debris deposition, that is, a mixture of lithogenic and biogenic materials. For this reason, large reef buildings do not develop (see Section 3.2.2). When carbonate ramps have a constant slope, they are called homoclines. Rimmed platforms (e.g., continental shelf of Florida and Belize) are steeper than ramps and reefs develop on the edge of the continental shelf, which protect a lagoon on the continental side from being directly attacked by the waves. Epeiric carbonate shelves (e.g., Murray Basin in South Australia) are generally extensive, are subject to accumulation of carbonate sediments, and have several low-tide terraces and lagoons. Isolated shelves owe their name to the fact that they are separated from continental influence by some sort of structure. An example of an isolated carbonate shelf is the Bahamas, where reef banks are isolated from continental detrital influence by a deep channel. Drowned carbonate shelves are located in subsidence regions and, as a consequence, the reef will perish as it gets below the photic zone (sunlight penetration zone). For this reason, carbonate production on carbonate shelves is sensitive to seabed subsidence.

According to the hydrodynamic factors that control the distribution of sediments (Figure 3.11), carbonate ramps are subdivided into: (i) inner ramp: the sedimentation is coastal, including beach face deposits, sand banks and intertidal deposits. The regime of tides plays an important role in the architecture of the inner ramp sedimentary facies; (ii) middle ramp: affected by storms, with sediment remobilization and subsequent redeposition. Positive gradation and cross-stratification are characteristic aspects of the sedimentary facies of this zone of the shelf. When the sediments are agitated by the waves, they are deposited again during a calmer period, from the heaviest to the thinnest in succession. This arrangement of the grains, with the coarsest at the bottom and the finest at the top, is called positive gradation; (iii) outer ramp: only activated by high magnitude storms or possibly tsunami.

However, in rare cases tempestities can occur, which are deposits resulting from the remobilization of the sediment by great power waves. In these highly energetic events, including tsunami, lithoclasts (rock and mineral fragments) and fragments of different organisms originating from the middle and inner ramps can be transported to these areas of the outer ramp and basin (Figure 3.11). On the basin, the sedimentary deposits show no evidence of remobilization. Here, the deposition can be siliciclastic (mainly quartz), while simultaneously in the shallower areas of the ramps, within the photic zone, the sedimentation is carbonate.

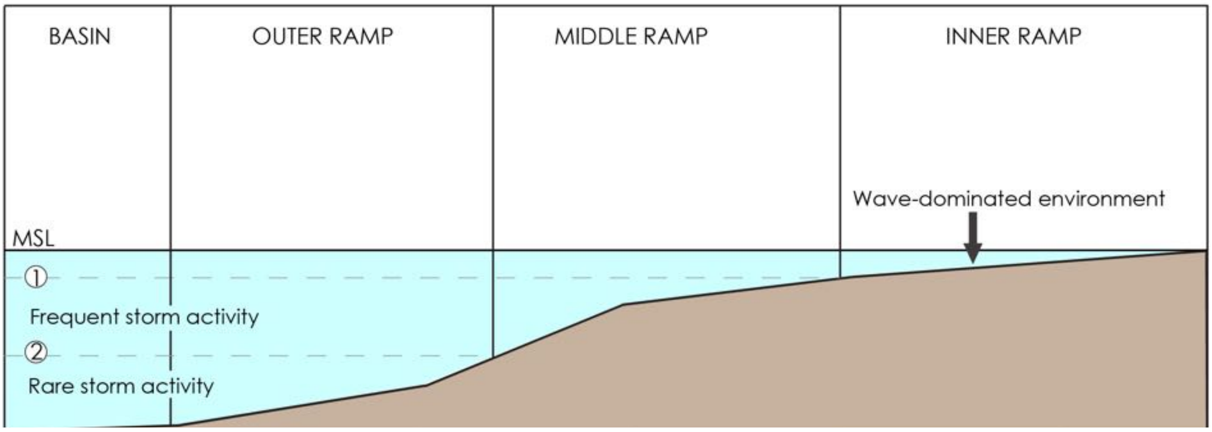


Figure 3.11. Schematic representation of a homoclinal carbonate ramp and its subdivisions. MSL: mean sea level; 1: base level of low energy waves; 2: base level of very high energy waves.

3.3.2. Pelagic domain

The pelagic domain corresponds to the mass of oceanic water inhabited by organisms that do not depend on the seabed, such as fish, squid, dolphins and various microorganisms, among many others.

Ammonites and belemnites were pelagic cephalopods that were abundant in the Jurassic Ocean, just as the squid and cuttlefish, their relatives, are abundant today. Ammonites have descendants that still live in the Indo-Pacific, although they are considered "living fossils" to highlight their rarity: the nautiloids (Figure 3.12). Judging by their morphology, ammonites were slow-moving and lived in poorly oxygenated environments to hide from predators. Belemnites seem to have been faster than ammonites, but some were probably as slow as modern cuttlefish.

From the Mesozoic onwards, mainly in the Late Jurassic and Cretaceous, the microorganisms that make up phytoplankton (dinoflagellates, collithophorids and diatoms – see figure 3.13) replaced the eukaryotic green algae (with nuclear membrane) as the predominant organisms living in the photic zone of marine environments.

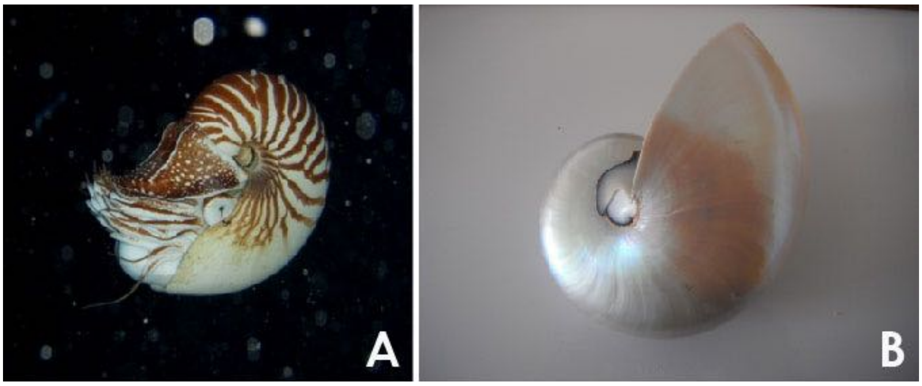


Figure 3.12. Nautiloids – cephalopod molluscs, characterized by a large external shell. A: *Nautilus macromphalus*; B: Nautiloid shell.

This massive development of phytoplankton is known as the "Mesozoic Phytoplankton Revolution". Alongside this development, the zooplankton (feed on phytoplankton), composed of radiolaria, foraminifera and tintinids (see Figure 3.13), diversified from pre-existing forms and new species emerged.

The fossil plankton preserved in limestone deposited on the Jurassic continental shelves points to the existence of two moments of intense productivity in the Central Atlantic Ocean. The first one was in the Tithonian (end of the Late Jurassic, ca. 145 million years) and second, in the Cenomanian (base of the Late Cretaceous, 100.5 – 93.9 million years) (Figure 3.13).

While dinosaurs diversified after the dramatic mass extinction at the end of the Triassic and developed their activities in coastal areas, lagoons, lakes and forests, in the ocean, benthic invertebrates, such as gastropods, bivalves and cephalopods, also underwent significant changes in their evolution during the so-called "Mesozoic Phytoplankton Revolution", probably as a result of changes in food webs.

The fossil record has strong evidences of increased predation throughout the Mesozoic. In order to defend themselves against predators, marine invertebrates adapted their morphology and conquered new habitats, either by developing spines or thickening their shells or by burying in the sediment. Fossils of ammonites and crinoids show unmistakable marks of predation.

The proliferation of calcareous plankton in two moments of the Mesozoic Era (Tithonian and Cenomanian) resulted in the shift of calcium carbonate precipitation from shallow environments to deeper environments in marine basins. This happened because, in addition to temperature and salinity, biological productivity is also important for the rate of carbonate production. This alteration in the distribution of carbonate sediment production had consequences for the global carbon cycle and, therefore, for the climate.

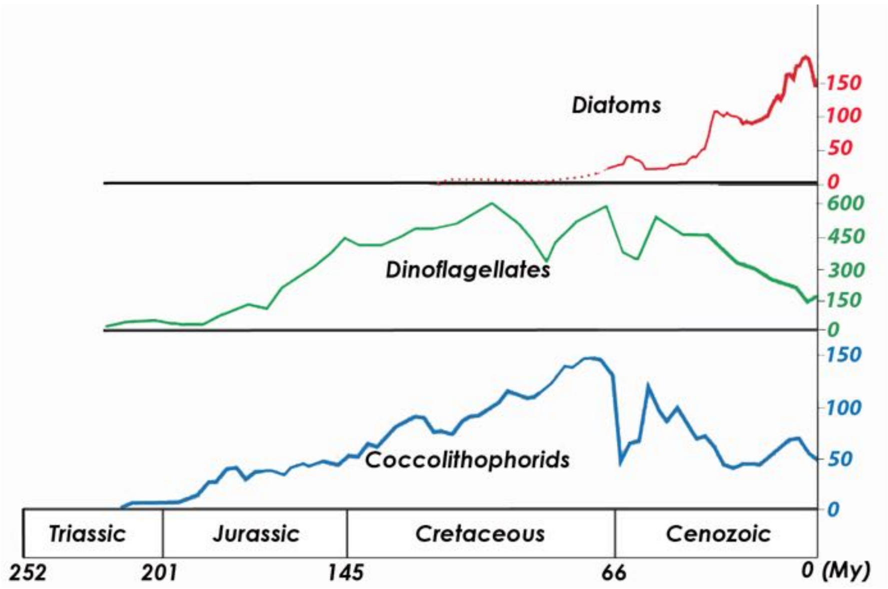


Figure 3.13. Development in the number of phytoplankton species during the Mesozoic and Cenozoic (see the chronostratigraphic chart in Figure 1.1). Horizontal axis: Ma = millions of years. Vertical axis: number of species.

CHAPTER 4
ESCARPÃO PLATEAU – A WINDOW WITH VIEW TO THE JURASSIC OCEAN

4.1. Escarpão Plateau

Plateau is an elevated landform with a flat surface. What differentiates the plateau from the plain (flat surface) is that in plateaus the streams and rivers run embedded in the substrate, while in plains they run at the surface.

At the centre of Barrocal of Algarve, in the extreme north of the territory that belongs to the Municipality of Albufeira, there is a plateau that rises to about 130 meters (Figure 4.1). Its name is Escarpão

The Portuguese name "escarpão" refers to a cliff with an impressive size. And it is indeed impressive. The Quarteira stream carved its valley deeply into the pile of rocks from the Late Jurassic that are the physical support of the Escarpão Plateau (Figure 4.2 A and B). That is why we feel we are "diving" more and more into time and into the depths of the Jurassic ocean (Figure 4.2 C) when we descend from the top of the Plateau and go down the steep slopes of the valley of the Quarteira stream.

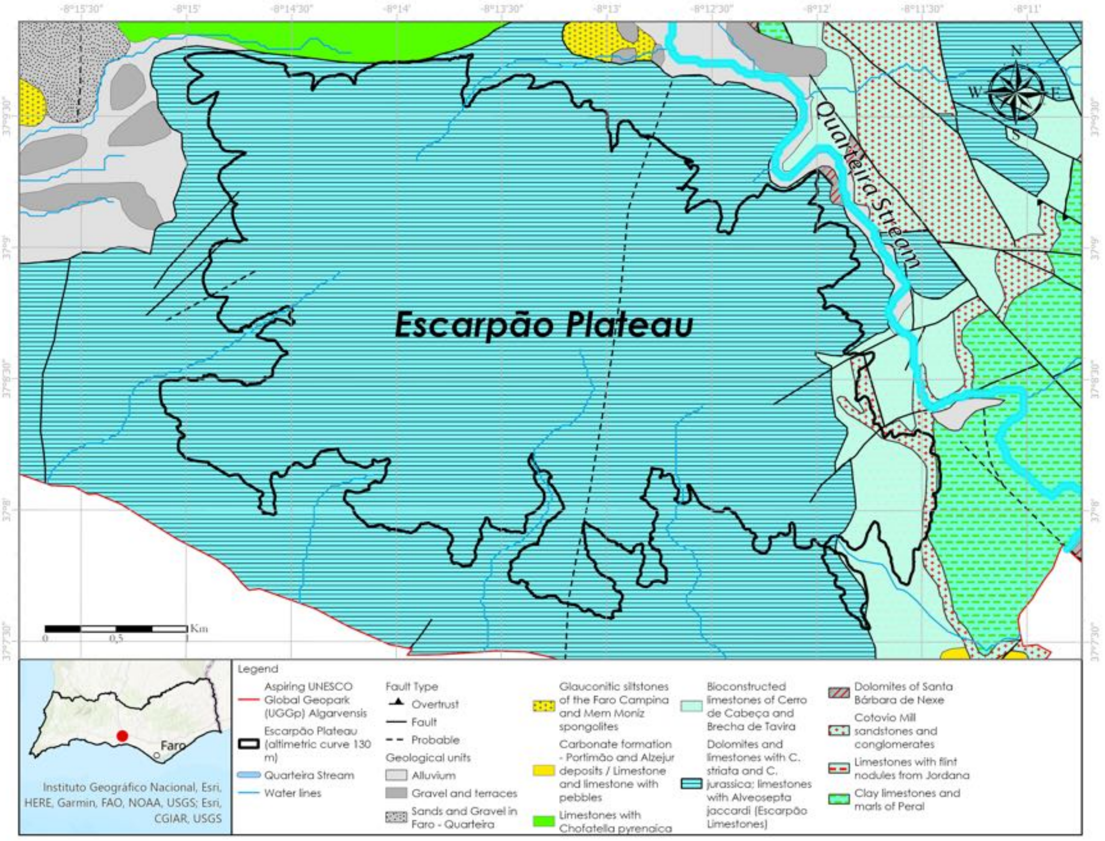


Figure 4.1. Location and geology of the Escarpão Plateau.

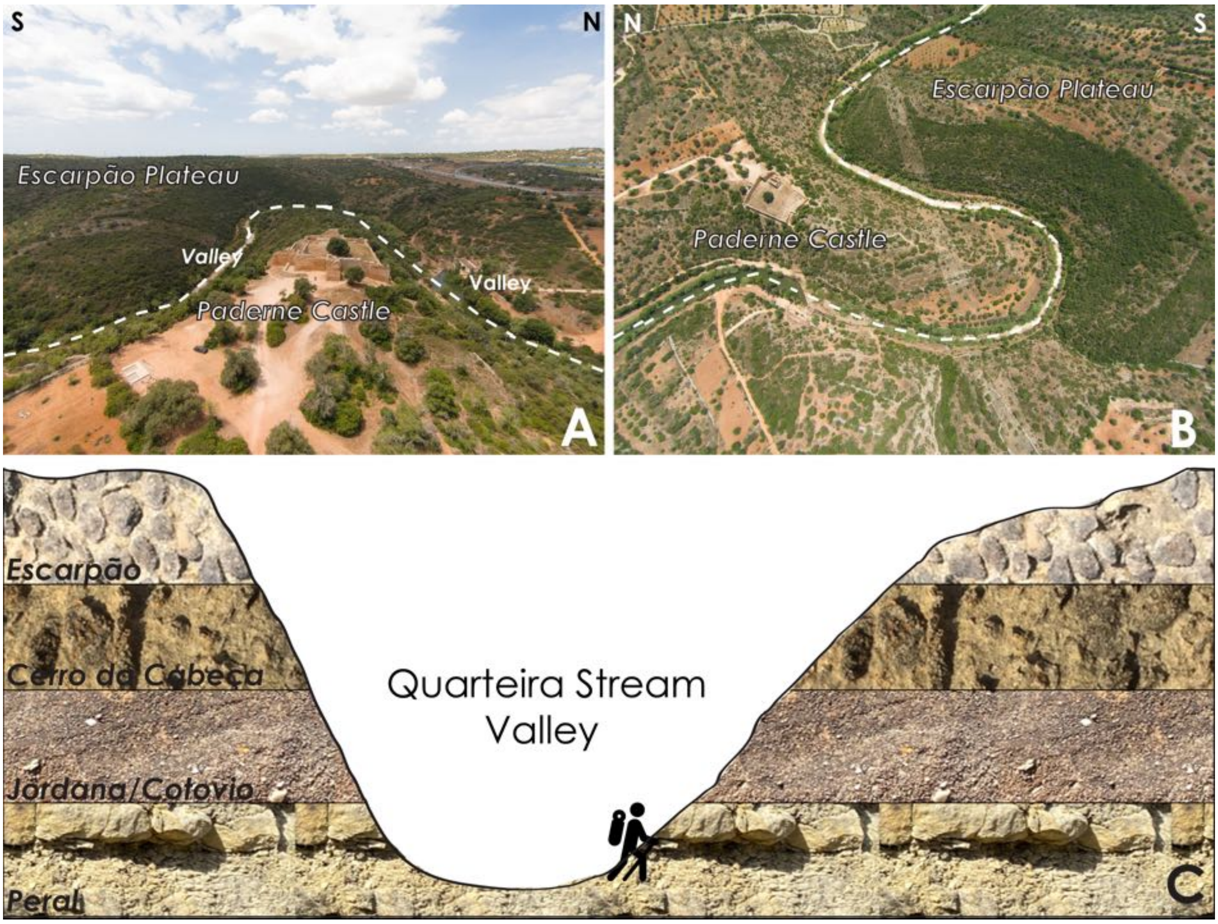


Figure 4.2. A and B: Photographs of the Escarpão Plateau centered on Paderne Castle embraced by the Quarteira stream meander (curve). C: Schema (without scale) of the stratigraphy of the geological formations on the Escarpão Plateau and the way they are intersected by the valley of the Quarteira stream.

The Escarpão Plateau offers the possibility of observing and studying the most complete Late Jurassic sedimentary sequence in Eastern Algarve (Figure 4.3). There are five geological formations exposed on the Escarpão Plateau (Figures 4.2 and 4.3). From the oldest (therefore, at the bottom of the valley) to the most recent (at the top of the Plateau), these formations are: Peral Formation, Jordana Formation, Cerro da Cabeça Formation, Escarpão Formation and Limestone Formation with Anchispirocyclina lusitanica (foraminiferous).

Formation is a geological entity large enough to be mapped that, due to its lithological, paleontological and structural characteristics, can be distinguished from adjacent units and bears witness to the environment where it was formed. It is important to mention here that the tectonic behavior of the Algarve Basin throughout the Jurassic, with the individualization of two sub-basins, makes it difficult to establish a correlation between the Formations of the western sub-basin and those of the eastern sub-basin, separated by the structural high Budens - Lagoa/Algoz (elevated surface due to tectonic movement).

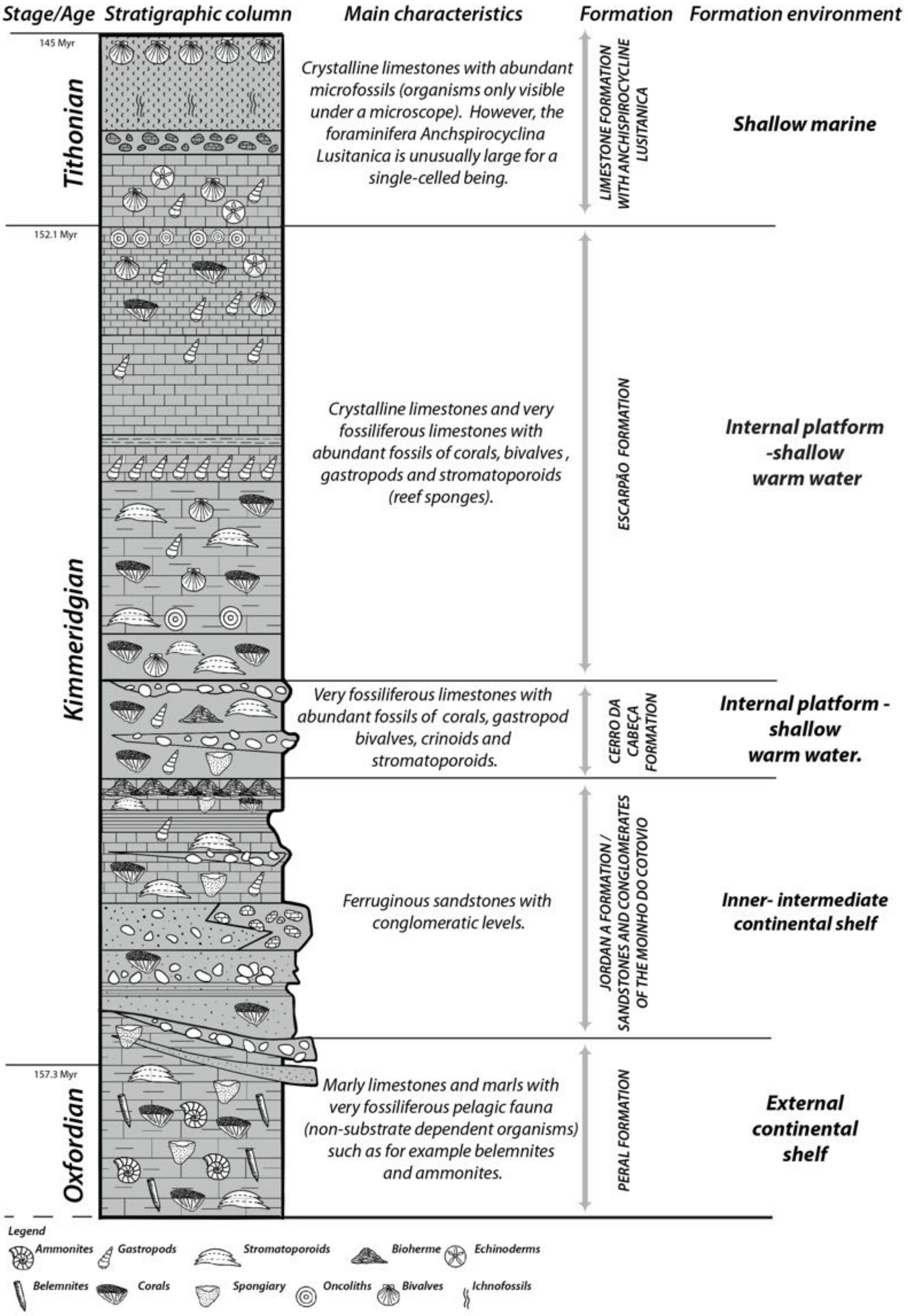


Figure 4.3. Lithostratigraphic column of the geological formations that constitute the physical substrate of the Escarpão Plateau.

In the west, the deposition took place mainly in deep water, while, in the east (Lagoa/Algoz – Tavira), the deposition took place in the domain of the continental shelf. This eastern sub-basin alternately underwent subsidence and uplift, which, along with marine transgressions and regressions, resulted in a profusion of different sedimentary facies. For this reason, it is not always easy to understand the geometric relationships between the Formations.

This architecture of the sedimentary facies organized into sub-basins is not just an attribute of the Algarve Basin. A rifting phase (extensional tectonics) that occurred in the Late Jurassic, between the end of the Oxfordian and the beginning of the Kimmeridgian, in the Lusitanian Basin (western region between Aveiro and Cape Espichel) led to the formation of several sub-basins filled with sediments in different environments, as palynofacies (pollen associations) and other fossil organisms indicate.

Based on fossils, composition and sedimentary figures, five formations were identified on the Escarpão Plateau, which are characterized below from the oldest to the most recent.

4.2. Peral formation

The Peral Formation exposed on the Escarpão Plateau is composed mainly of sequences of marl and marl limestone with frequent fossils of ammonites and belemnites (cephalopods – Figures 4.4 and 4.5) and also layers of micritic limestone (limestone formed almost entirely by small crystals of calcite with 4 to 31 micrometers). Some layers contain stromatolite structures. The microfossiliferous content includes some pelagic organisms, such as coccolithophores and dinoflagellates (Figure 4.5).

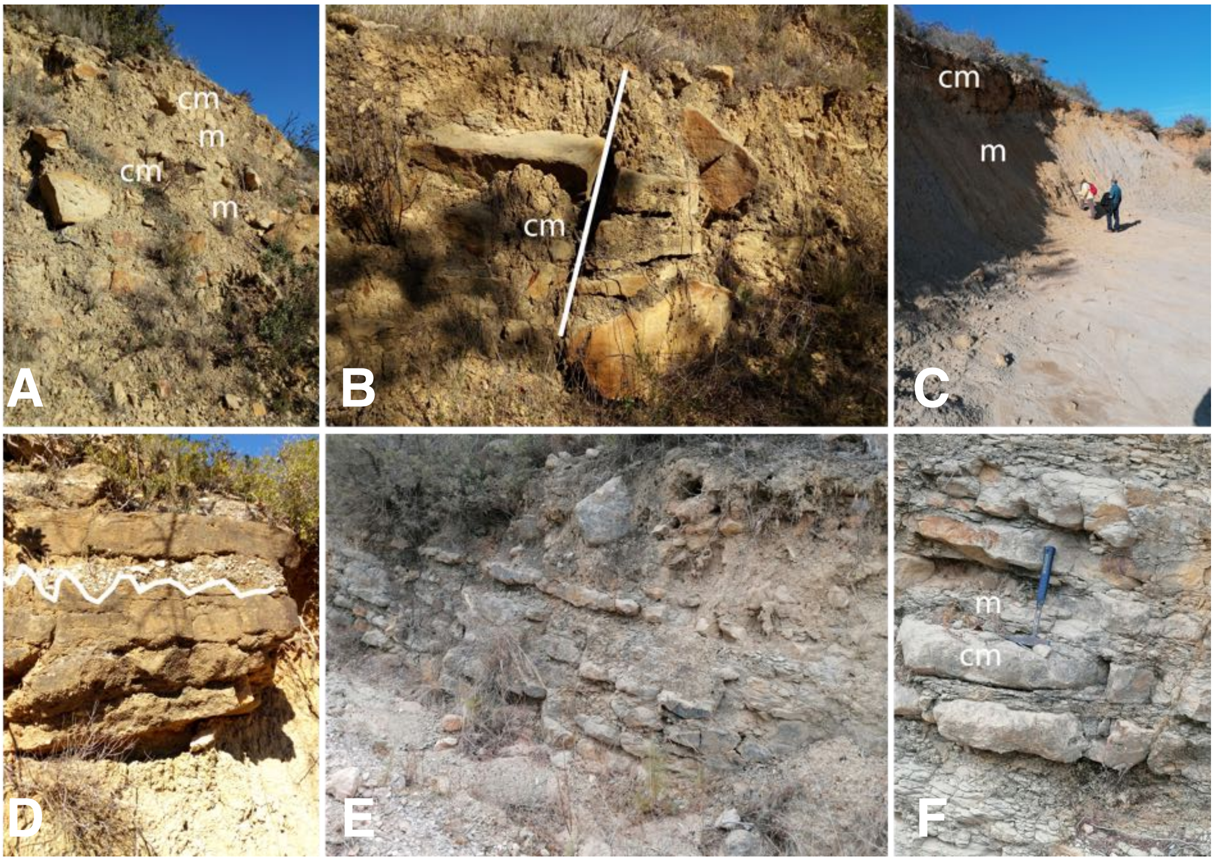


Figure 4.4. Field photographs of the Peral Formation, showing the succession between marls (m), some with foliation (photographs E and F) and marl limestones (cm). In B, a fault displacing the layers (white line). In photograph D, a clastic deposit of pebbles with erosive contact over the lower layer, evidenced by the white line.

Figure 4.5 Fossils found on the Peral Formation. A – F: Ammonite molds; G and H: Belemnite rostrum; I: Iron crusts associated with microbial activity.

The lithological and paleontological characteristics of the Peral Formation are compatible with pelagic and hemipelagic deposition in the outer ramp and in the basin (see Figure 3.11). Occasionally, there are clastic and bioclast deposits that came from the shallower zones of the ramp, which show transport, probably as a result of storms (Figure 4.6).

Although in general the characteristics of the Peral Formation are indicators of carbonate ramp deposition in the external domains and basin, there are also facies characteristic of a shallower environment. The layers of micritic limestone interspersed with marls and marly limestones reveal an association of benthic foraminifera compatible with a middle platform, the photic zone, where they occupied various habitats and niches. Some of them are encrusting forms, such as the *Subdelloidina* sp., which colonizes the upper part of bioclasts larger than 2 millimeters because it gives them some substrate stability. Other encrusting species, such as the *Nubecularia* sp. and *Bullopora irregulares*, used ammonite shells to fasten to by excreting calcium carbonate, which works as a binding cement. *Tolypammina* sp. forms were observed associated with ferromanganese crusts and nodules. Other species such as *Placopsilina* sp. and *Nautiloculina oolithica* lived fixed or attached to the skeletons of dead sponges in sponge reefs, adapted to the constant flow of detritus.

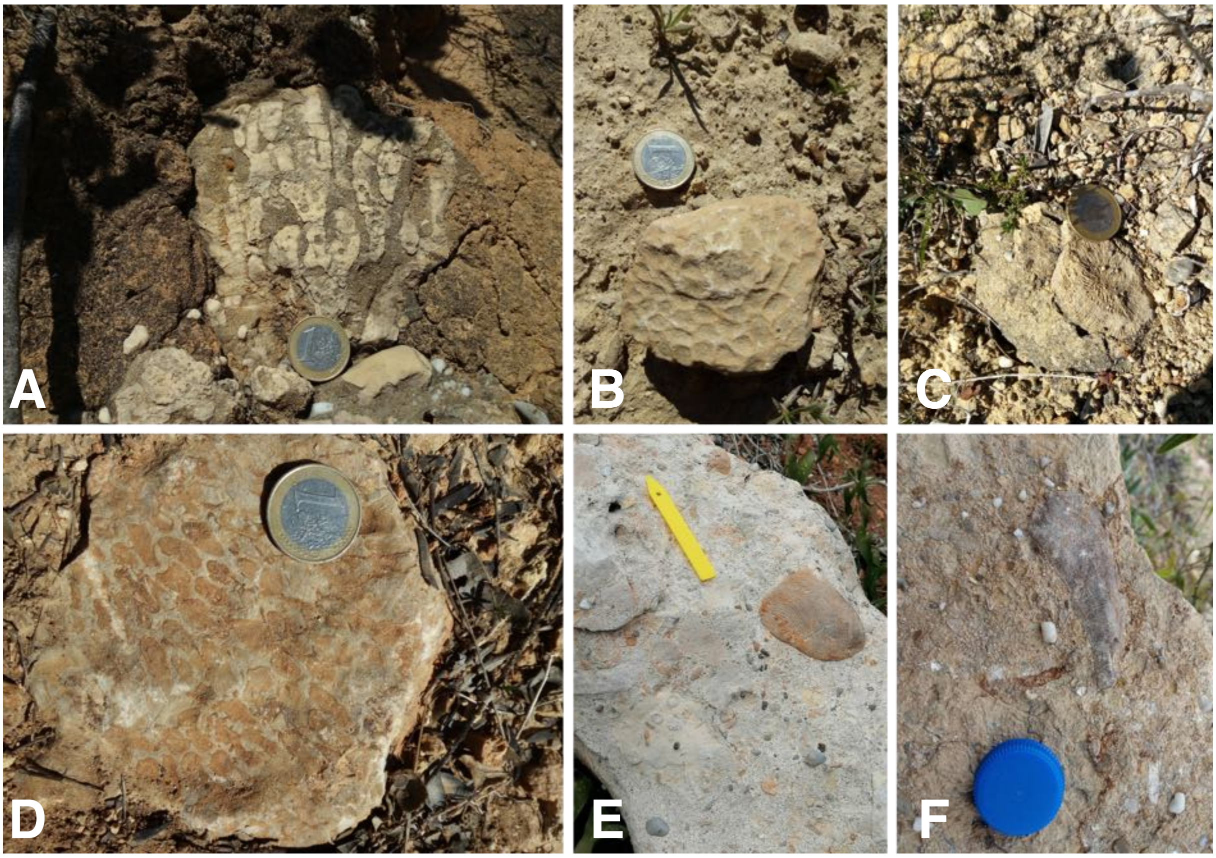


Figure 4.6. Bioclasts that occur in the marls of the Peral Formation and were remobilized from the middle or inner ramp. A, B, C and D: Coral fragments; E and F: Mixture of elements detritus elements and fragments of stromatoporoids.

It is now accepted that the form *Tubyphytes morronensis* occurred in a symbiotic coexistence between foraminifera and microbial crusts.

According to the microfossil content, it is necessary to admit that the Peral Formation represents an alternation between more and less deep environments of a carbonate ramp, that is, it consists of rows of pelagic, hemipelagic and even neritic facies. This architecture of sedimentary facies can be explained by variations in the mean sea level, by tectonic movements with successive subsidence and uplift, and even by the combination of the two processes.

4.3. Jordana Formation. Cotovio sandstones and conglomerates

As mentioned in section 4.1, in Eastern Algarve, the architecture of the sedimentary facies in the Late Jurassic is not always easy to understand. This difficulty is due to successive transgressions (sea level rise) and regressions (sea level fall) that, combined with tectonic movements, created distinct, albeit contemporary, sedimentary environments. These different deposits were sometimes assumed to be distinct formations and, other times, lateral variations of facies within the same geological formation. These doubts arise due to the absence of fossils of age (see Chapter 1) that would allow to established temporal correlations between the deposits. An example of this the unit referred to as "Arenitos e Conglomerados do Moinho do Cotovio" (Sandstones and Conglomerates of Moinho do Cotovio). The 1/100 000 scale geological map (eastern sheet) assigns it the status of Formation. In this same geological map, the Jordana Formation is not marked as described by Choffat (1883-87), Marques (1983) and Ramalho (2015). The Jordana Formation passes alongside the Sandstones and Conglomerates of Moinho do Cotovio (Oliveira, 1984, 1992; Manuppella et al., 1987) and the limestones with silicified fossils of Foupana (Marques, 1983; 1985).

The silicification of fossils (that is, the partial or total replacement of calcium carbonate by silica) has been attributed to increase in the alkalinity (pH>7) of sea water. This increase in alkalinity could have resulted from the ammonia released by the decomposition of organic matter. The dissolution rate of silica is low, although constant, but it increases very significantly when the pH of the water rises above eight (alkaline water). Therefore, in this type of environment, the silica from the very abundant reefs of siliceous sponges dissolved on a large scale, becoming available for later precipitation inside the dead organisms, which is a common type of fossilization.

Sponges are common on reefs. However, the Jordana Formation at the Escarpão Plateau is of a detritus nature, and further east, in the Tavira region, this aspect of the silicification of fossils can be observed in the silicified limestones of Foupana, lateral equivalents of the Jordana Formation. In order to better understand what lateral variations in sedimentary facies are, let's call the current examples of deposit formation, which, although contemporary, are very different. While on the estuary of a river fine sediments rich in organic matter are deposited, on the adjacent oceanic beaches, the sediments are mainly sandy quartz. And, a little further away, out in the sea, the deposits are finer and rich in shell fragments.

The Jordana Formation, attributed to the base of the Kimmeridgian (see Figure 1.1), overlaps the Peral Formation (Figure 4.7 A) and exposes reddish-colored sandstones due to the iron content. The contact between these formations is marked by conglomeratic levels (Figure 4.7 B, C), which also occur in sandstones, and scattered quartz pebbles (Figure 4.7 D).

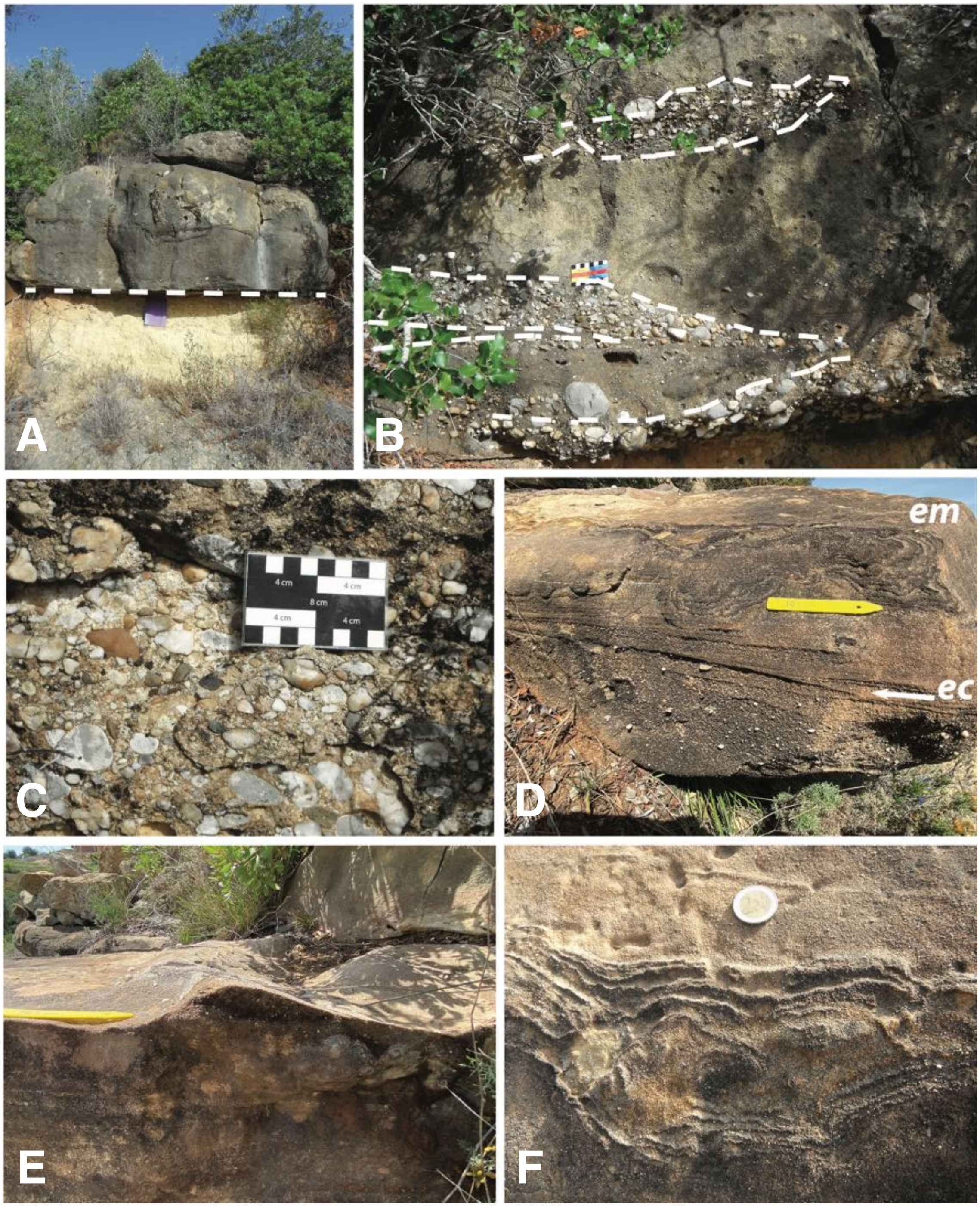


Figure 4.7. Field photographs illustrating aspects of the Jordana Formation. A: Contact between the formations of Peral (P) and Jordana (J); B: Cross-bedding in the Jordana Formation and basal conglomerate (the larger side of the colored scale is 8 centimeters); C: Detail of the conglomerate in the transition from the Peral Formation to the Jordana Formation; D: Cross-bedding (ec) in the Peral Formation sandstones and microbial structures (em); E: Waves of sand (ripple marks); F: Elephant skin-type microbial structures.

In some places, organized vertical sequences of grains can be found, from the coarsest at the bottom to the finest at the top (positive gradation). The Jordana Formation ends with layers of dark gray limestone containing silicified coral fragments, on top of which a coral bioherm (see section 3.3) about 2 meters thick is preserved. Cross-bedding and wavy cross-bedding (hummocky bedding) are common sedimentary structures in sandstones (Figure 4.7 B, D, E), where microbial structures are also frequent and easily identified by their rough "elephant skin-type" appearance. (Figure 4.7 D, F).

Positive gradation and hummocky cross stratification are diagnostic features of vigorous hydrodynamics. The waves agitate the particles which, after an energetic event, probably a storm, are deposited by gravity, the coarsest being the first and, on top of these, finer sediments in succession. Likewise, hummocky stratification has been associated with the oscillatory flows promoted by energetic waves from maritime storms.

The continental shelves are grouped into three types, according to the predominant hydrodynamic process: (i) dominated by tides, (ii) dominated by waves and storms (they represent 80% of current shelves), and (iii) dominated by ocean currents. The basal unit of the Jordana Formation was deposited on a shelf dominated by waves and storms. Tempestites, which are deposits resulting from the action of high power waves associated with storms, are characterized by a basal erosive surface superimposed by pebbles and gravel that transitions into sand with different sedimentary figures, as mentioned above.

The sedimentological features of the ferruginous sandstones of the Jordana Formation described above are compatible with an environment of middle carbonate ramp dominated by storms. The middle ramp is located between the fair-weather wave base and the storm wave base (see Figure 3.11).

The macrofauna is scarce, fragmented and silicified, consisting mainly of sponges, corals, brachiopods, crinoids, belemnites and ammonoids, the latter two being rare and poorly preserved. They correspond to a mixture of fragments of fauna from the different areas of the ramp, compatible with an energetic environment.

The limestone layers at the top of the Jordana Formation, resting on sandstones, can only mean transition to the inner carbonate ramp domain, as demonstrated by the presence of a bioherm, albeit isolated. The fossil record of foraminifera contains an association of several species common to the Peral Formation, most of which are typically encrusting forms.

4.4. Cerro da Cabeça Formation

Cerro da Cabeça Formation is so rich in coral fossils and other reef organisms that it is also known as "Bio-constructed Limestones of Cerro da Cabeça" (Figure 4.8). The interpretation of the environment in which it was formed offers no doubts: the inner domain of a carbonate ramp with transparent and tepid water, favorable to the installation of reef buildups with corals, crinoids and sponges. The micro flora (microalgae) and microfauna (foraminifera) also confirm this type of environment.

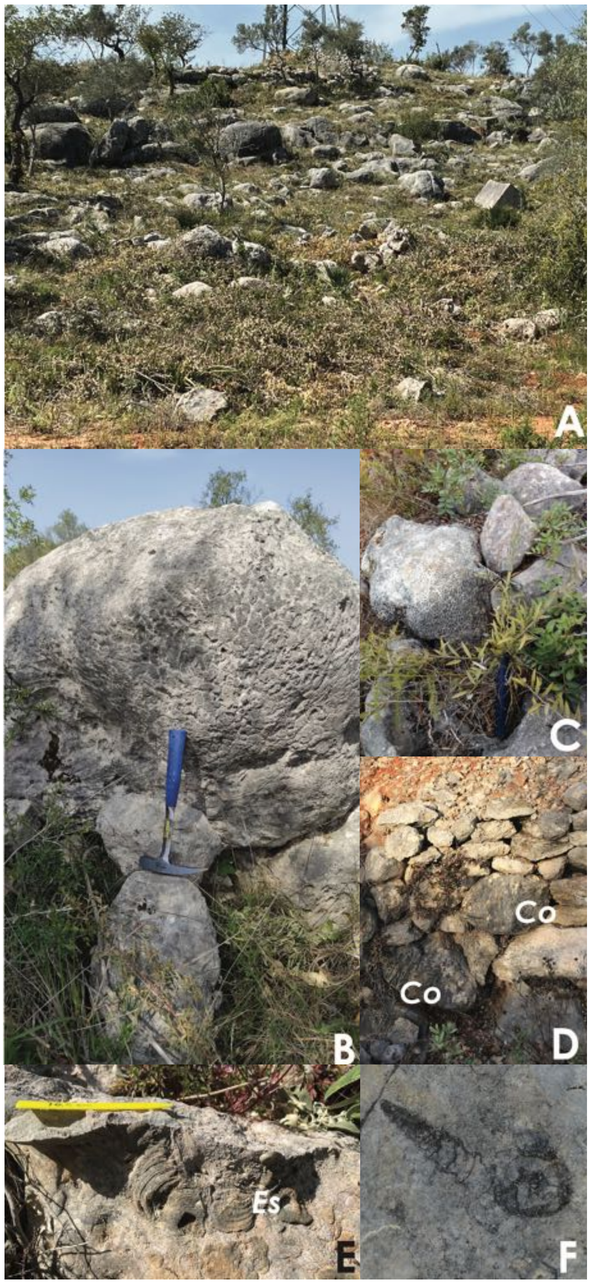


Figure 4.8. Field photographs showing aspects of the Cerro da Cabeça Formation. A: Scattered blocks, many of them large coral blocks; B: Coral block in life position; C: Coral blocks; D: Dry stone wall, where several of the blocks are coral fragments (marked with "Co"); E: Stromatoporoid fragments (marked with "Es"); F: Fossil of gastropod.

Among the microfossils, the species *Lithocodium aggregatum* (Oxfordian – middle Cretaceous) and *Bacinella irregulares* are ambiguous as to the taxonomic group to which they belong and, therefore, are part of a group called "micro problematic microfossils". Such is the ambiguity that, for example, the species *Lithocodium aggregatum* came to be considered as an incomplete stage of *Bacinella irregulares*, which in turn has also been classified as a cyanobacterium. Whatever the taxonomic group that best fits these species, the mentioned calcimicrobial association (they precipitate calcite) occurs in crusts in which coral fragments rest in the deepest levels of the photic zone, from 15 to 60 meters. The green algae *Thaumatoporella parvovesiculifera* is common in the shallow environments of Mesozoic carbonate platforms. It occurs either attached to the upper part of *Bacinella* crusts, or inside them, filling cavities. Another encrusting species is *Koskinobulina socialis*. Oncolites, which occur in great abundance, are rolled fragments from microbial crusts. In summary, the association of algae is a clear indication that the deposition environment of Cerro da Cabeça Formation is an inner ramp, with warm and shallow waters, within the photic zone. Furthermore, the species *Dehornella choffati* (stromatoporoid) that occurs in this Formation is typical of the Tethysian domain in the Late Jurassic (see Chapter 2). As already mentioned, stromatoporoids are reef-building sponges that live in warm, well-oxygenated waters with low sedimentation rate and have a preference for carbonate substrates.

The association of benthic foraminifera is very similar to that identified in the Peral and Jordana Formations, with the exception of the species *Troglotella incrustans* and *Alveosepta jaccardi*, both characteristic of a warm water inner continental shelf. The species *Alveosepta* *jaccardi* is considered a fossil of age and has been used as a biostratigraphic indicator for the late Oxfordian and early Kimmeridgian in the Tethysian basin.

Escarpão Formation

The Escarpão Formation (Kimmeridgian – Lower Tithonian; ca. 153.3 – 152.1 million years ago) is, among all those that outcrop on the Escarpão Plateau, the one whose facies has the greatest vertical variation. Layers of bioclastic limestone, marly limestone and micritic limestone follow each other. The transition between the Formation of Cerro da Cabeça and that of Escarpão is marked by a notable profusion of oncolites, oolites and pisolites.

Oolites are formed where tepid water favors inorganic precipitation of calcium carbonate around a nucleus gradually tumbled by waves and currents. In this way, carbonate precipitation occurs concentrically, in a very regular manner, around the nucleus, which may be a shell fragment or a mineral grain (Figure 4.9).

Along with water temperature, the pressure of the carbon dioxide dissolved in water is also an important parameter for the geochemistry of calcium carbonate (see Chapter 3). In rough water, carbon dioxide is released into the atmosphere. Thus, being naturally degasified, the water becomes less acidic and the precipitation of calcium carbonate is therefore easier. A modern example of the formation of oolites are the so--called "soft sands" of the Bahamas, whose grains are oolites. When passing through areas of banks (submerged shallows), the water of the Gulf Stream becomes warmer and saline. Salinity is also an environmental parameter that influences the solubility of carbon dioxide (CO_2) and, therefore, of calcium carbonate (see Chapter 3).

Salinity varies inversely with CO2 solubility. This means that very saline water has less capacity to dissolve carbon dioxide, thus favoring the formation of calcite. When calcite grains are smaller than two millimeters, they are called

Figure 4.9. Oolites and pisolites in the Escarpão Formation, at the transition with the Cerro da Cabeça Formation.

oolites. If the dimension is greater, close the size of a pea grain, they are called pisolites. Oncolites, measuring between one and ten centimeters, are particles that, although rounded, are not spherical and with concentric layers like oolites and pisolites. They result from the accretion of cement around non-skeletal parts of algae and bacteria. All these structures, oncolites, pisolites and oolites, have paleobathymetric significance, since they are formed in shallow, tepid and agitated waters.

The abundance of rudists and gastropods in some layers of limestone is absolutely remarkable. Some of the gastropods are oriented, which allows reconstituting the direction of paleocurrents. Another fossil common in this Formation are the stromatoporoids (Figures 4.10, 4.11, 4.12).

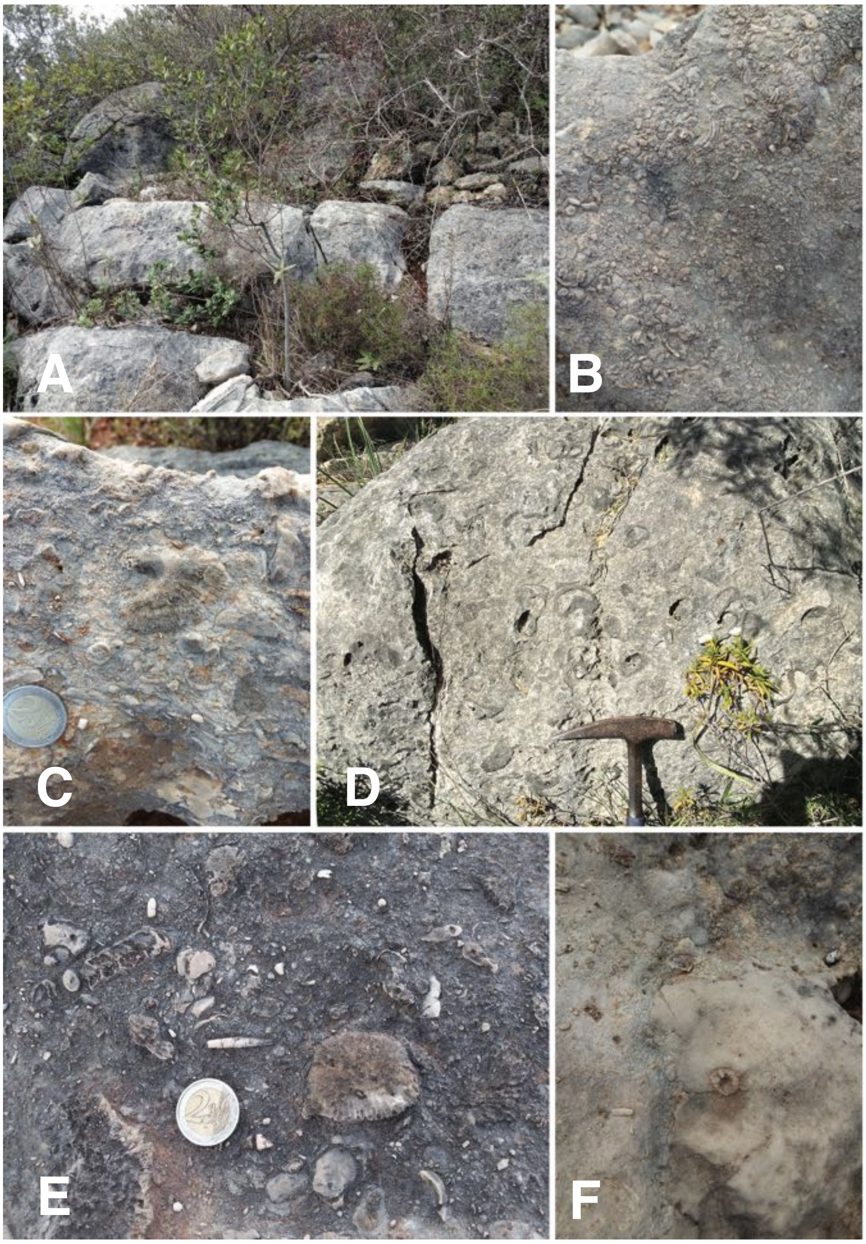


Figure 4.10. Field photographs of the Escarpão Formation. A: Marly limestone thick layers; B, C, D and E: Bioclastic limestone thick layers; F: Stromatoporoid.

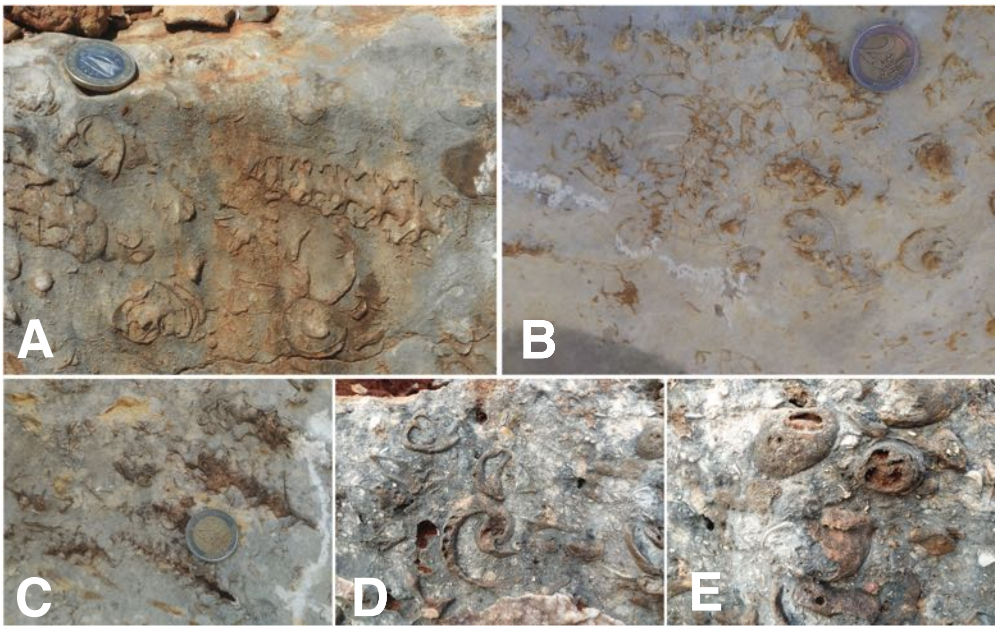


Figure 4.11. Field photographs of the Escarpão Formation. A, B and C: Fossils of Gastropods; D: Fossils of bivalve rudists; E: Fossils of ostreidae.

Figure 4.12. Field photographs of the Escarpão Formation. Blocks of coral, resulting from the erosion of the bioherm.

In the field, it is not always easy to distinguish this Formation from the Cerro da Cabeça Formation. What distinguishes the Escarpão Formation from all others in the Plateau are the associations of microorganisms, such as microalgae and foraminifera (Tables 4.1 and 4.2).

The richness of foraminifera species in the Escarpão Formation has no parallel in the other formations. Furthermore, only eight of them are common species (Table 4.1), being encrusting forms such as the *Mohlerina basiliensis*, *Nubecularia* sp. and *Tubyphytes morronensis*.

The benthic foraminifera of the Escarpão Formation are mainly the large ones, characteristic of the shallow marine environment of the Tethys domain. They are species from a warm-water inner platform, many of them adapted to constant influx of debris, such as *Everticyclammina virguliana*, *Freixialina planispiralis*, *Rectocyclammina chouberti* and *Pseudocyclammina lituus*. The large benthic foraminifera are good indicators of a shallow, warm, high-energy water environment and are, therefore, of stratigraphic importance. In the absence of other bioindicators, the large benthic foraminifera have been used to establish correlations between the different basins of the Tethys domain during the Oxfordian-Kimmeridgian, as is the case of the species *Alveosepta jaccardi*.

Green algae from the dasicladaceae family, such as *Salpingoporella* gr. *Pygmaea*, *Petrascula bursiformis* and *Heteroporella lemmensis*, typical of shallow waters, are abundant in the Escarpão Formation (Table 4.2).

It should also be noted that, considering the associations of microfossils, the stratigraphic unit named Limestones of São Romão is a lateral variation of facies in the Escarpão Formation. The stromatoporoids are very abundant in the Limestones of São Romão, indicating a lagoon environment probably shallower than that of the Escarpão Formation.

4.6. Limestone Formation with *Anchispirocyclina lusitanica*

The layers of the Limestone Formation with *A. lusitanica* contain frequent conglomerate levels of limestone, that is, generated in the deposition basin itself and resulting from the erosion of the original limestones. This may have been the result of a temporary subaerial exposure. Other evidences contribute to this interpretation, such as the occurrence of interstratified paleosols with limestone layers. From a lithological point of view, the fossiliferous limestones of this formation are similar to those of the Escarpão Formation. However, the microfossil content is unequivocally distinct (Tables 1 and 2).

The foraminifera *Anchispirocyclina lusitanica* (Egger, 1902) is one of the few fossils of age (characteristic fossil) of the Late Jurassic in Portugal, chronologically restricted to the Jurassic – Cretaceous transition (Upper Kimmeridgian to Berriasian – see Figure 1.1) and with a wide geographic distribution, allowing inter-regional correlations. However, its occurrence in Portugal has only been documented for the Late Tithonian – Early Berriasian. Thus, the Limestones with *A. lusitanica* represent the culmination of the filling of the basin at the end of the Jurassic. Also in the southernmost region of the Lusitanian Basin, the Late Jurassic ends with Limestones with *Anchispirocyclina lusitanica*.

Table 4.1. Comparison of benthic foraminifera species present in four of the geological formations outcropping on the Escarpão Plateau (blue indicates presence).

Benthic Foraminifera Species	Peral	Jordana	C. da Cabeça	Escarpão
Aeolosaccus sp.	🟦			
Subdelloidina sp.	🟦			
Tolypammina sp.	🟦			
Placopsilina sp.	🟦	🟦		
Bullopora irregularis	🟦	🟦	🟦	
Mohlerina basiliensis	🟦	🟦	🟦	
Nubecularia sp.	🟦	🟦	🟦	
Nautiloculina sp.	🟦	🟦	🟦	
Tubyphytes morronensis	🟦	🟦	🟦	
Miliolidae		🟦	🟦	
Troglotella incrustans			🟦	
Textulariidae			🟦	
Alveosepta jaccardi			🟦	
Pseudocyclammina gr. Parvula				🟦
Everticyclammina virguliana				🟦
Audienusina furcadei				🟦
Kurnubia palastiniensis				🟦
Labyrinthina mirabillis				🟦
Freixialina planispiralis				🟦
Nautiloculina oolithica				🟦
Trocholina elongata				🟦
Rectocyclammina chouberti				🟦
Otaina magna				🟦
Levantinella egyptiensis				🟦
Parurgonina caelinensis				🟦
Charentia atlasica				🟦
Valvulina gr. Lugeoni				🟦
Neotrocholina sp.		🟦		🟦
Trocholina alpina				🟦
Eoguttulina sp.				🟦
Pseudocyclammina muluchensis				🟦
Pseudocyclammina parvula				🟦
Trocholina elongata				🟦
Terquemella sp.		🟦		
Anchispirocyclina lusitanica		🟦		

In addition to an agglutinated carapace and discoidal shape, the foraminifera *A. lusitanica* has a centrimetic dimension, which is uncommon among other foraminifera. With the exception of this species and *Anchispirocyclina neumannae* and *Pseudocyclammina lituus*, all other foraminifera are common in the Escarpão Formation, although the richness of species is noticeably lower. The charophytes, which are freshwater green algae well adapted to temperate waters rich in carbonates, and ostracods (small crustaceans, 0.1 – 32 millimeters) are also fossil groups represented in the Limestone Formation with *A. lusitanica*.

Table 4.2. Comparison of species of algae present in four of the geological formations outcropping on the Escarpão Plateau (blue indicates presence).

Algae Species	**Peral**	**C. da Cabeça**	**Escarpão**	**C. com *A. lusitanica***
Lthocodium aggregatum			🟦	
Bacinella irregularis		🟦	🟦	
Thaumatoporella parvovesiculifera		🟦	🟦	
Arabicodium		🟦	🟦	
koskinobulina socialis		🟦		
Chaetelidae		🟦		
Dehornella choffati		🟦		
Girvanella			🟦	
Cayeuxia gr. Moldavica			🟦	
Picnoporodium aff.lobatum			🟦	
Permocalculus sp.			🟦	
Salpingoporella gr. Pygmaea			🟦	
Petrascula bursiformis			🟦	
Lickanella bartheli			🟦	🟦
Heteroporella lemmensis			🟦	🟦
Clypeina calciformis			🟦	
Russuella triangularis			🟦	🟦
Terquemella sp.			🟦	🟦
Thaumatoporella parvovesiculifera			🟦	
Campbeliella striata			🟦	
Salpingoporella annulata			🟦	
Clypeina jurassica			🟦	🟦
Lithophylum maslovi			🟦	🟦
fragmentos de dasicladácias			🟦	
Charophyta			🟦	
Clypeina solkani			🟦	🟦
Permocalculus inopinatus			🟦	🟦
Bucurella espichelensis			🟦	🟦
Pithonella sp.	🟦			
Cadosina sp.	🟦			
Globochaete sp.	🟦			

CHAPTER 5
PALEOENVIRONMENTAL EVOLUTION DURING THE JURASSIC AND CRETACEOUS

5.1. An ever-changing marine basin

The geological formations that constitute the physical support of the Escarpão Plateau originated in a homoclinal carbonate ramp (see Chapter 3) throughout the Late Jurassic. For more than 6 million years between the Oxfordian and the base of the Kimmeridgian, sediments from the Peral Formation were deposited in pelagic domain (outer ramp-basin – see Chapter 3). This Formation, at least 200 meters thick, presupposes a sedimentation environment located on a subsident continental margin of the Tethys domain, when future Europe was still a mere group of islands (Figure 5.1).

The architecture of the sedimentary facies in the Escarpão Plateau is in accordance with the decrease in the depth of the water column over time. What causes can we invoke? The organisation of the sedimentary facies depends on the space to accommodate the sediments, which is, in turn, controlled by tectonic movements (continental uplift or subsidence), mean sea level variations (eustatic and relative) and the amount of terrigenous sediments (controlled by the climate) arriving at the basin. Eustatic variations in mean sea level are those that result from changes in the volume of water in ocean basins

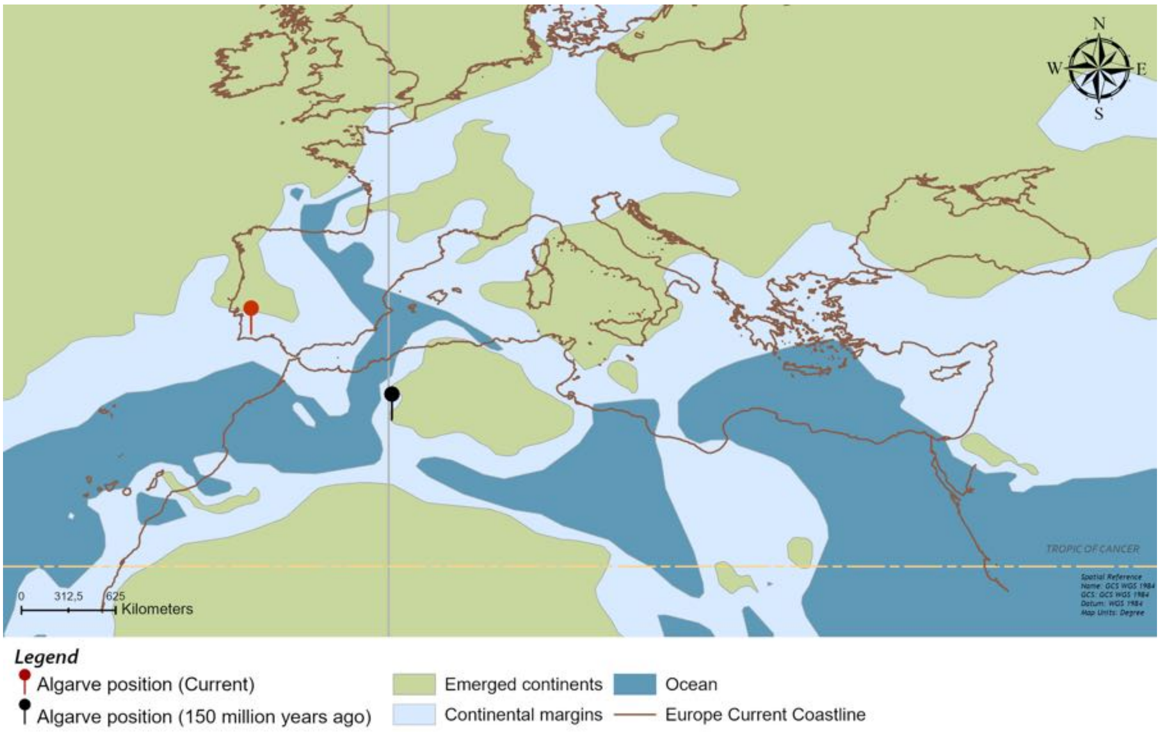


Figure 5.1. Paleogeography at the end of the Jurassic.

When changes in mean sea level result from local causes, such as tectonic and sedimentary, that modify the capacity of ocean basins, they are called relative variations in mean sea level.

The pattern of sedimentation in the Algarve Basin during the Mesozoic seems to have been controlled by tectonics related to halokinesis (movement of salt bodies), which caused deformation in previously formed layers. Horst-graben structures, which are blocks that are uplifted (horst) or lowered (graben) in relation to the adjacent regions (Figure 5.2), were generated between normal faults. The space to accommodate sediments was therefore unequally distributed throughout the Algarve Basin, as was also the case in the Lusitanian Basin, where halokinesis was equally determinant in the organisation of space during the Mesozoic. In the uplifted zones (Horst - high bottoms), reef buildups dependent on the photic zone developed, while, in the depressed zones (graben), the thickness of the sediments reached hundreds of meters and sediments, pelagic and hemipelagic organisms predominated. The result was a profusion of sedimentary facies throughout the Jurassic, whose geometric relationships are not yet fully understood in the Algarve Basin, as referred in Chapter four of this book. The importance of saline structures in the organisation of sedimentary basins during the Late Jurassic has been recognized in many other regions. For example, the highly variable thickness of the sedimentary sequences in the mountains of the Swiss Jura has been interpreted as the result of differential subsidence, determined by the movement of Triassic evaporites (salt rocks). The game of faults created a structuring in independent blocks, with high elevations and depressions, generating accentuated lateral facies variations.

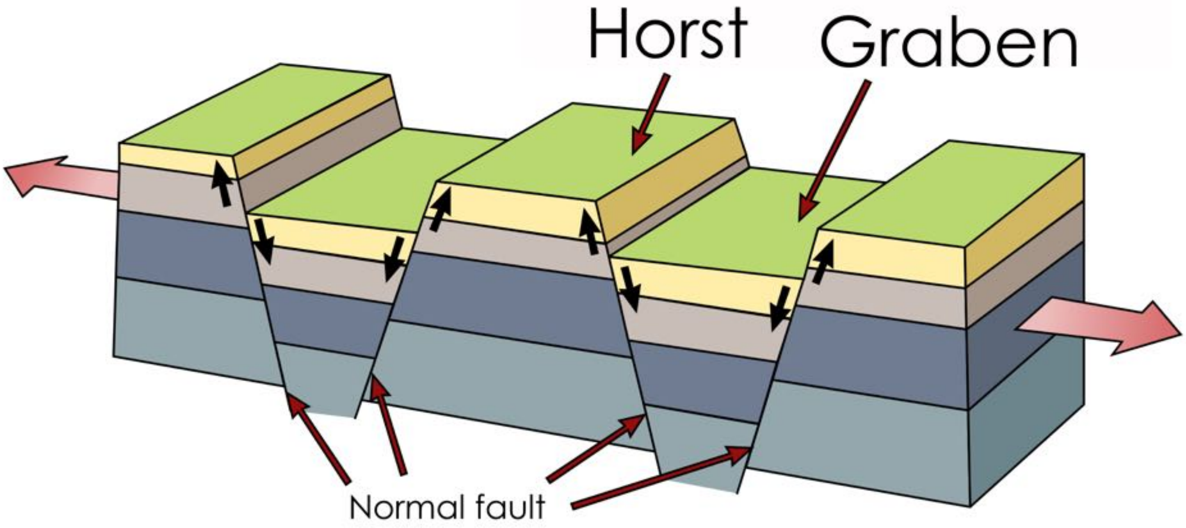


Figure 5.2. Horst and Graben geological structures.

The thickness of the sedimentary series is a direct indicator of the accommodation space and, therefore, of the magnitude of subsidence in a sedimentary basin. In turn, the pattern of accumulation of sediments is the result of complex interactions between tectonics, isostasy (vertical movement of the earth's crust) and eustasy (variation in mean sea level). In addition to tectonics, the factors that affect subsidence are the compaction of the sediments, the sedimentary load, variations in mean sea level and also the thermal state of lithosphere, which determines its flexural response (deformation).

Along with tectonics, eustatic or relative variations in mean sea level play a leading role both in the sedimentation pattern and in the space available to accommodate the sediments. During regressions of larger magnitude, the seabed is reduced, with the coastline close to the point the continental shelf breaks and the slope starts. Shallower water facies are then superimposed upon deeper facias: regressive sequence. On the contrary, during transgressions, the coastline moves towards the continent and sediments from deeper waters are superimposed upon coastal environments: transgressive sequence.

Several transgressive peaks were identified in the Jurassic, with those of highest magnitude occurring during the Kimmeridgian and Tithonian (Late Jurassic). Although some periods of low mean sea level have been identified, the trend was globally transgressive throughout the Late Jurassic. However, the mean sea level curves for this Period are far from being agreed upon, especially with regard to smaller cycles of transgression-regression. According to the Haq's curve (2005), a regressive trend began at the end of the Kimmeridgian that continued into the Tithonian. However, some authors report a transgressive peak at the base of the Tithonian (e.g., Hallam, 1988) or, on the contrary, a regressive peak at the Kimmeridgian – Tithonian boundary, followed by transgression (e.g., Li and Grant-Mackie, 1993). Nonetheless, all eustatic mean sea level curves agree that the general trend throughout the Late Jurassic was transgressive, with short regressive intervals. Sequential analysis of litho- and biofacies gives us the evolution of paleoenvironments, but it is necessary to frame the analysis in the tectonic context for a more complete and cohesive understanding of paleoenvironmental evolution.

The sequential analysis of the Late Jurassic Formations exposed on the Escarpão Plateau is in accordance with an unequivocal trend of evolution from deep facies (Peral Formation) to middle ramp facies (Jordan Formation), followed by inner ramp facies (Cerro da Cabeça and Escarpão formations) and, finally, restricted marine environment or even lagoon facies (Limestone Formation with *Anchispirocyclina lusitanica*) (Figures 5.3). Thus, the sedimentary sequence exposed on the Escarpão Plateau is regressive.

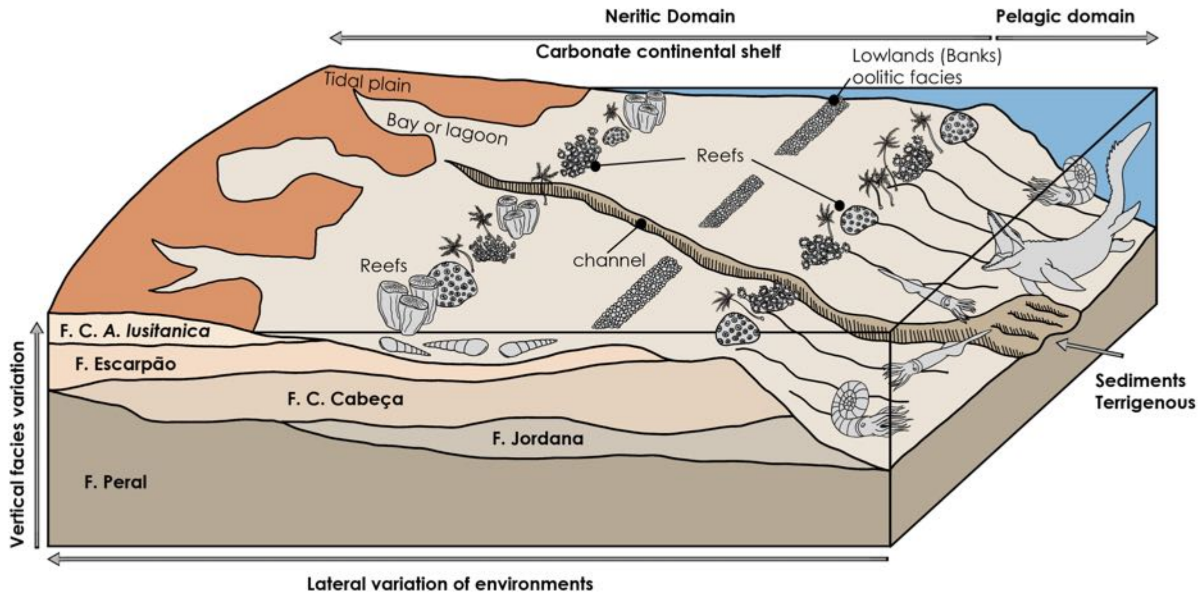


Figure 5.3. Schema of the subenvironments of a carbonate continental shelf, with illustration of some of inhabiting organisms. Interpretation of deposition environments of the Escarpão Plateau formations.

5.2 A lagged regression sequence of the eustatic mean sea level (MSL) curve?

The regressive sequence of the Escarpão Plateau (Table 5.1) seems out of phase with the global mean sea level curves referred to in the previous section. The progression from deep waters to increasingly shallow waters may have several causes: (i) marine regression starting from the Kimmeridgian, contrary to the eustatic curves proposed for the Late Jurassic; (ii) decrease in the relative mean sea level, resulting from successive uplifts of the continent; (iii) basin structure with high bottoms due to halokinesis; (iv) successive loading (filling) of the basin (therefore, a decrease in depth), as it received important volumes of terrigenous sediment from the erosion of continental masses. Hypotheses (ii) and (iii) imply a compressive tectonic regime. However, the inversion of the tectonic regime from distensive (extensional) to compressive only set in at the entire Tethys domain at the end of the Cretaceous. We can, however, admit compressive pulses in a tectonic context mainly of rifting (distensive). These events can be justified within the scope of restoration of the lithosphere thermal equilibrium, which determined different behaviors in the speed with which tectonic inversions occur. For example, while the compression phase in the Pyrenees region was immediately followed by the extensional phase, in the Atlas (NW Africa), a rather long period of time, from 145 to 83 million years, was necessary to achieved a thermal rebalancing of the lithosphere. Hypothesis (iv) is compatible with a humid climatic phase, promoting intense weathering and erosion in the peripheral areas of the Basin. The Jordana Formation, separated from the Peral Formation by a basal conglomerate and its essentially terrigenous sediments (see Chapter 4), is an argument in favor of this hypothesis. But, in this case, the sedimentation rate would need to have greatly exceeded both the subsidence rate and the eustatic rise in mean sea level (assuming a transgressive regime). The introduction of large amounts of terrigenous material is incompatible with the development of reef buildups. Thus, although we recognize that there pulses of terrigenous sedimentation, they was not significant during the genesis of the Escarpão and Cerro da Cabeça formations. As mentioned before, all these conjectures show how complex is the interaction between the various environmental parameters involved in the paleobathymetric evolution of ocean basins.

Table 5.1. Synthesis of the formations exposed on the Escarpão Plateau, paleoenvironments and paleoenvironmental indicators.

FORMATION	AGE	ENVIRONMENT (see Schema in Figure 5.3)	BIOLOGICAL AND GEOLOGICAL INDICATORS
Limestone with *A. lusitanica*	Tithonian	Restricted marine – lagoon	Foraminifera *A. lusitanica*; Charophyta
Escarpão Formation	Kimmeridgian – Early Tithonian	Inner carbonate platform. Type: homoclinal ramp	Reef buildups; Large benthic foraminifera
Cerro da Cabeça Formation	Early Kimmeridgian	Middle carbonate platform. Type: homoclinal ramp	Reef buildups; Large benthic foraminifera
Jordana Formation	Early Kimmeridgian	Middle carbonate platform. Type: homoclinal ramp under the action of energetic waves	Terrigenous sediments; hummocky-type cross-bedding; positive gradation
Peral Formation	Late Oxfordian – Early Kimmeridgian	Outer carbonate platform and basin. Type: homoclinal ramp	Fine detritus sediments; Pelagic fauna (e.g., Ammonites and Belemnites)

5.3. The relevancy of bioproxies for paleoenvironmental reconstitution

We may question the interpretation of the paleobathymetric indicators (mainly bioindicators) used in any of the hypotheses suggested in section 5.2. However, there is not a large margin for error with regard to paleoenvironments, even if doubts persist as to the optimal conditions for development of some organisms.

Reef buildups with stromatoporoids, such as those that occur at the Cerro da Cabeça and Escarpão formations, were very common in the Jurassic. However, paleoenvironmental studies based on the distribution of stromatoporoids are still scarce, which may be attributed to the debate around their taxonomy, although most researchers consider them to be demosponges. Stromatoporoids and corals overlap in terms of environmental significance, although the latter seem to be characteristic of waters deeper than those of stromatoporoids. In Jurassic buildups, these organisms represent only 7% of the entire reef. However, this percentage rises to 10% if only Late Jurassic reefs are considered. Almost all reefs with significant amounts of stromatoporoids were located in the southern part of the Tethys Ocean, near the paleolatitude 25ºN. In Portugal, stromatoporoids and Chaetetids (calcareous demosponges made up of fused tubules), despite not being dominant in the Jurassic reefs, are frequent in inner platform and lagoon facies, both in the Lusitanian Basin and in the Algarve Basin (northern domain of Tethys). The association of stromatoporoids and Chaetetids is indicative of shallow marine waters.

The Limestone Formation with Anchispirocyclina lusitanica (Tithonian), which overlies the Escarpão Formation, is the top formation of the Late Jurassic sequence and represents the completion of the Basin sedimentary filling in this region. The biofacies is compatible with depths close to the mean sea level in the Tithonian (145 million years ago). This chronological milestone is given by the fossil of age *A. lusitanica*. The Formation represents the transition to a subaerial environment, on a confined inner platform, with less and less marine influence. In the Municipality of Vila do Bispo (Algarve), at Praia da Fóia do Carro, there are dinosaur footprints in layers with *A. lusitanica*, confirming that the type of biofacies is a shallow coastal lagoon with these unusually large benthic foraminifera.

5.4. From a tropical sea to a continental environment

In the Early Cretaceous (145 - 100.5 million years ago) profound changes occurred in the geography of the continents and in oceanic circulation. South America broke away from Africa and the opening of the circum-equatorial surface current had a profound effect on the pattern of global ocean circulation.

During the Cretaceous, the Iberian Peninsula was located in the interface of two climatic bands: (i) in the north, a hot humid climate, (ii) in the south, a very hot dry climate. The distribution of continental masses and the oceanic circulation were very different from today. The Arctic Ocean was still ice-free and the middle

Cretaceous was even characterized by extreme greenhouse-effect conditions.

It was from the Late Cretaceous that a cold circumpolar oceanic current settled in, isolating the Antarctic continent from the influence of the warm equatorial current. But this warm current was successively destructured due to the approximation of the North America and South America continents and the migration of Australia to the North.

Although the Algarve Basin did not differentiate into sub-basins during the Cretaceous, contrary to what happened during the Jurassic, preserved Lower Cretaceous outcrops in the central Algarve are scarce, terrigenous and little fossiliferous, making their correlation with the Cretaceous units on the western and eastern Algarve difficult.

In the transition from the Tithonian (Late Jurassic) to the Cretaceous, the mean sea level trend continued to be regressive, as it had been at the end of Jurassic. Sedimentation continued during the Early Cretaceous, in environments closer to the coast with a high terrigenous and even continental influence. Wetlands and freshwater coastal lagoons were formed. The Wealden facies is common: lenticular conglomerates of siliceous pebbles associated with positive sequences of obliquely laminated sandstones and clay layers. The designation Wealden facies is used due to its similarity with the Berriasian to Aptian (Cretaceous) sequence in southeastern England, whose sediments are

Figure 5.4. Example of anastamosed river system. Walmakariri River, Canterbury, New Zealand (27/06/2007).

characteristic of freshwater environments, composed of alternating sands, deposited in alluvial plains of anastamosed river systems (Figure 5.4), and coastal lagoon clays.

Despite the general regressive trend that prevailed throughout the Early Cretaceous, changes in mean sea level were frequent. That is why the facies that represent this Epoch vary between marginal marine environment and freshwater lacustrine with frequent spills of material terrigenous. The Barremian (Early Cretaceous, ca. 129-125 million years ago) is represented in central and western Algarve by lagoon-lacustrine deposits, while in the eastern sector mainly fluvial facies occur.

There was precipitation of carbonate in freshwater environments, whose genesis is related to variations in lake depth, tectonic movements, nutrient supply and ecology of organisms that precipitate calcium carbonate, such as ostracods, mollusks and calcareous algae. The changes in lacustrine environments were so rapid that lateral and vertical facies variations are common. Lacustrine sedimentary facies rich in microfossils are often referred to as purbeck facies, after the island of Purbeck in Dorset (UK) where the Purbeck Formation (Late Jurassic – Cretaceous) was formally described and characterized. The clays that were explored in the Cretaceous belt Tunes–Mem Moniz (Figure 5.5) were deposited in coastal lagoons and exhibit purbeck facies.

Figure 5.5. Sedimentary sequence of clays from the Cretaceous in one of the exploration walls of the factory Fábrica de Cerâmica do Algarve (FACEAL), in Mem Moniz.

At the end of the Early Cretaceous, a transgressive maximum gave rise to the formation of limestones rich in ammonites, brachiopods, rudists and echinoids.

The peak of this transgression is marked by a ferruginous crust generated in marine environment, coinciding with an anoxic (poorly oxygenated waters) event that occurred in the global ocean. A wide marine transgression in the transition to the Late Cretaceous resulted in the development of reef environments. The large thickness of this series is the outcome of the important subsidence (sinking) due to thermal contraction that marked the end of the extensional regime (widening) of the Algarve Basin. However, these marine facies are not represented in the inland central Algarve where, as we have already mentioned, sedimentation took place in a fluvial-lacustrine environment. Even in the coastal area of the Arrifes-Albufeira region, sedimentation during the Early Cretaceous took

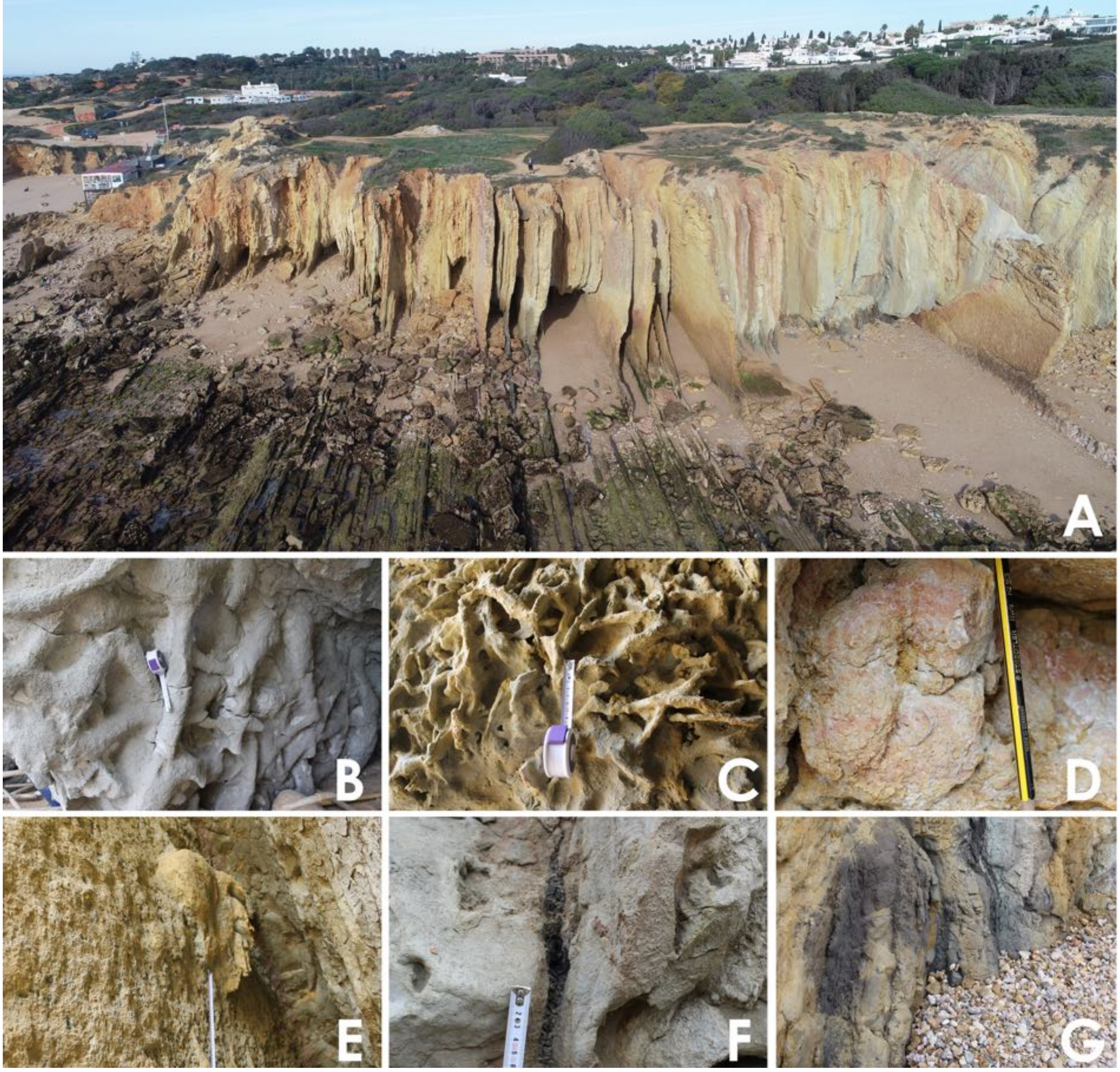


Figure 5.6.A: Coastal cliff in the Arrifes-Albufeira region. Nowhere else in the Algarve can this deformation of the cretaceous layers be seen, brought almost to the vertical by halokinesis associated with the Albufeira diapir, during a compressive phase of the Alpine Orogeny; B and C: Ichnofossils; D: Macroscopic foraminifera; E: Dinosaur footprint; F and G: Layers of vegetation matter (continental influence).

place in a marginal environment with strong continental influence, as attested by the dinosaur footprints, leaves, pollens and spores found in some layers of marls and clays (Figure 5.6).

There are no known sedimentary formations from the post-Cenomanian Cretaceous (93.9 million years ago) in the Algarve. There were phenomena of volcanism and intrusion of igneous rocks in the Late Cretaceous (around 83 million years ago), as those we can observe, respectively, on the coastal cliff of Luz de Lagos (Figure 5.7) and in the Massif of Monchique.

From the Campanian (83.6 million years ago), the Iberian microplate was subjected to a compressive regime, following approximately a north-south direction, that put an end to the counterclockwise rotation that predominated during the mainly distended regime of the Triassic and Jurassic. It was during that intense compressive phase that some of the most important reliefs of Iberia were generated, such as the Pyrenees, the Cantabrian Mountains, the Spanish-Portuguese central system and the Cordilleras Béticas. This compressive regime was also responsible for intense halokinesis in the Mesozoic Lusitanian and Algarve basins.

Figure 5.7. Coastal cliff in Luz Beach in Lagos. In the background, black rock from a volcanic chimney from the Late Cretaceous, which intersects the multicolored stratified clays and marls from the Early Cretaceous.

Figure 5.8. Coastal cliff west of Albufeira (Castelo) consisting of Miocene sedimentary rocks.

The coastal cliffs between Porto de Mós (Lagos) and Olhos de Água are carved in Miocene rocks (except in the region of Albufeira-Arrifes) (Figure 5.8).

However, in the inland region, from the extensive marine transgression that occurred in the Late Miocene (Serravallian ca. 13.8-11.6 million years ago) only the enigmatic deposits of Mem Moniz, known as Spongoliths of Mem Moniz, still remain. It is their origin that is enigmatic, as well as the morphotectonic context that allowed their preservation in an isolated patch with about 332 square meters. At the time of their deposition, an Early Cretaceous unconformity, the coastline was located near Tunes, about ten kilometers further inland than its current location. It is, in all aspects, a particular Formation, both lithologically and genetically. It is composed of yellow clayey silts, very rich in microfauna and spongiary spicules, and there are no similar formations in Portugal. Calcium carbonate accounts for 62% of the total mass of sediments. Coccolithophores have an important representation in these sediments and diatoms are also frequent (Figure 5.9). But what stands out the most is the abundance of spongiary spicules. Some researchers have suggested that the Spongoliths of Mem Moniz were formed in a small tectonic trench at the intersection of the Quarteira Fault and the Algibre Flexure.

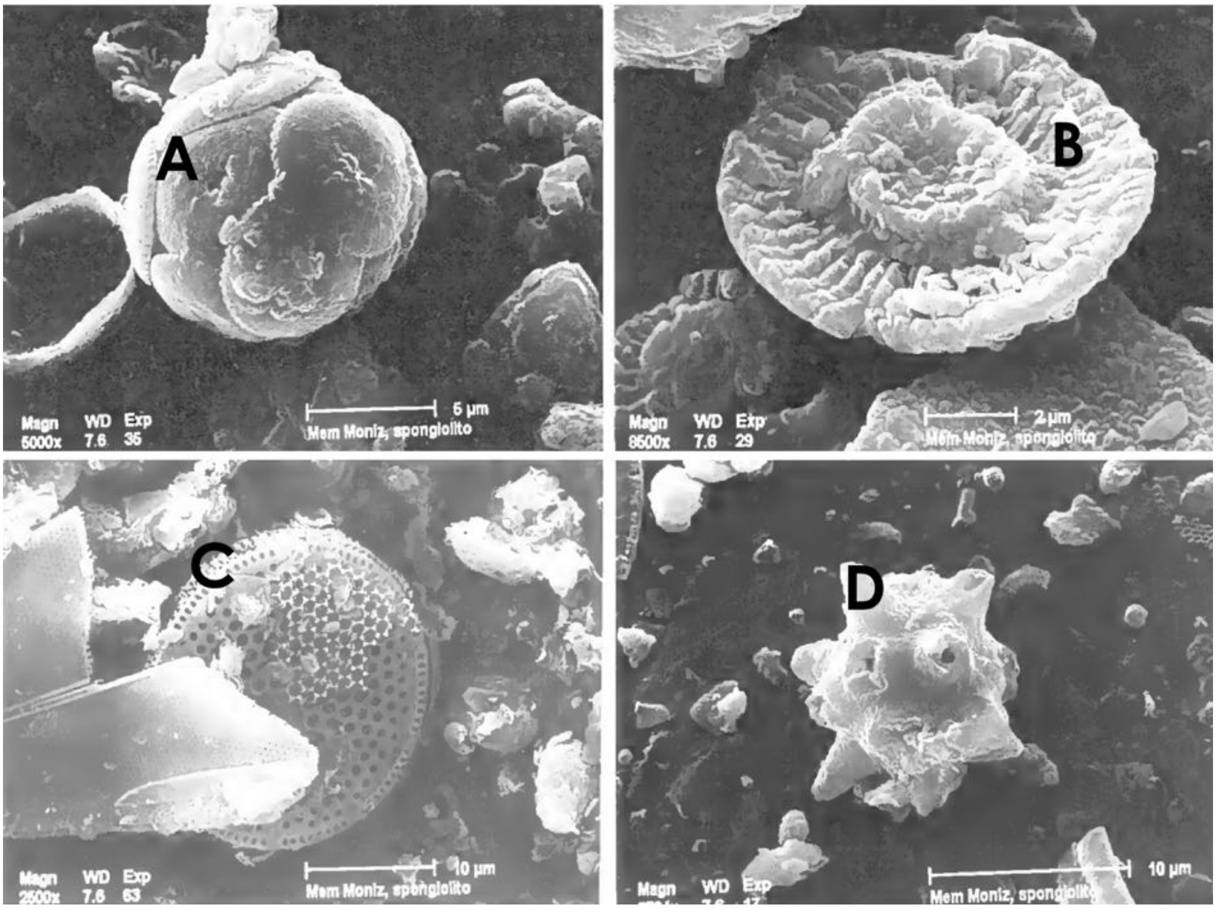


Figura 5.9. Microfossils from the Mem Moniz Spongoliths. A: *Reticulofenestra minuta* (cocosphere); B: *Coccolithus miopelagicus* (cocosphere); C: *Coscinodiscus tuberculatus* (diatom); D: *Microscleva* (sponge). Note: 1µm=0.01 millimeters.

CHAPTER 6
FROM THE PLATEAU TO THE HILLS (CERROS)

6.1. Concept of Landscape

Landscape, as defined by the Florence Convention in 2000, is a territorial area, as perceived by people, whose nature is the result of the interaction between human and natural factors. The landscape plays an important role in the cultural, ecological, environmental and social areas. It is also a favorable resource for economic activity, as its protection, management and adequate planning can contribute to job creation (Official Gazette, Series I-A, Decree Decree-Law no 4 /2005 of 14 February).

The agents of internal and external geodynamics are part of the natural processes of landscape modeling. Among these, rivers and glaciers are the greatest sculptors in temperate and glacial climates, respectively. In hot desert regions, the wind is responsible for the most abundant forms of accumulation on the surface of the planet: the dunes. Among the agents of internal geodynamics, earthquakes, volcanism and tectonics are worth mentioning. The role of organisms in the evolution of the landscape should be emphasized, either as agents of erosion (bioerosion) or as facilitators of sediment accumulation (for example, dune vegetation). Well known to all of us is the growing impact of Man on the landscape, often putting the survival of ecosystems at risk.

The agents that contribute to landscape evolution operate on different time scales, from minutes (catastrophic events, such as landslides and tsunami) to thousands of years (deepening of valleys). Many of the most conspicuous forms that we observe today, such as mountains and mountain ranges, are the result of tectonic forces that operated many thousands of years ago, bending (ductile deformation) and breaking (brittle deformation) the rocks.

6.2. The hills inherited from the Jurassic

To understand the geodynamic evolution of this region, let's start by “reading” the landscape. In contrast with the somital flatness of the Escarpão Plateau, the area that surrounds it to the north and east is undulating and several hills rise on both sides of the Quarteira stream/Quarteira Fault. The top of some of these hills corresponds to geodetic vertices of the national geodetic network (Figure 6.1).

The contrast between the east and west compartments of the Quarteira Fault could not be greater (Figure 6.2). To the west, the Late Jurassic formations of the Escarpão Plateau, identified in chapter four and interpreted in chapter five, are sequentially organized from the Oxfordian (ca. 163 million years ago – Peral Formation) to the Tithonian (ca. 145 million of years ago – Limestone Formation with *Achispirocyclina lusitanica*), with a general inclination to the southwest (Figure 6.3). Throughout the Plateau, it is the limestones from the Escarpão Formation that emerge and define the somital surface, which stands at altitudes close to 130 meters.

Figure 6.1. Examples of geodesic vertices (GV) on tall hills on the outskirts of the Escarpão Plateau, some of them standing on top of windmills. A: Cerro do Ouro (hill) (144 meters); B: Cerro de S. Vicente (hill) (175 meters); C: Cerro do Moinho do Leitão (hill) (154 meters) - old mill (1980); D: Current position of the Moinho do Leitão's GV (it was moved), in relation to the current mill (photo E).

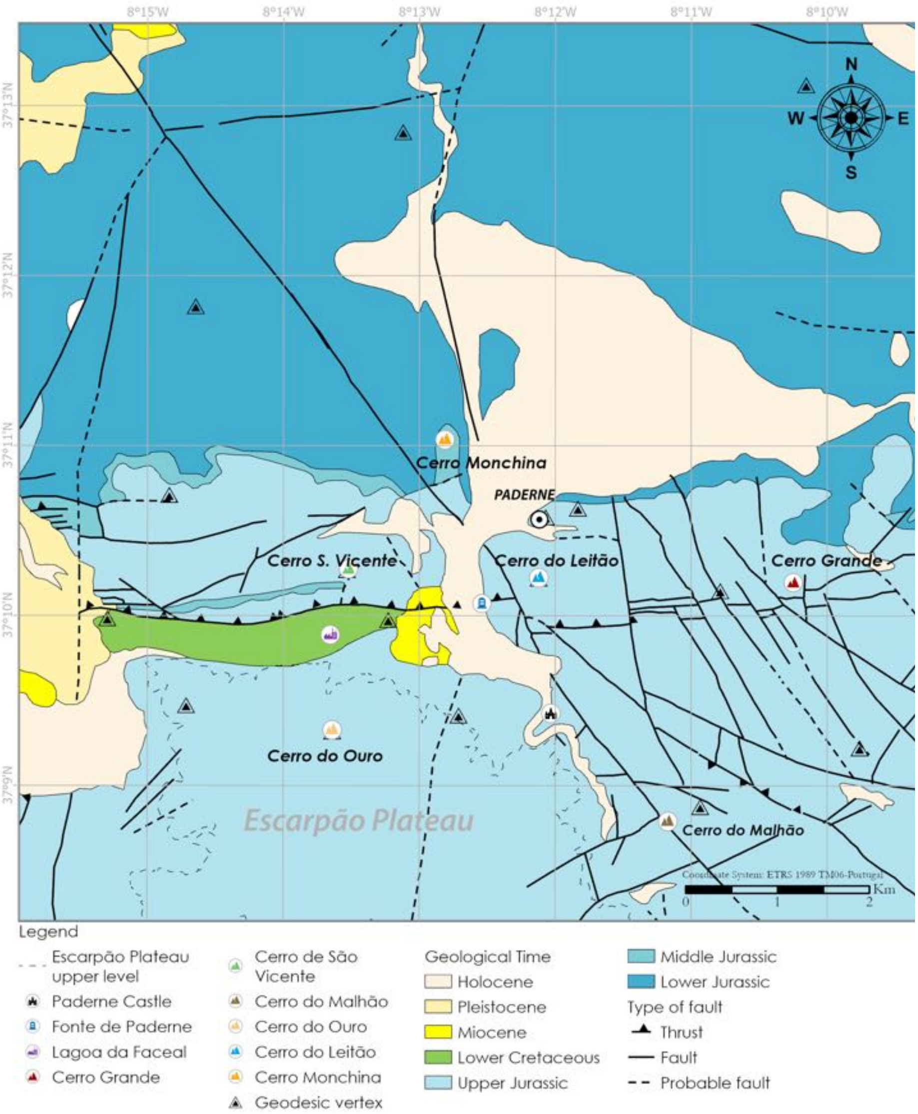


Figure 6.2. Location of the hills and geodesic vertices mentioned in the text. The base on which they were marked is the geological map of Portugal, on a scale of 1/100 000, Occidental Page, Geological Services of Portugal.

Figure 6.3. Limestone layers of the Escarpão Formation at the margin of the valley of the Quarteira stream. Note the southwest-facing slope layers.

The region to the east of the Quarteira fault corresponds to a corridor of intense deformation affecting all the Late Jurassic formations that crop up there in patches, displaced by faults, some of which corresponding to thrusts (Figure 6.4).

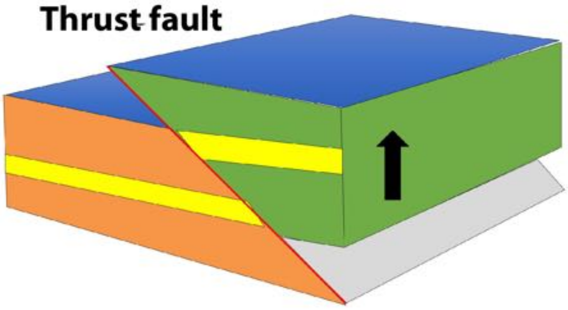


Figure 6.4. Schema of a thrust. Fault in which one of the blocks partially or completely slips over the other.

Cerro Grande (hill)

Cerro Grande (hill), located southeast of the village of Paderne (see Figure 6.2), has an elongated NE-SW oriented summit and rises to an altitude of 224 meters. The geodesic vertex of Almeijoafas is located at the southwest end of the summit, 203 meters above sea level. The slope facing northeast is the smoothest. The topographically elevated position of Cerro Grande is the result of the tectonic movement of two fault systems that displace geological formations. One of them, with an approximate orientation E-W, displaces the formations of Peral (Oxfordian-Kimmeridgian) and Cerro da Cabeça (Kimmeridgian), revealing a strip of the so-called Santa Bárbara de Nexe dolomites standing between those formations.

According to several authors, the lithostratigraphic unit of the dolomites of Santa Bárbara de Nexe is the result of secondary dolomitization of older geological formations. An argument in favor of this interpretation is the fact that the Santa Bárbara de Nexe dolomites have heterochronous boundaries (of different ages). The diagenetic process of dolomitization results from the replacement of calcium ions by magnesium ions in the crystal lattice. The high density of faults may have contributed to this process, by facilitating the rise and circulation of fluids rich in magnesium.

Another family of faults that affects the region of Cerro Grande has an approximate orientation NW-SE, being roughly parallel to the Quarteira fault (tectonic accident of S. Marcos). Although it is not visible to the north of Ribeira do Algibre (east-west direction), it cuts through all Jurassic outcropping formations in the region. This family of NW-SE faults and also the Quarteira fault displace the east-west faults and, hence, their movement is more recent than that of the east-west faults, being at least from the Late Jurassic, as they affect the Escarpão Formation (Kimmeridgian – Tithonian). Although they disappear below the Late Quaternary river terraces, at the confluence of the Algibre and Alte streams (Chapter 7), some faults with the same NW-SE orientation, and therefore probably from the same family, affect quaternary sediments more to the south. As a consequence, the NW-SE fault system, which includes the Quarteira fault, is a system of active faults, that is, their movement happened after the Pliocene (5.3 million years ago). This explains why the Oxfordian-Kimmeridgian Peral Formation, displaced by faults, is topographically higher than the more recent Cerro da Cabeça Formation (Kimmeridgian).

Cerro do Malhão (hill)

Cerro do Malhão (hill) (see Figure 6.2), located south of Paderne, has a 194 meters-high geodesic vertex and the triangle is completed with geodesic landmarks in this region on the left bank of the Quarteira stream, formed by Cerro Grande, Cerro Leitão and Cerro Malhão.

Cerro do Malhão is located next to one of the most pronounced meanders of Quarteira stream and is controlled by a NE-SW-oriented fault. This fault is moved by the Quarteira fault, which intersects Cerro do Malhão. Like Cerro Grande and Cerro do Leitão, Cerro do Malhão is formed by oldest rocks of the Peral Formation (Oxfordian-Kimmeridgian). The rocks of the Cerro da Cabeça and Escarpão formations, more recent (Kimmeridgian), emerge at lower heights on the periphery of the hills. As previously mentioned, the morphotectonic context in this region is very complex, with the majority of contacts between the various Late Jurassic formations being made by faults, some of them thrust faults (see Figure 6.4). This brittle deformation corridor (fractured rocks) has no correspondence on the west side of the Quarteira Fault. Here, Cerro Monchina and Cerro do Ouro correspond to anticline folds, respectively in marl limestones and Telheiro marl, attributed to the Middle Jurassic (Callovian: 166.1 – 163.6 million years ago), and in limestones of the Escarpão Formation (Late Jurassic: 157.3 – 152.1 million years ago). The Jurassic formations constrained geographically and morphologically between the Escarpão Plateau and the Picavessa Mountain are arranged in narrow E-W-oriented strips, separated by faults in the same direction.

Cerro Monchina (hill)

Cerro Monchina (hill) (see Figure 6.2) rises to 120 meters in the southern limit of the Picavessa Mountain at the intersection of the NW-SE oriented Quarteira Fault with another fault running in the NE-SW direction. It is through this fault that contact is established in this zone between the Early Jurassic Picavessa Formation, to the north, and the Late Jurassic Peral Formation (Figure 6.5).

The Picavessa Formation, attributed to the Early Jurassic (Sinemurian to Toarcian: 199.3 to 174.1 million years ago), has an estimated thickness between 300 and 500 meters. The sediments, later transformed into the rocks that we observe, were deposited in a shallow marine environment. They were the first marine sediments that followed the deposition during the Triassic in a continental environment, predominantly swampy and fluvial, where large amphibians lived, such as Metoposaurus algarvensis.

Middle Jurassic is poorly represented in the Algarve, as a regression occurred before the marine environments were reconstituted in the Late Jurassic. However, Cerro Monchina is built on marl limestone and Telheiro marl attributed to the Middle Jurassic (Callovian: 166.1 – 163.6 Ma ago). The sediments that gave rise to them were deposited in a marine environment, but they are not very fossiliferous. They are only known south of the Algibre flexure, often in the centre of anticlines such as Cerro Monchina, some of them saliferous anticlines.

With the exception of Cerro do Ouro, folded in anticline in the Kimmeridgian-Tithonian Escarpão limestones, all the other hills have as physical substrate Oxfordian formations (Peral Formation: Malhão, Leitão, Grande, S. Vicente hills) or Middle Jurassic formations (Cerro Monchina). This morpho-tectonic context

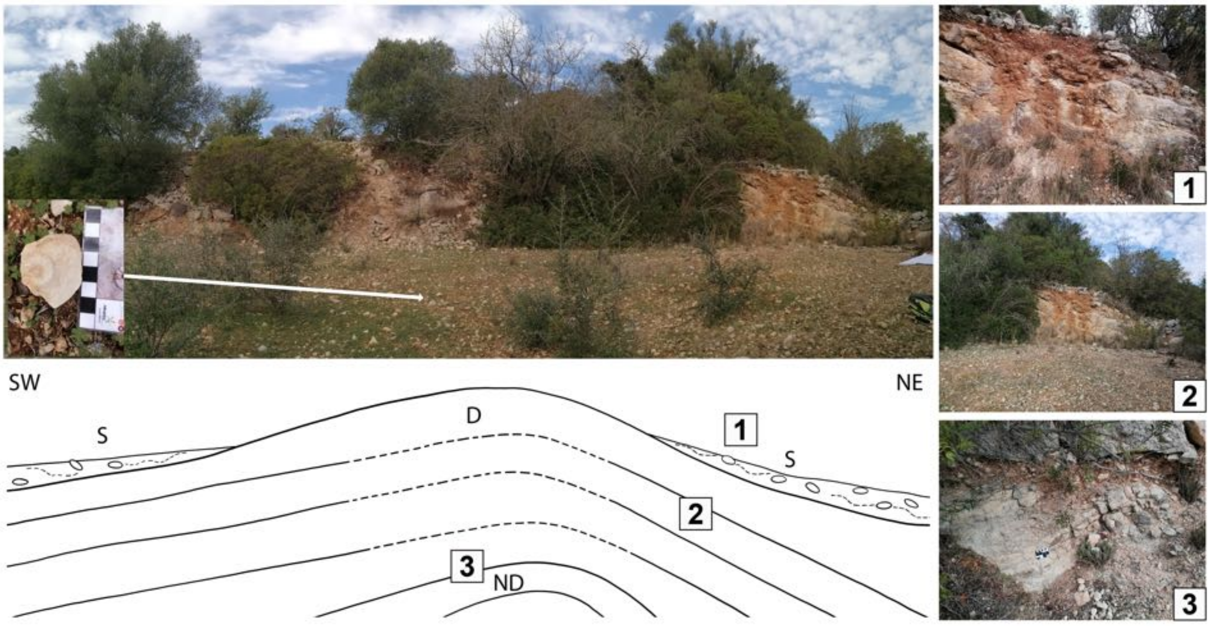


Figure 6.5. Cerro Monchina. Above: photograph of an anticline folding in the Telheiro Limestones and Marls and fossil of ammonite found in soil; Below: Interpretative schema of the geological section of the southern slope of Cerro Monchina, corresponding to photograph A, in which 1) detail of the layers on the northeast flank of the fold and soil ("S"); 2) layers of metric thickness, leaning 60° to the east; 3) fold core ("ND"). The dashed lines in schema B correspond to the mass of rock that has disappeared due to erosion.

means that hundreds of meters of sediment deposited in the subsequent floors (Kimmeridgian and Tithonian) are missing.

The explanation may lie in the intense erosion that occurred as a result of the continental uplift during the compressive tectonics that settled in from the Cretaceous onwards.

Cerro do Ouro (hill)

Cerro do Ouro stands on the northeast edge of the Escarpão Plateau (see Figure 6.2), at an altitude of 141 meters, its highest point being marked by a geodesic vertex (see Figure 6.1A). Folded in anticline in the limestones of the Escarpão Formation, it is surrounded by a peripheral depression excavated in the Cretaceous and Miocene formations (Figures 6.6 and 6.7).

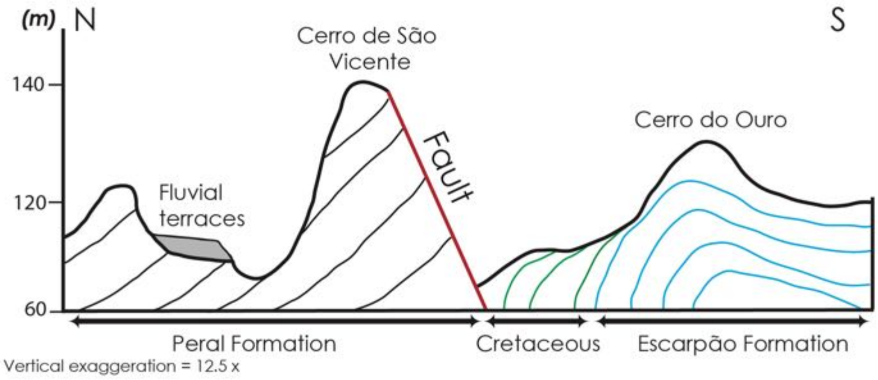


Figure 6.6. Depression filled with clay and marls from the Early Cretaceous between Cerro do Ouro and Cerro de São Vicente. They are the clays that were explored for ceramic production by Fábrica de Cerâmica do Algarve (FACEAL).

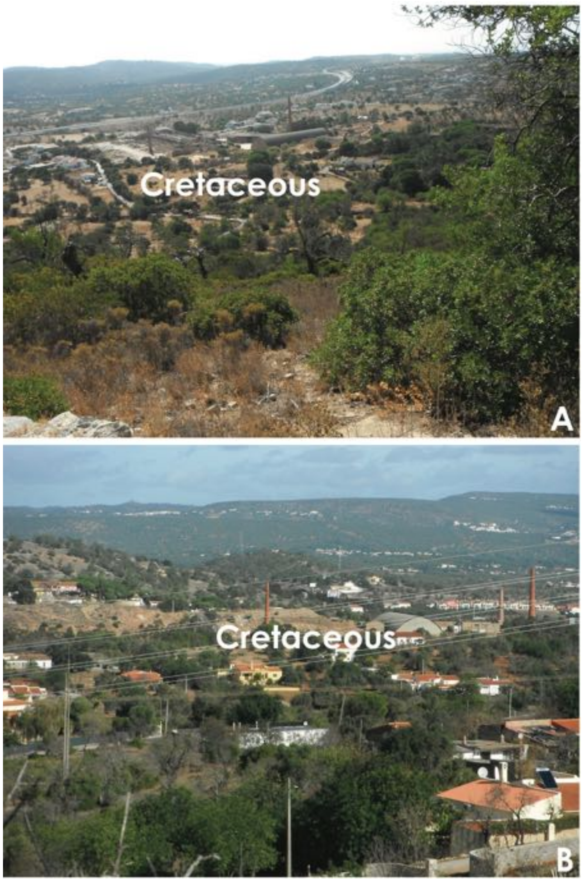


Figure 6.7. View of the outcrops of Cretaceous clays, observed from Cerro de São Vicente (A) and Cerro do Ouro (B). Note the FACEAL chimneys in both photographs. See also Figure 6.6.

CHAPTER 7
THE LAST RETOUCH IN THE LANDSCAPE TO CREATE THE *BARROCAL*

7.1. Landscape diversity

The morphological diversity of landscapes is the result of complex interactions between the lithosphere, the hydrosphere, the biosphere and the atmosphere. The landscapes we enjoy today result from the interaction between geodiversity, biodiversity, land use and human occupation and are still adapting to the legacy from the Pleistocene Epoch (see Figure 1.1), during which climate changes were frequent and of great magnitude. The last form of the Earth's surface is mainly, and it could not be any other way, the result of processes active during the last portion of geological time: the Quaternary Period (last 2.58 million years). The surface of the Planet is being altered by processes of external geodynamics, some processes slower than others, at times constructive and other times destructive. Extreme events also contribute to this modification, such as volcanic eruptions, earthquakes, tsunamis, floods and landslides, which, in minutes, profoundly alter the landscape.

The peaks and valleys, plains and plateaus, beaches and dunes, islands and capes are some of the elements of the natural landscape that resulted from the balance between construction and erosion processes. The rocky substrate plays a fundamental role in the speed at which the landscape changes and the rocks change, along with the climate and the amount of time during which the modeling agents exerted their action.

7.2. Rock weathering

When exposed on the Earth's surface, rocks are almost always out of balance with the conditions surrounding them, as they are different from those that existed in the environment in which they were formed. Therefore, through various processes and mechanisms, rocks are changed to more stable materials under surface conditions: clay minerals, the main components of the soil. The agents of external geodynamics, that is, the agents that promote the weathering of rocks under surface conditions, are the water, ice, wind and thermal amplitudes. At the same time, water, ice and wind are also agents of erosion and transport.

Weathering is the alteration of rocks found on the Earth's surface or very close to it and involves two different mechanisms: (i) chemical weathering – alteration through chemical reactions, leading to the modification of the composition of the rocks and sometimes to the formation of new minerals (neoformed minerals); (ii) physical weathering – a mechanism that solely includes mechanical breakdown of rocks. Although they involve distinct processes, chemical weathering and physical weathering rarely operate separately. On the contrary, the effects of one process favor the action of the other (Figure 7.1). However, depending on climatic conditions, one of the above forms of weathering may largely predominate over the other. This means that the type of weathering is a latitudinal process. For example, physical weathering predominates at high latitudes, where water occurs mainly in the form of ice and snow, while chemical weathering predominates in intertropical regions with high precipitation rates and high temperatures.

Carbonate rocks, such as limestones, dolomitic limestones, dolomites and marly limestones, are particularly vulnerable to chemical weathering, through a process known as "dissolution".

Dissolution is the process of chemical breakdown of minerals through the action of a solvent, which in nature is water. Each mineral has its own solubility balance, which reflects how easily it dissolves in water. Calcium (Ca) is among the most soluble elements, contrary to iron (Fe), which is soluble only under particular environmental conditions. For this reason, iron and clay minerals are the residual elements that remain in situ (Figure 7.2) after leaching, forming the clayey soil with a reddish color so characteristic of calcareous regions: *terra rossa*.

Terra rossa is the characteristic soil of carbonate regions with a Mediterranean climate. It is little

Figure 7.1. Alteration in the limestone of the Escarpão Formation. The fractures represented with white dashed lines and the layer planes represented with black lines make it easy for water to penetrate. Note that the layer planes are almost completely obliterated due to the alteration. The alteration results in limestone fragments and red clay (terra rossa). The two forms of weathering – chemical (dissolution) and physical (fracture) – contributed to the alteration of this outcrop.

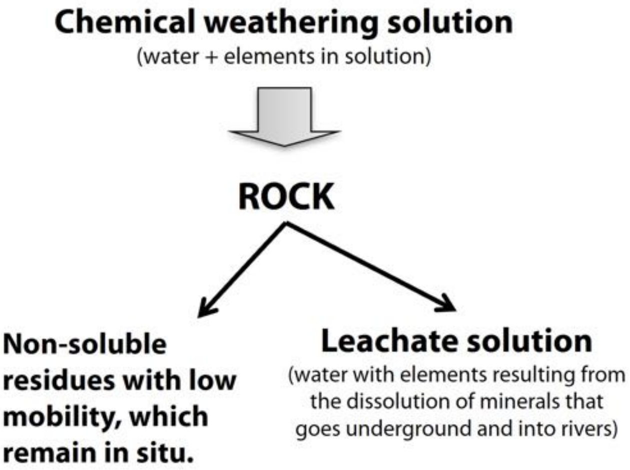


Figure 7.2. General schema of the chemical weathering of a rock.

dense, generally rocky, poor in organic matter and difficult to work with. During the wet season, it becomes waterlogged and, during the dry season, it opens deep cracks – retraction (or desiccation) cracking (Figure 7.3).

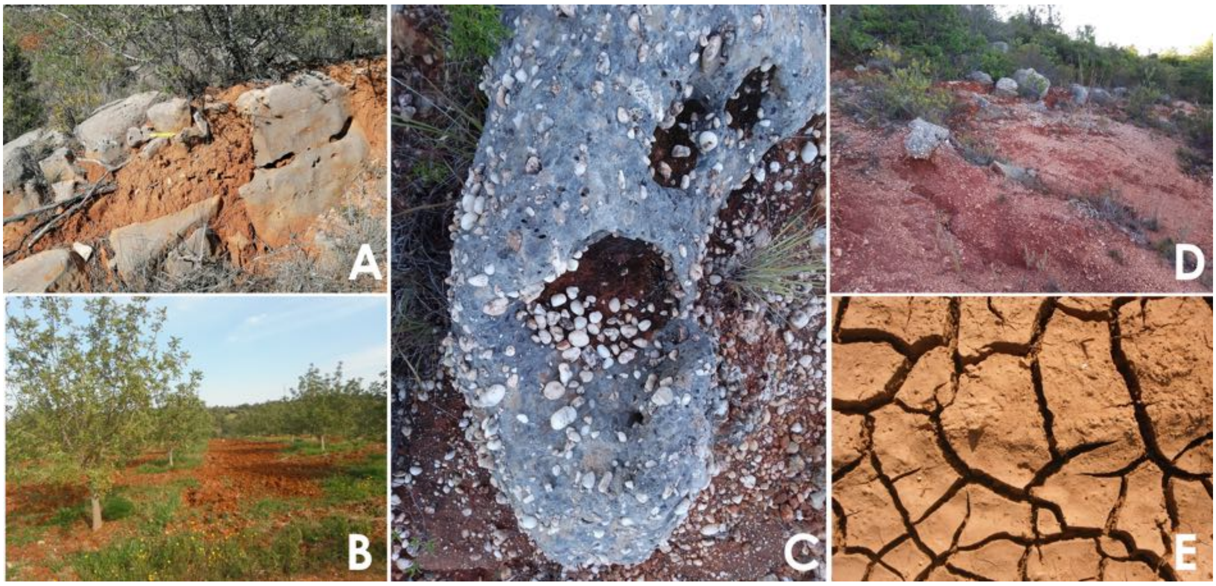


Figure 7.3. A: *Terra rossa* resulting from the dissolution of limestone. Note that dissolution was favored along the plane between the layers; B: Soil typical of limestone regions, this one in the Escarpão Plateau; C: Quartz pebbles that broke loose from the carbonate matrix due to its dissolution; D: Detritus residual phase composed of pebbles, mainly of quartz, silica sand and red clay due to the presence of iron oxides; E: Retraction cracks (or desiccation) in clays

7.3. Karst landscapes

Karst landscapes are a particular type of dissolution landscape characteristic of limestone regions that occur at all latitudes and altitudes, from the mountains to the coast. Although the name "karst" is traditionally used for the dissolution of carbonate rocks, it is sometimes also applied to other types of substrate, such as gypsum.

The progress of karst in carbonate rocks is governed by temperature, precipitation and the amount of carbon dioxide in the water. Therefore, it is easy to understand that the potential for carbonate dissolution is greater in humid and hot weather. In arid regions with a Mediterranean climate, such as the *Barrocal* of the Algarve, the development of karst is usually very slow. However, there were several humid phases throughout the Quaternary that boosted its development. For example, around 125,000 years ago, during the event known as the "Eemian", the climate was humid and warm enough for soils to be formed and the rate of karstification to increase.

Karst landscapes are usually very beautiful, with an enormous diversity of forms. On the coast, they contribute to the formation of capes, peninsulas, coves and caves (Figure 7.4).

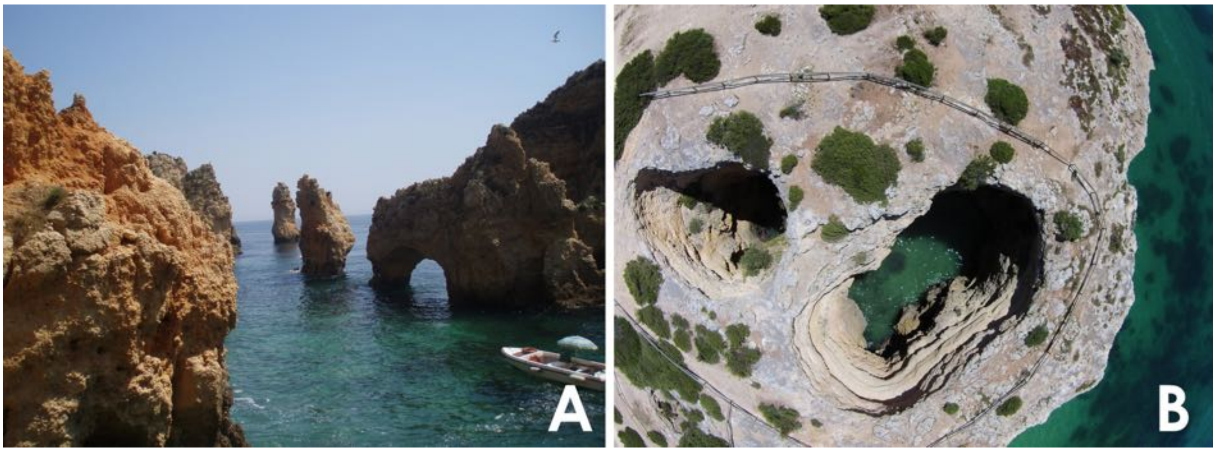


Figure 7.4. A: Ponta da Piedade, Lagos (Algarve); B: Drone image of the Albandeira gullies, Algarve.

The development of karst in deep areas generates a complex pattern of underground circulation (Figure 7.5) and poses serious problems for the management of the territory. These problems must be faced with particular care, both with regard to potential contamination of water aquifers and to seismic risk. Karst systems are the ones that contain the largest reserves of freshwater on the planet. For many decades before some river were dammed in the Algarve, as in many other arid regions, almost 90% of the freshwater needed for human consumption, agriculture, livestock and industry came from Jurassic aquifers.

The karst begins to develop on the surface ("epikarst"), originating during the first phase a morphology called "karren" (Figure 7.6). The rock exposed to meteoric water (rain) develops secondary porosity, which results in diffuse superficial circulation.

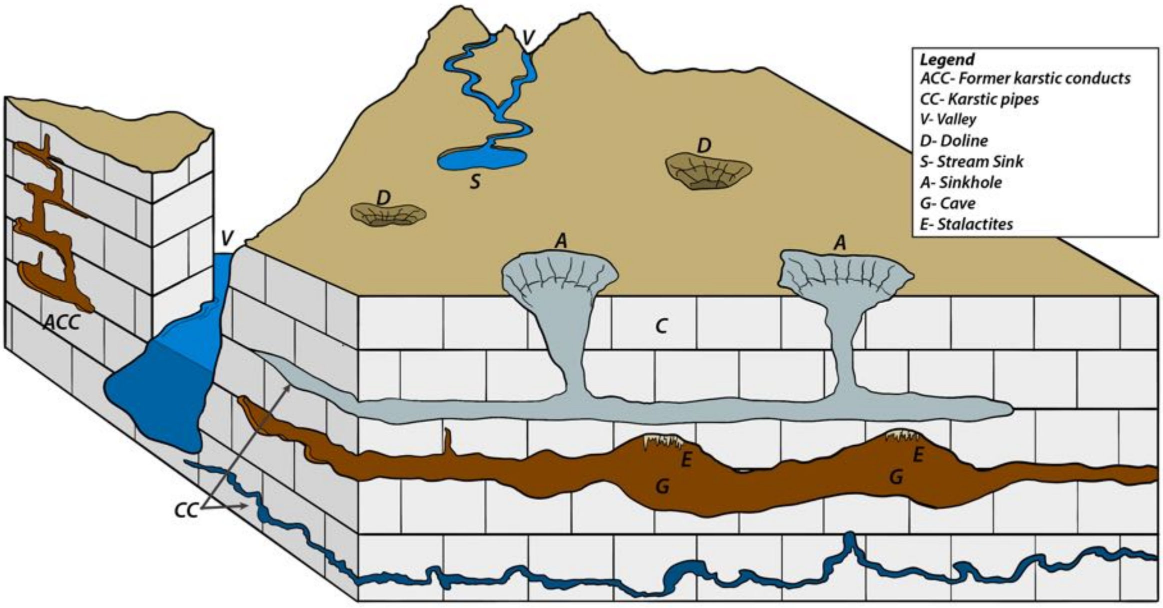


Figure 7.5. Schema of a karst system.

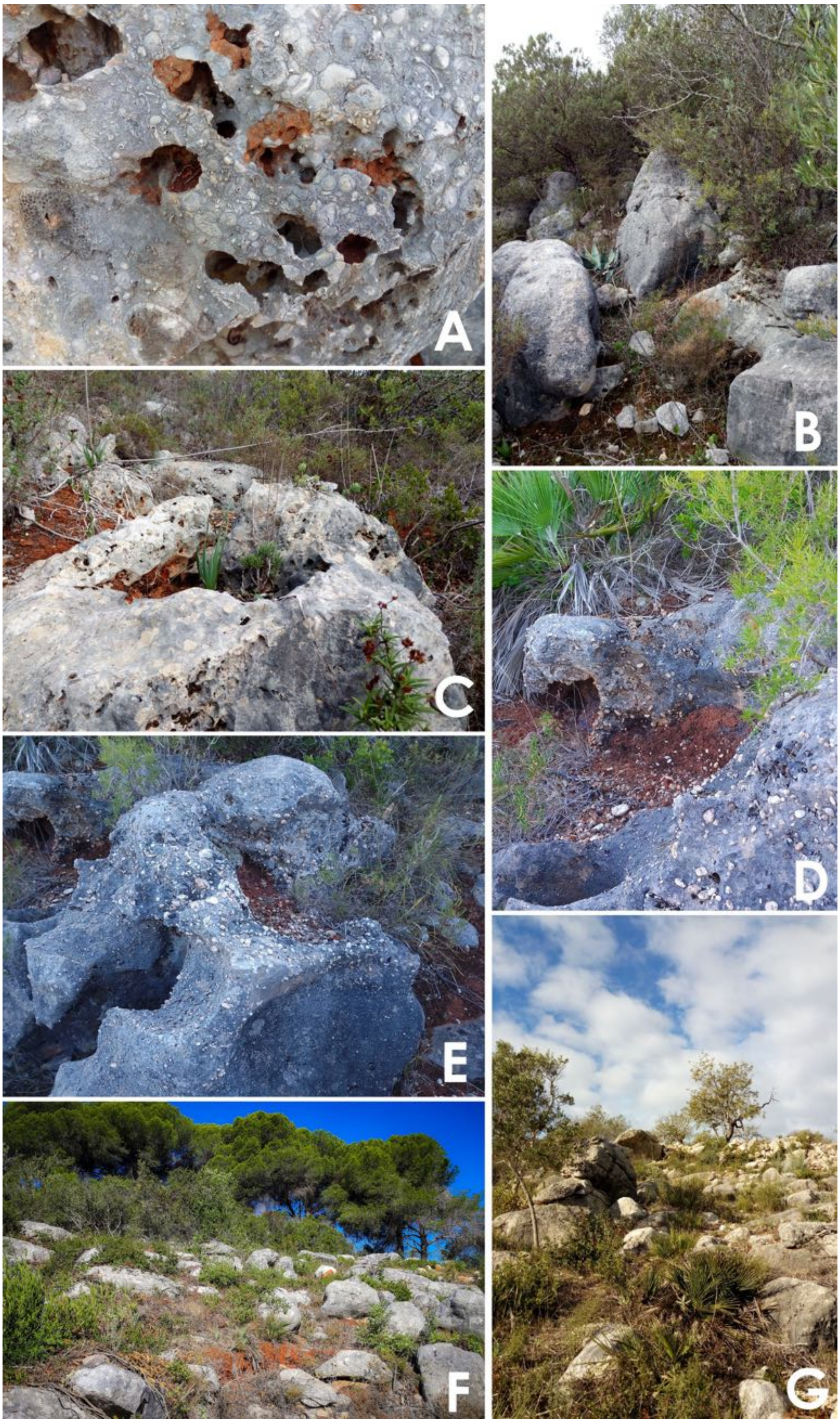


Figure 7.6. Field photographs on the Escarpão Plateau showing examples of karren (epikarst). A: Secondary porosity resulting from the dissolution of carbonate fossils; B to E: The result of the dissolution of the Terra rossa (reddish sediment in the dissolution vats); F and G: Characteristic landscape of karst zones (chaos of blocks).

The depth to which the epikarst extends is very variable, typically from 10 to 15 meters. The sinkholes, dolines and gullies are karst cavities that allow the infiltration of water into the subsoil (Figure 7.7).

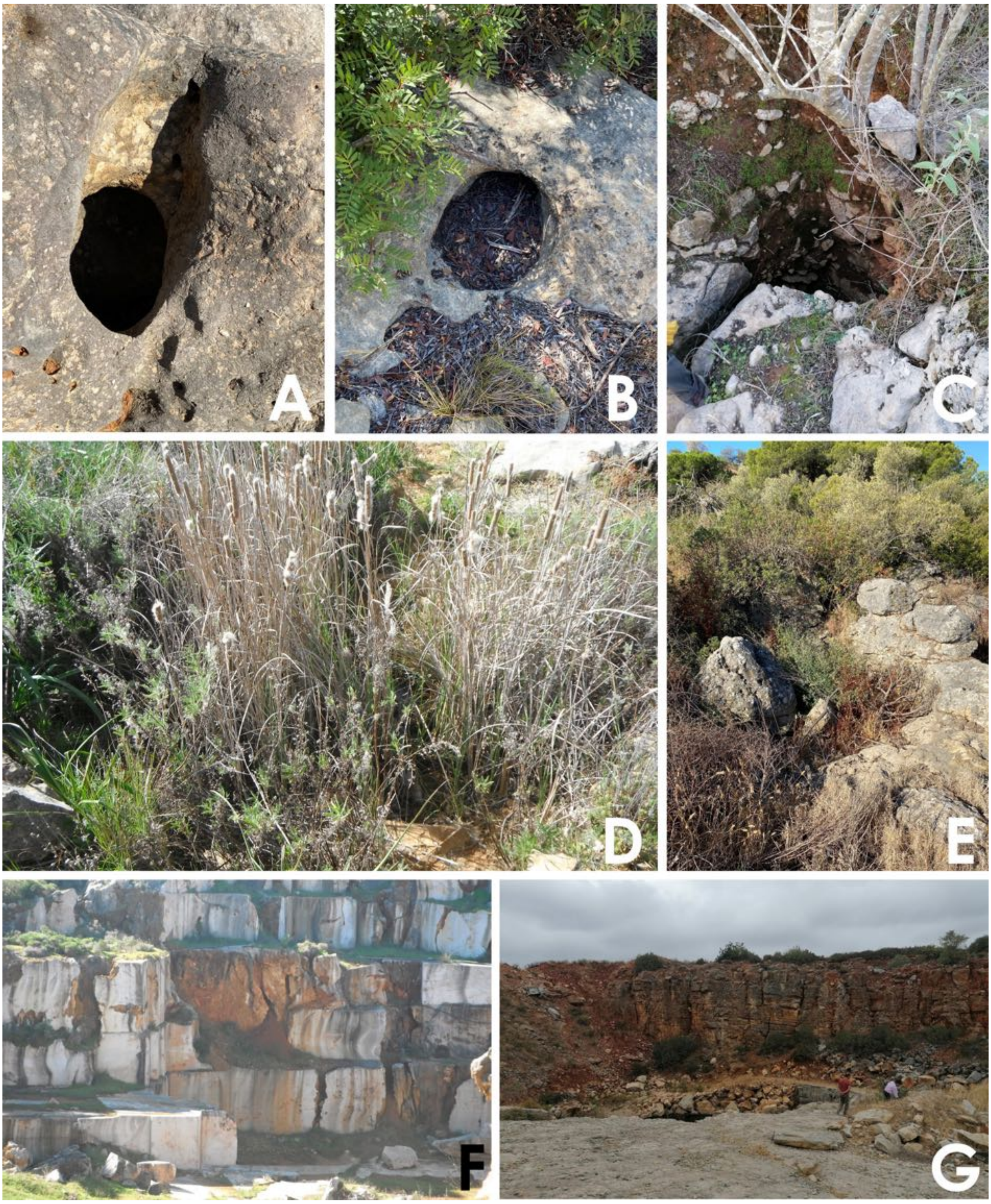


Figure 7.7. Aspects of karst related to water drain into the subsoil on the Escarpão Plateau, except for photograph F, which corresponds to a quarry between S. Brás and Moncarapacho. A, B, C and D: Sinkholes; E: Gully (local name: algarão) partially obstructed by soil and vegetation; G: Quarry on the Escarpão Plateau. In F and G, vertical fractures affecting the limestone thick layers and facilitating the infiltration of water.

Diffuse infiltration is replaced in deep areas with more organized flows through karst ducts, generally associated with fracture systems and planes between the layers to form aquifers.

In the Escarpão Plateau, large lapies did not develop (Figure 7.8), contrary to what happened in other places in the *Barrocal* of the Algarve, such as Varejota, where the mega lapies are truly remarkable.

The continued action of limestone dissolution led to the formation of karst plains, whose morphology is also called "chãs" in Portuguese. With the removal of the stones in those plains and the construction of support walls over generations, the soil holds and supports cereal crops (Figure 7.9). The location of karst plains depends on the original topography, most of the times structurally controlled.

Figure 7.8. Lapies on the Escarpão Plateau.

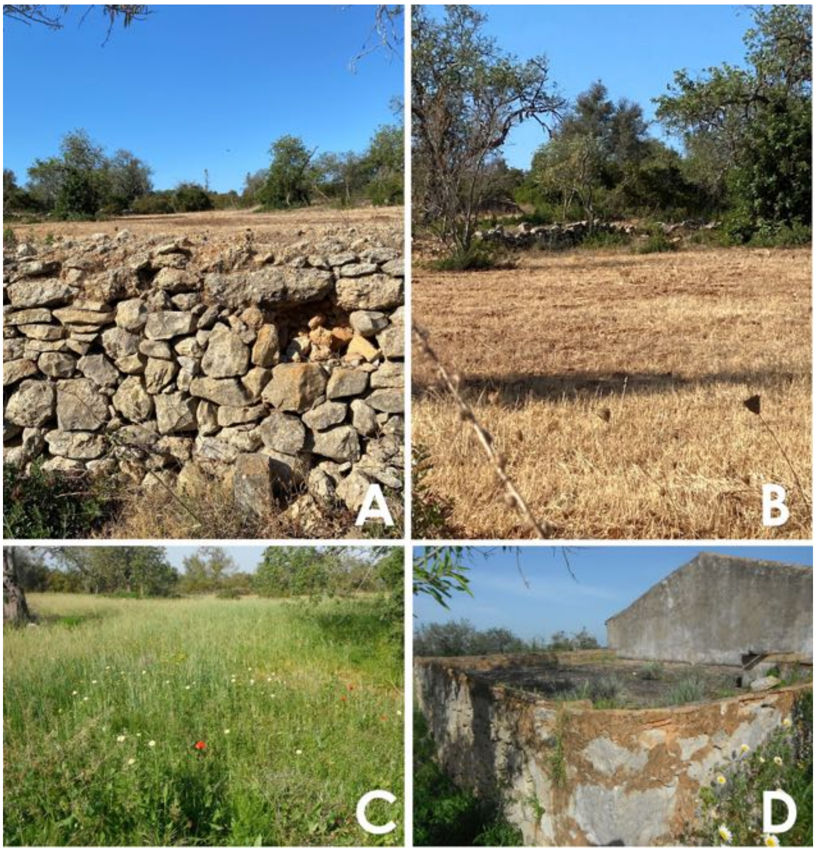


Figure 7.9. A and B: "Chãs" (in this case, karst plains) on the Escarpão Plateau; C: "Chã" cultivated with cereals; D: House with threshing floor, adjacent to the field in photograph C. In photograph A, note the wall built in dry stone, which does not constitute an ecological barrier.

7.4. Hydrographic network

The rainwater that falls on continental areas can follow four combined pathways: (i) infiltration, (ii) surface runoff, (iii) evaporation, and (iv) retention on the surface in lakes and ponds. The ratio between the water that infiltrates and the water that runs off the surface depends on two main factors: (i) permeability of the rock and soil, (ii) inclination of the topographic surface. It is the surface runoff water that gives rise to water lines of different lengths, from a simple ravine from where the water only flows during the period of precipitation, to rivers with a more or less constant regime.

The natural form of the land in Serra do Algarve contrasts strongly with that of the *Barrocal*. In addition to their obviously distinct lithology, the relationship between surface runoff and infiltrated water is also very different in these two natural regions of the Algarve. In Serra do Algarve, the water lines fit deeply into the substratum, forming tight valleys and ravines and the hydrographic network is very dense (numerous water lines per each surface unit). The drainage pattern is dendritic, that is, similar to the arrangement of branches in a tree. The explanation is simple. The rocks of Serra do Algarve are schist and greywacke (from the Paleozoic Era), quite impermeable, making it difficult for rainwater to infiltrate. For this reason, it runs mainly on the surface, through slopes and small water lines, which thicken to form streams and rivers. In the Barrocal, the relationship between the water that runs off the surface and that which infiltrates is the opposite of that described for Serra do Algarve. *Barrocal* rocks are mainly carbonate, very vulnerable to chemical attack. This, favored by the fractures and layer planes, opens cavities that facilitate water infiltration (karstification – see Sections 7.2 and 7.3). Contrary to Serra do Algarve, the drainage network in the *Barrocal* is not very dense and has a parallel or rectangular pattern that shows structural control (faults or lithological contacts). For example, only few and small streams get out from the Escarpão Plateau, running towards the base of the plateau. The high infiltration capacity of this region allows three aquifer systems to be fed: (i) Querença–Silves, (ii) Albufeira–Ribeira de Quarteira, and (iii) Quarteira. Several natural springs are surface manifestations of these aquifers. One example is Fonte de Paderne (Figure 7.10), but there are many others throughout the *Barrocal*.

The water carves and deepens its valley year after year, in a more or less quick process depending on the hardness of the substrate, the slope of the bed and the amount of water and solid load (sediments) transported. Regarding the control exerted by the rocky substrate over the process of valley-carving, we can consider three types of channels: (i) channels controlled by the substrate, (ii) alluvial channels, not controlled by the substrate, and (iii) channels semi-controlled by the substrate.

Quarteira stream is clearly controlled by the substrate. Its valley winds up in meanders dictated by fractures. There are no river beaches. The bed is all rocky, formed by layers of limestone, and is well embedded in the plateau (Figure 7.11).

The Quarteira and Algibre streams are structurally controlled by the Quarteira and Alportel faults, respectively. In the case of the Algibre fault, also known as the Algibre flexure, it corresponds to a thrust of Early Jurassic formations over Late Jurassic formations.

Figure 7.10. A: Public washhouse at Fonte de Paderne; Channeling of water to be afterwards transported by dikes and water channels to irrigate the flooplain; C:

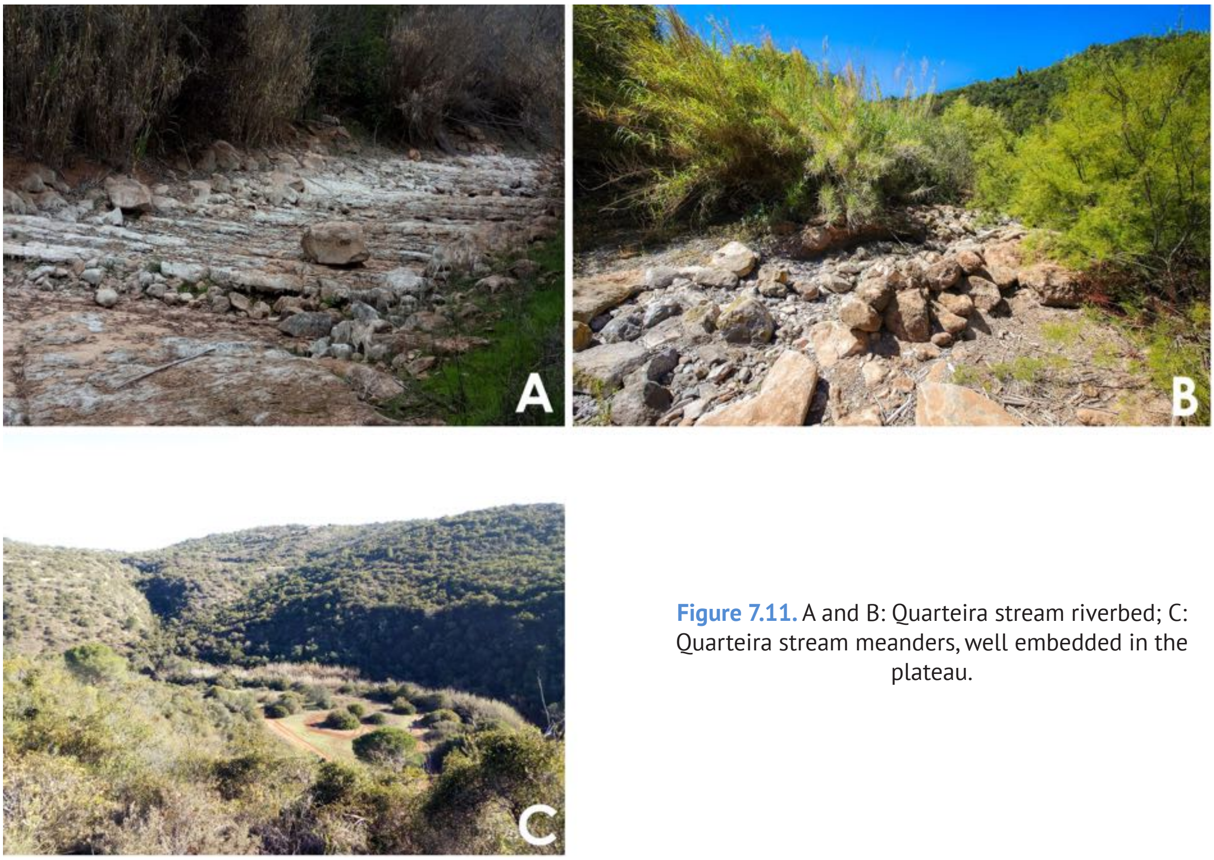


Figure 7.11. A and B: Quarteira stream riverbed; C: Quarteira stream meanders, well embedded in the plateau.

The Quarteira stream, NW-SE oriented, is the main stream in the region and takes this name after the confluence of two other streams, Alte and Algibre, about a kilometer north of Paderne. It is here that we find the most extensive floodplains ("várzeas", in Portuguese) in the region (Figure 7.12). "Várzeas" are flat lands located on the banks of rivers that were formed by the alluvium deposited when the water overflows the bed. They are naturally fertile areas. In a morphoclimatic context with little rainfall (Mediterranean climate) and infiltration promoted by rocky substrate, the streams have an ephemeral nature. One week is enough for the flood caudal typical of a period of intense precipitation to be reduced to a stony bed with only a few puddles, which will also disappear (Figure 7.13).

Figure 7.12. Landscape seen from Cerro Monchina. A: Confluence of the streams of Algibre and Alte, forming Ribeira de Quarteira, with the village of Paderne in the background. B: Floodplain (modern alluvium). Note the dike to carry water, very common in these regions where it is vital to make the best use of the scarce surface water.

Figure 7.13. A and B: Algibre stream on 20/12/2020; C: Algibre stream on 26/12/2020; D and E: View of the Quarteira stream facing south from the Purgatório Bridge (Paderne), on 20/12/2021 and 26/12/2021, respectively.

7.5. Evolution of the hydrographic networks

The introduction of feldspars and iron oxides in the basin at the end of the Pliocene (Figure 7.14) was interpreted as a result of the tectonic readjustment responsible for the uplift of Serra do Algarve, which rose by about 300–400 meters in relation to the Alentejo plain. This movement resulted in the reorganisation of the drainage networks. The main waterway routes that drained to the Alentejo plain were disorganized and began draining to the southern coast of the Algarve.

In addition to being subject to tectonic control, hydrographic networks also respond to changes in their base level. In most cases, the base level of hydrographic networks is the mean sea level, although it may also be a lake into which the river runs.

Figure 7.14. Coastal cliff between Praia de Olhos de Água and the mouth of Quarteira stream (extreme right). The upper orange part of the cliff corresponds to feldspathic sands with iron oxides from the Late Pliocene. The white feldspathic sand in the lower part of the cliff corresponds to a delta (mouth of a river) of the Middle-Early Pliocene.

The modification of the water lines base level results in the adjustment of their profiles to the new base level, which is the level below which there is no erosion and only the deposition of sediments carried by the river takes place. During regressions (mean sea level fall), the difference in level between the headwaters and the base level increases, and the erosion and transport capacity is reinforced. In these phases, the rivers deepen the valleys, which fit into the previously deposited alluvium (Figure 7.15).

Alluvial deposits abandoned at higher levels than the river's current layout, after its channel downcutting, and therefore disconnected from the processes that caused them, are called “fluvial terraces” (Figure 7.16). The granulometry (particle size) in the terraces depends on the transport capacity of the river and the available sediments to erode and transport. Sediments can be transported over long distances. The terraces on the section of Quarteira stream located in the Barrocal, and even at the stream’s mouth, have pebbles of greywacke and shale, transported from Serra do Algarve (Figure 7.16 B and C).

When there is a transgression (mean sea level rise), the river loses its ability to erode and transport, and preferentially deposits sediments (alluvium) in places where erosion and transport previously took place.

In somes places, the exploitation of alluvial clays for ceramics has produced changes in the morphology of the landscape. That has happened in the area of Barreiros area, where the extraction of clay by the factory FACEAL (Fábrica de Ce-

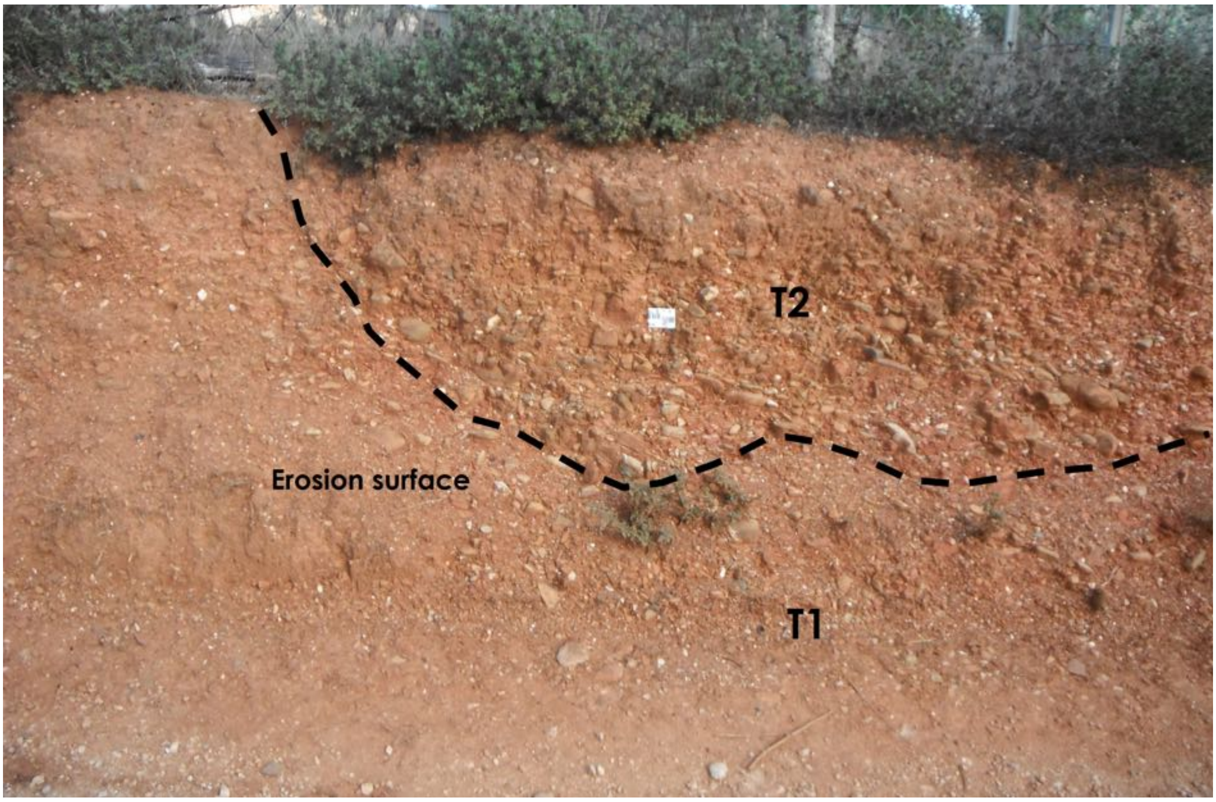


Figure 7.15. Two generations of fluvial terraces more than 270 meters away from Ribeira de Algibre and raised 12 meters from the current bed. The coarsest sediments from the most recent T2 terrace settle over the finer sediments from the oldest T1 terrace, through an erosive surface. It means that, in a more energetic phase, the stream excavated the oldest alluvium.

râmica do Algarve) produced an inversion of relief (Figure 7.16 D and E). This means that what was originally a slope (dotted line in photograph 7.16 D) is now a depression lined with clays where rainwater accumulates to form temporary ponds. Among other organisms, branchiopods – the tadpole shrimp Triops vicentinus, a rare species – live in these ponds (Figure 7.16 F).

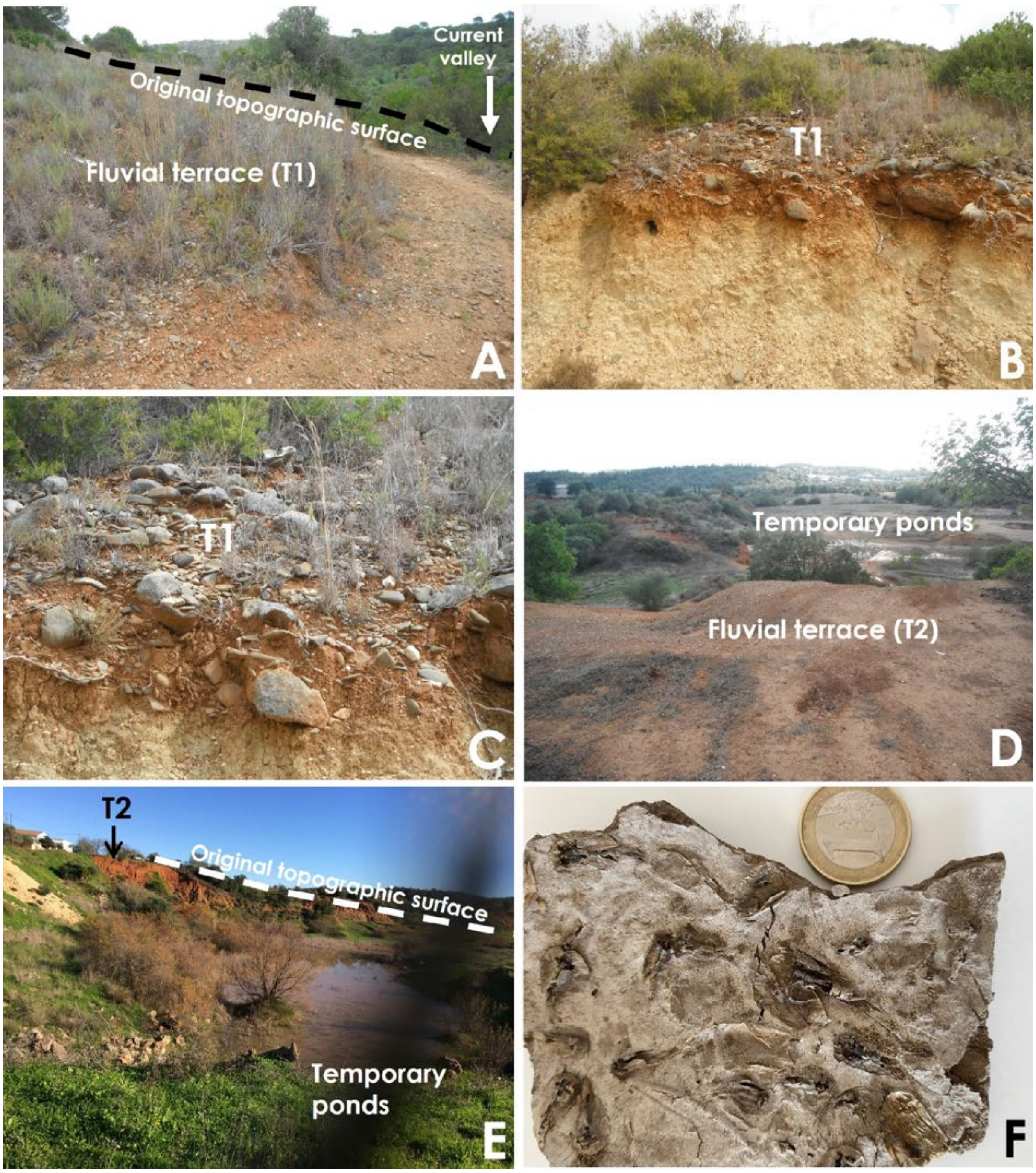


Figure 7.16. A, B and C: Fluvial terrace on the left bank of the Quarteira stream, about 5 to 10 meters above the current bed. The black dotted line in A represents the original topographic surface of alluvium deposition by the stream; D and E: Fluvial terraces of Ribeira de Algibre, in the Barreiros area, near Paderne (in the background of photo D) and Mediterranean Temporary Ponds (priority habitat 3170 - Habitat Directive 92/43/EEC); F: Fossils of small *Triops vicentinus* trapped in the mud of a temporary pond.

At present, the rate of mean sea level rise is about 3.1 millimeters per year. Rivers are finding it increasingly difficult to export sediments to the coast. Combined with the damming of water lines, this causes an enormous deficit of sediment in the coastal areas and the thinning of the beaches. Coastal erosion is currently one of the major concerns of all countries bordering the sea.

AFTERWORD

"Somewhere, something incredible is waiting to be known."

These words by Carl Sagan are perfectly suited to the project of the aspiring Algarvensis to UNESCO Global Geopark, to which this book contributes in an unprecedented way.

When reading this work, the Escarpão Plateau naturally appears as one of the most relevant geosites within the territory of the aspiring Geopark Algarvensis. One can understand the scientific importance of its geological history, the pertinence of its rocks and fossils for educational purposes, the cultural relevance of its landscape. As a whole, these aspects open up new perspectives for the region, including that of a more diversified type of tourism.

In the case of the Escarpão Plateau, the potential for tourism took the form of a new pedestrian route: the PR4 – "A Dive in the Jurassic Sea". It is the first route specifically designed from scratch for the aspiring Algarvensis and it was developed from the knowledge presented in this book. There are interpretive plaques along the route, inspired by the history and illustrations that make up the chapters of this work, and it also has complementary, multidisciplinary and georeferenced digital information, available in the story map of the same name.

Those who wants to see live all things described in this book will be able to take advantage of this new proposal for scientific and nature tourism, and make the memories created by their five senses take precedence over their reading. See the vivid colors of the vegetation covering the terra rossa; smell the freshness of Quarteira stream; touch the grooves of an ammonite or the wrinkles of a coral; hear the birds singing and, even, taste some delicious arbutus berries. This book is undoubtedly a structuring work, a milestone, which the authors bequeath to the project of the aspiring Algarvensis to become a UNESCO Global Geopark. An example of the scientific work that should be developed for other geosites. An inspiration on how to disseminate science in the area of Geology.

And for the concept underlying the UNESCO Global Geoparks to become a reality, a second volume is now needed to highlight the close connection that exists between the landscape, the environmental resources and the evolution of humanity and, in particular, of local communities.

So, we leave you here these challenges because...
... there are still many incredible things waiting to be known somewhere in the aspiring Algarvensis.

Cristina Veiga-Pires

GLOSSARY

Alkalinity. A measure of the ability of a solution to neutralize acids, which can be indicated by the pH.

Alpine Orogeny. Geodynamic phase on the formation of a mountain that occurred in the Cenozoic Era and which originated, for example, the genesis of the Pyrenees and the Alps.

Asthenosphere. Zone of the Earth's mantle, less rigid than the lithosphere, extending from about 80 to 200 kilometers below the Earth's surface.

Atoll. Ring-shaped oceanic island, consisting of reef buildups surrounding an interior lagoon.

Benthic. Organism that lives in or on the substrate of aquatic environments.

Bioclasts. Fragments of skeletal parts of organisms.

Biofacies. Set of fossil fauna and flora that characterizes the deposit where it is contained and individualizes it from other adjacent deposits.

Brachiopods. Exclusively marine benthic mollusks. They have a shell formed by two valves, similar to bivalve mollusks. Most of them have become extinct, with only 120 genera being still alive.

Calcite. Mineral composed of calcium carbonate ($CaCO_3$).

Catastrophism. Theory defended by Cuvier (French naturalist of the first half of the 19th century) according to which the Earth evolved as a result of catastrophic events. During these events, the fauna and flora in the region affected by the cataclysmic became extinct, the region being subsequently repopulated. Thus was explained the occurrence of fossils of marine organisms in places that are currently very distant from the sea.

Cephalopods. Exclusively marine predator mollusks, with excellent eyesight (e.g., squid, cuttlefish and octopus). Some cephalopods, like the nautiloids, ammonites and belemnites, had an external shell.

Chronostratigraphic table. Representation of geological time divisions.

Clasts. Fragments of rocks (lithoclasts), minerals (mineraloclasts) or shells (bioclasts) that occur in sediment.

Coccolithophorids. Unicellular photosynthetic marine algae, with a skeleton formed by calcium carbonate (coccoliths = skeletal plates).

Continental crust. Superficial layer of the lithosphere that constitutes the continents, with thickness varying from 20 to 80 kilometers.

Continental Drift. Theory that formulates the movement of continental masses over the geological time.

Crinoids. Exclusively marine echinoderms. Some species are known by the informal name of sea lilies.

Cyanobacteria. Group of bacteria that obtain energy by photosynthesis. Although inappropriately, according to some authors, they are also known as "blue algae" due to their color.

Dasicladaceae. A family of green algae with an erect thallus.

Demosponges. A class that includes most modern sponges. They have a skeleton formed by a substance exclusive to these animals (spongin). Most are irregular, but the growth pattern is varied and some are encrusting.

Diagenesis. Set of geological post-deposition processes that occur at low temperature (e.g., dehydration, compaction, dissolution and cementation) and lead to the transformation of sediments into consolidated rocks (lithification).

Diapir. Rocky mass of clayey-evaporitic nature. Its plasticity and low density allows it to ascend hundreds or thousands of meters vertically, due to the pressure exerted by the overlying layers.

Diatoms. Microscopic unicellular and photoautotrophic algae, with a siliceous skeleton (frustula).

Dinoflagellates. Unicellular beings that have flagella (filaments) and can carry out photosynthesis.

Dolomite (dolomite rock). Chemical sedimentary rock composed of double carbonate of calcium and magnesium $(Ca\ Mg)_2(CO_3)$.

Dolomitic limestone. Sedimentary rock formed by calcium carbonate in which some calcium ions (Ca) have been replaced by magnesium ions (Mg).

Earth's mantle. Layer of the Earth's structure below its crust, extending to 2900 kilometers in depth where it transitions into the Earth's core.

Echinoids. Family of Echinoderms to which sea urchins and starfish belong.

Equinoctial tide. Tide that occurs near the time of one of the equinoxes (March and September), when the Sun crosses the Earth's equatorial plane. On these occasions, the amplitude of the tide is maximal.

Erosion. Process acting on the Earth's surface that removes particles resulting from the alteration of rocks and soil. Wind, ice and water are the main agents of erosion.

Eukaryotes. Beings with a nuclear membrane.

Evaporites. Sedimentary rocks resulting from the crystallization and precipitation of salts dissolved in water due to its evaporation.

Exoskeleton. External skeleton (e.g., shells) that covers the body of some organisms.

Food web. Feeding relationship between organisms in an ecosystem.

Foraminifera. Single-celled organisms that produce a mineral shell (usually of calcium carbonate) or a shell of agglutinated detritus material (agglutinated shell).

Frustules. Frustules of diatoms are the carapaces of these microscopic algae, made up of silica (SiO_2).

Geodesic vertex. Point marked by a construction, usually conical, located in topographically elevated places, with visibility to other geodesic vertices, which indicates the exact geographic coordinates and height of that point. Each geodesic vertex is part of a triangulation network: national geodesic network. The towers of some churches are part of this network.

Geodynamics. Set of processes that occur on Earth and their consequences.

Heterochronous. Of different ages.

Horst-graben. Blocks between faults which are higher or more depressed than adjacent regions. The horst corresponds to a raised block, while the graben corresponds to the sinking area.

Hydrodynamism. Action of waves, currents and tides in the transport of sediment and in the modeling of coastal zones and seabeds.

Invertebrates. Multicellular animals without a backbone.

Isostasy. Vertical movement resulting from the need to maintain the gravitational equilibrium between the lithosphere and the asthenosphere.

K-T boundary. Cretaceous–Tertiary boundary coinciding with a Mass Extinction that occurred about 65.5 million years ago at the end of the Cretaceous.

Limestone. Sedimentary rock of biochemical origin formed by calcium carbonate ($CaCO_3$).

Lithify. Transform sediments into consolidated rocks.

Lithology. Composition of rocks.

Lithosphere. The outermost solid layer of the Earth, with variable thickness, composed of the crust (terrestrial and oceanic) and the upper mantle. It is thicker under the mountain ranges.

Lithostratigraphy. Study of the properties and sequencing of geological strata (layers).

Loading. Filling of a depression by successive deposition of sediments.

Marl. Carbonate rock containing from 35 to 60% clay.

Marly limestone. Carbonate sedimentary rock that contains a substantial amount of clay (up to 35%).

Micrite. Carbonate "mud" consisting of very small calcite crystals (less than 4 micrometers), which results from the precipitation of calcite by inorganic or organic processes.

Micrometer. One thousandth of a millimeter.

Monocline. Geological structure with inclined tabular layers, composed of two slopes, one more gently inclined than the other. It may originate an asymmetrical topographic form.

Morphotectonics. Branch of Geology that studies landforms produced by tectonic processes.

Normal faults. Also called gravity faults, they occur mainly in the distensive tectonic regime (pressure relief). The collapsed block slides in the direction in which the original fault plane was tilted.

Oceanic crust. Surface layer of the lithosphere that constitutes the bottom of ocean basins. Its thickness varies from 5 to 10 kilometers. It is denser than the continental crust.

Oncolites. Spherical sedimentary structures of an organic nature, millimeter to centimeter in size, formed in energetic marine environments.

Oolites. Spherical sedimentary structures of millimeter size (0.25 to 2 millimeters). They are formed by inorganic precipitation of calcium carbonate in concentric layers around a nucleus, which can be a grain of sand or a fragment of a shell. They occur in warm and agitated waters, with little input of terrigenous material.

Oozes. Pelagic sediments with at least 30% biogenic material.

Ostracods. Small crustaceans (0.1–32 millimeters) with a body encased in a two valves-shell.

Paleogeography. Reconstitution of the Earth's surface pattern or that of a given continental or marine area over geological time.

Paleontology. Study of fossil organisms.

Pelagic (domain). Aquatic domain where organisms do not depend on the bottom to settle.

pH. Dimensionless numerical scale used to measure how acidic or basic a solution is. It translates the activity of the hydrogen ion. Solutions with a pH of less than 7 are said to be acidic. If the pH is greater than 7, the solution is basic or alkaline. They are neutral if the pH is equal to 7.

Pisolites. Centimeter-sized (0.5 to 1 cm) spherical sedimentary structures. They are formed by inorganic precipitation of calcium carbonate in concentric layers around a nucleus that can be a grain of sand or a fragment of a shell. Like oolites, they occur in rough waters with little input of terrigenous material.

Precipitation of salts. Chemical reaction leading to the formation of solid material from a liquid, in which the components have been dissolved.

Quartz. Mineral composed of silica (SiO_2).

Radiolarians. Single-cell beings that secrete intricate mineral skeletons, usually of silica.

Regression. Mean sea level drop relative to a given reference positioned on land.

Rifts. Areas of the globe where oceanic crust is created accompanied by a drift in opposite directions from the rift valley, such as on the Mid-Atlantic Ridge.

Rudists. Exclusively marine bivalve mollusks with elongated or coiled and strongly asymmetrical valves. They lived in colonies, attached to the substrate. Very abundant during the Cretaceous, in the Tethys Sea, they became extinct at the end of the Cretaceous, on the K-T boundary.

Sedimentary facies. Set of physical, chemical and biological characteristics of the sediment that reflects the environment where it was deposited.

Sedimentation. Accumulation of sediment at a given location. Particles arriving at reception basins, such as lakes, estuaries, deltas and marine basins, settle by gravity at the bottom of these basins.

Siliciclastic sediment. Sediment composed of minerals and rock fragments. These minerals are mainly formed by silica, such as quartz, which is very resistant to changes.

Spongiary. Aquatic sessile (live attached to surfaces) animals, mainly marine. They can form extensive colonies and are common inhabitants of reef buildups.

Stratigraphic column. Schematic representation of geological strata arranged in vertical succession, from the oldest at the bottom to the most recent at the top.

Stratigraphy. Branch of Geology that studies the succession of strata, or layers of rocks.

Stromatolites. Organo-sedimentary structures built by microorganisms involved in mucilage. They trap sediment, forming mats with overlapping layers of decimetric to metric dimensions. Although rare, they can now be found in the shallow warm waters of Australia. They are the oldest known form of life on Earth.

Stromatoporoids. Reef-building sponges, living in warm, well-oxygenated waters with a low sedimentation rate and preferring carbonate substrates.

Subduction zone. Zone of convergence of lithospheric plates, in which the more dense oceanic plate slides under the less dense continental plate.

Subsidence (sinking). Downward vertical movement. It may be the result of tectonic movement and/or sediment compaction.

Tectonics. Branch of Geology that studies the structure and properties of the Earth's crust, in particular the forces and movements that gave rise to geological structures, like faults and folds.

Thrust. Geological structure formed by tectonic processes in compressive regimes. Fault in which one of the blocks partially or completely overlaps (carriage) the other.

Tintinnids. Single-cell beings that inhabit the interior of a shell of protein origin.

Trace fossils. Fossil records of the activity of organisms, such as footprints and tracks.

Transgression. Mean sea level rise relative to a given reference positioned on land.

Uplift (lifting). Upward vertical tectonic movement.

Upwelling (or coastal upwelling). Vertical currents that rise from the ocean floor towards the surface, cold and loaded with nutrients. Oceanic areas close to upwelling currents are very productive.

Zircon. Mineral composed of zirconium silicate ($ZrSiO_4$).

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CREDITS FOR FIGURES AND TABLES

Chapter 1

Figure 1.1
Sá, A.A., Meireles, C., Pereira, Z., Henriques, M.H., Pereira, D.I. & Piçarra, J.M., 2013. Tabela Cronoestratigráfica Internacional: versão portuguesa, Laboratório Nacional de Energia e Geologia (LNEG) https://repositorio.lneg.pt/handle/10400.9/2381
https://stratigraphy.org/ICSchart/ChronostratChart2021-10PTPortuguese.pdf

Figure 1.2
A: Jack Hills location in Australia. Image source: NASA Earth Observatory. Public domain, via: https://earthobservatory.nasa.gov/features/Zircon/zircon.html;
B: Jack Hills Mountains. Image taken by the Landsat satellite (July 27, 1999). Public domain via: https://upload.wikimedia.org/wikipedia/commons/1/13/Jackhills_etm_1999208_lrg.jpg;
C: Jack Hills zircon grains. Photographs by Aaron Cavosie, University of Puerto Rico. Free use, via: https://serc.carleton.edu/NAGTWorkshops/earlyearth/questions/zircons.html.

Figure 1.3
A: James Ussher portrait. Public domain, via: http://www.agen.ufl.edu/~chyn/age2062/OnLineBiology/OLBB/www.emc.maricopa.edu/faculty/farabee/BIOBK/ussher.gif;
B: Portrait of Georges Louis Leclerc, Count of Buffon, painted by François-Hubert Drouais. On display at the Buffon Museum. Public domain, via:
https://upload.wikimedia.org/wikipedia/commons/5/5e/Buffon_1707-1788.jpg;
C: William Thomson (Lord Kelvin). Public domain, via: https://en.wikipedia.org/wiki/William_Thomson,_1st_Baron_Kelvin#/media/File:Lord_Kelvin_photograph.jpg.

Figure 1.4
A: Portrait of James Hutton (public domain), via:
https://commons.wikimedia.org/wiki/File:James_Hutton.jpg;
B: Cover of the book *New Theory of the Earth*, by James Hutton. Source: https://www.milestone-books.de/pages/books/001667/james-hutton/theory-of-the-earth-with-proofs-and-illustrations;
C: Portrait of William Smith, painted in 1837, by Hugues Fourau. Public domain, via: https://commons.wikimedia.org/wiki/File:William_Smith_(geologist).jpg.

Figure 1.5
A: Marly limestone strata from the Peral Formation. Quarry in Agostos (Santa Bárbara de Nexe). Photograph by Delminda Moura, January, 2021;
B: Cretaceous marl stratification in a ceramics manufacturing exploitation front for Fábrica de

Cerâmica do Algarve (FACEAL), Mem Moniz. Photograph by Delminda Moura, September, 2020;
C: Granite outcrops on the Parque Barrocal [*Barrocal* Park] in Castelo Branco. Photograph by Delminda Moura, November, 2020;
D: Nepheline syenite outcrops at Fóia-Serra de Monchique. Photograph by Delminda Moura, September, 2016.

Figure 1.6
A: Photograph placed in the public domain by Mark Wilson (Department of Geology, The College of Wooster), via:
https://upload.wikimedia.org/wikipedia/commons/0/06/StromatoporoidSideDevColumbus.jpg;
B: Photograph placed in the public domain by Herve, via:
https://commons.wikimedia.org/wiki/File:Stromatoporoid1_Keyser_Formation.jpg;
C: Free-use image, licensed by Creative Commons Attribution 2.0 Generic license, via https://commons.wikimedia.org/wiki/File:Stromatoporoid_fossil_(Columbus_Limestone,_Middle_Devonian;_Ohio,_USA)_2_(28135552738).jpg;
D: Stromatoporoid, with structure replaced by calcite, due to diagenesis. Photograph by Luís Pereira, December, 2019.

Figure 1.7
A and B: Respectively, ammonite internal mold and belemnite rostrum from the Peral Formation, Escarpão Plateau. Photographs by Luís Pereira, 22/05/2020 and 29/02/2020, respectively.
C: Sample from an outcrop in Contessa, Italy, courtesy of Sarita Camacho. Property of Delminda Moura.

Table 1.1
Geological eras and some of the fossils dated by Periods. Produced by Delminda Moura.

Chapter 2

Figure 2.1
A: Map of the world by Gerardus Mercator, 1569. Public domain, via:
https://www.ncpedia.org/media/map/map-world-gerardus;
B: Portrait of Gerardus Mercator (1574), by Franz Hogenberg. Public domain, via:
https://pt.wikipedia.org/wiki/Ficheiro:Gerardus_Mercator2.jpg.

Figure 2.2
A: Supercontinent Pangea (541-252 million years old). Free use, via:
https://commons.wikimedia.org/wiki/File:Pangaea_continents.svg, licensed under *GNU Free Documentation License*;
B: Portrait of Alfred Wegener (1910, unknown author). Public domain, via: https://upload.wikimedia.org/wikipedia/commons/87/Alfred_Wegener_1910.jpg;

C: Drawing of a *Lystrosaurus murrayi* (dicynodont) from the beginning of Triassic, found in South Africa. Free use, via: https://commons.wikimedia.org/wiki/File:Lystrosaurus_BW.jpg, under the *Creative Commons Attribution-ShareAlike* license (*CC BY-SA)*;
D: Fossil of a *Mesosaurus* found in limestone from the Irati Formation (Paraná basin, Brazil). The specimen is on display at the Copenhagen museum of geology. Free use, via: https://commons.wikimedia.org/wiki/File:Mesosaurus_fossil.jpg licensed by: https://creativecommons.org/licenses/by-sa/3.0/deed.en.

Figure 2.3
Schema of the processes involved in continental drift- plate tectonics. Free use via: https://en.wikibooks.org/wiki/File:Plate-tectonics.png, licensed by Creative Commons Attribution-Share Alike 4.0 International https://creativecommons.org/licenses/by-sa/4.0/deed.en.

Figure 2.4
Topobatimetric map. National Oceanic and Atmospheric Administration. Public domain, via: http://www.ngdc.noaa.gov/mgg/image/2minrelief.html.

Figure 2.5
Scotese, C.R., 2002. "Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)." http://www.scotese.com, (PALEOMAP website). Adapted by Gabrielle Descamps and Sónia Oliveira.

Figure 2.6
Paleogeographic evolution of the continents from 225 million years ago to today. Image source: https://oceanexplorer.noaa.gov/okeanos/explorations/ex1803/background/geology/welcome.html.

Table 2.1
Events relating continental drift and global climate, from the Late Jurassic to the base of the Pliocene. Produced by Delminda Moura.

Chapter 3

Figure 3.1
Balance of particulate flows in the ocean. Figure adapted from Mosley& Liss, 2019.

Figure 3.2
Schema of a continental margin. Author: León Hormiga. Free use, licensed by Creative Commons Attribution-Share Alike 4.0 International license, via:
https://commons.wikimedia.org/wiki/File:Continental_shelf_(letters).png.

Figure 3.3
Worldwide distribution of continental shelves. Public domain, GEBCO world map 2014.

Figure 3.4
Distribution of marine sediments. Map created by Paul Webb. Credit: Steven Earle, *Physical Geology*- open textbook. Free use, via: https://commons.wikimedia.org/wiki/File:Distribution_of_sediment_types_on_the_seafloor.png, licensed by Creative Commons Attribution-Share Alike 4.0 International license.

Figure 3.5
Carbonate oozes
A: Foraminifera *Globigerina* sp. Author: Hannes Grobe. Free use via: https://upload.wikimedia.org/wikipedia/commons/c/c1/Foram-globigerina_hg.jpg, licensed by Creative Commons Attribution 3.0 Unported license;
B: Coccolithophores, *Coccolithus pelagicus*. Author: Richard Lampitt, Jeremy Young, The Natural History Museum, London. Free use, via: https://commons.wikimedia.org/wiki/File:Coccolithus_pelagicus_2.jpg, licensed by Creative Commons Attribution 2.5 Generic license;
C: *Coccolithus miopelagicus* from the Mem Moniz Spongoliths (Moura, 1998);
Siliceous oozes
D: *Lyrella_hennedy* diatom (1500 magnification). Author: Massimo Brizzi, free use, via https://commons.wikimedia.org/wiki/File:Lyrella_hennedy_1600x_contrast_invertion.jpg. Licensed by Creative Commons Attribution-Share Alike 4.0 International license;
E: Diatom from the Mem Moniz Formation (Moura, 1998);
F: Radiolarium *Calocycloma* sp. Author: Picturepest, free use, via:
https://commons.wikimedia.org/wiki/File:Calocycloma_sp._-_Radiolarian_(32163186535).jpg, licensed under Creative Commons Attribution 2.0 Generic license.

Figure 3.6
A: Olivine crystal from Naran-Kagan Valley, Pakistan. Author: Robert M. Lavinsky. Free use, via: http://www.irocks.com/db_pics/pics/gem7-10a.jpg, licensed by Creative Commons Attribution-Share Alike 3.0 Unported license;
B: Peridotite. Free use via: https://eos.org/wp-content/uploads/2016/09/peridotite-is-a-man- tle-xenolith-800x600.jpg;
C: Hand sample from the rock collection of the Department of Earth, Sea and Environmental Sciences, Faculty of Sciences and Technology, University of Algarve;
D: Galé Beach. Photograph by Delminda Moura, March, 2014;
E: Monte Velho Beach, Azores. Photograph by Sónia Oliveira, October, 2015;
F: Quartz crystals of different varieties. Property of Delminda Moura;
G: Ferromagnesian minerals from Fogo Island, Cape Verde. Property of Delminda Moura;
H and I: Microscope photographs courtesy of Cristina Veiga-Pires, from Búzios (Brazil) and Reunion Island, respectively.

Figure 3.7
Examples of carbonate platforms.
A: Satellite image (August 26, 2000) of the Australian Great Barrier Reef. Public domain, via: http://photojournal.jpl.nasa.gov/catalog/pia03401;
B: Satellite image (June 26, 2018) of the Belize atoll. Public domain, via: https://whc.unesco.org/en/news/1838;
C: Satellite image (March 16, 2002) of the Bahamas coral banks, by NASA. Public domain, via: http://www.ioccg.org/gallery/bahamabank.html;
D: Coral reef in Papua New Guinea. Free use, via: https://commons.wikimedia.org/wiki/File:Coral_reefs_in_papua_new_guinea.JPG, licensed under GNU Free Documentation License, Version 1.2.

Figure 3.8
Distribution of coral reefs and surface ocean currents. Map created with data from https://www.arcgis.com/home/item.html?id=26e71d14067c4b3f8dd31d1a4e008cfb by Sónia Oliveira.

Figure 3.9
Beautifully ornate and colorful shells characteristics of warm waters and coral fragment. Property of Delminda Moura.

Figure 3.10
A and B: Bioclasts collected on a Hawaiian beach, resulting from the breakup of the adjacent modern reef, property of Delminda Moura;
C and D: Respectively, sand from a beach in Cuba, and from a beach in Maldives, microscopically photographed, courtesy of Cristina Veiga-Pires;
E and F: Reef breccia, with fragments of stromatoporoids, sponges and rudists (Escarpão Formation);
G: Fossil of coral (Escarpão Formation);
H: Shell of present-day bivalve with intense bioperfuration, an indication it will break easily;
I: Ventral face of the same H shell.
Field photographs by Delminda Moura.

Figure 3.11
Schematic representation of a homoclinal carbonate ramp and its subdivisions. Schema prepared by Delminda Moura, Sónia Oliveira and Gabrielle Descamps.

Figure 3.12
A: Photograph of the nautiloid *Nautilus macromphalus* (Sowerby 1848). Author: Pujolle. Free use, via: https://upload.wikimedia.org/wikipedia/commons/b/be/Nautilus_macromphalus_-_edited_image.jpg, licensed by Creative Commons Attribution-Share Alike 4.0 International license;
B: Nautilus shell. Property of Delminda Moura.

Figure 3.13

Development in the number of phytoplankton species during the Mesozoic and Cenozoic. Figure adapted from: Knoll, A.H., Wörndle, S., Kah, L.C., 2013, Published by the Royal Society under the terms of the Creative Commons Attribution License http://creativecommons.org/licenses/by/4.0/, which permits unrestricted use provided the original author and source are credited.

Chapter 4

Figure 4.1

Location and geology of the Escarpão Plateau. Authored by Sónia Oliveira, based on the Geological Map of Portugal, scale 1/100 000.

Figure 4.2

A and B: Photographs of the Escarpão Plateau. Authored by Rui Gregório;
C: Schema (without scale) of the stratigraphy of the geological formations on the Escarpão Plateau and the way they are intersected by the valley of the Quarteira stream. Author: Delminda Moura and Sónia Oliveira.

Figure 4.3

Lithostratigraphic column of the geological formations that constitute the physical substrate of the Escarpão Plateau, in: Sónia Oliveira & Delminda Moura, July 2021, Report no 1/2021, "Conteúdos Placas Informativas, produzido no âmbito da criação de placas informativas no território de Albufeira incluído no Aspirante a Geoparque Algarvensis" [Informative Plaques Contents, produced within the framework of the creation of informative plaques in the territory of Albufeira included in the Aspirant Algarvensis Geopark], p.64.

Figure 4.4

Field photographs of the Peral Formation. Authors: A: Luís Pereira (31/12/2019); B: Luís Pereira (22/05/2020); C, D and E: Luís Pereira (29/02/2020); F: Delminda Moura (19/10/2019); G and H: Sónia Oliveira (10/11/2019).

Figure 4.5

Fossils found in the Peral Formation. Authors of the field photographs: Delminda Moura; Sónia Oliveira and Luís Pereira over 2020 and 2021.

Figure 4.6

Bioclasts that occur in the marls of the Peral Formation and were remobilized from the middle or inner ramp. Author: A, B, C, D and F: Luís Pereira (23/02/2020); E: Sónia Oliveira (11/10/2019).

Figure 4.7

Field photographs of aspects of the Jordana Formation. Author: Delminda Moura (08/2020).

Figure 4.8
Field photographs of aspects of the Cerro da Cabeça Formation. Photographs by Delminda Moura and Sónia Oliveira.

Figure 4.9
Oolites and pisolites in the Escarpão Formation, at the transition with the Cerro da Cabeça Formation. Photograph by Luís Pereira, Cerro do Malhão area, 2021.

Figure 4.10
Field photographs of the Escarpão Formation. A: Marly limestone thick layers; B, C, D and E: Bioclastic limestone thick layers; F: Stromatoporoid. Author: Luís Pereira.

Figure 4.11
Field photographs of the Escarpão Formation A, B and C: Gastropod fossils; D: Fossils of bivalve rudists; E: fossils of ostreidae. Author: Luís Pereira.

Figure 4.12
Field photographs of the Escarpão Formation. Blocks of coral, resulting from the erosion of the bioherm. Author: Luís Pereira.

Table 4.1
Comparison of the benthic foraminifera species present in four of the geological formations outcropping on the Escarpão Plateau. Produced by Delminda Moura. The species listed in the table were identified by Miguel Ramalho (2015).

Table 4.2. Comparison of the species of algae present in four of the geological formations outcropping on the Escarpão Plateau. Produced by Delminda Moura. The species listed in the table were identified by Miguel Ramalho (2015).

Chapter 5

Figure 5.1
Paleogeography at the end of Jurassic. Figure created by Sónia Oliveira based on Paleo reconstruction data from Kocsis & Scotese, 2021 and current coastline obtained at: https://www.eea.eu- ropa.eu/data-and-maps/data/eea-coastline-for-analysis-1/gis-data/europe-coastline-shapefile.

Figure 5.2
Schematic representation of horst-graben structures. Adapted from U.S. Geological Survey. Public domain, via: https://upload.wikimedia.org/wikipedia/commons/thumb/e/e3/Fault-Horst- Graben.svg/-2560px-Fault-Horst-Graben.svg.png.

Figure 5.3
Schema of the subenvironments of a carbonate continental shelf. Interpretation of the deposition environments of the Escarpão Plateau formations. Author: Delminda Moura, Gabrielle Descamps and Sónia Oliveira.

Figure 5.4
Anastamosed river system. Walmakariri River, Canterbury, New Zealand (27/06/2007). Free use, licensed from https://creativecommons.org/licenses/by/2.5/deed.en, via https://commons.wikimedia.org/wiki/File:Waimakariri01_gobeirne.jpg.

Figure 5.5
Cretaceous clays sedimentary sequence, in Mem Moniz, in one of the exploration walls of Fábrica de Cerâmica do Algarve (FACEAL). Photograph by Delminda Moura, 08/09/2020.

Figure 5.6
A: Coastal cliff in the Arrifes-Albufeira region;
B and C: Ichnofossils;
C: Macroscopic foraminifera;
D: Dinosaur footprint;
F and G: Layers of vegetation matter (continental influence). Photographs by Sónia Oliveira, 17/02/2013.

Figure 5.7
Coastal cliff in Luz de Lagos. Photograph by Delminda Moura, 23/11/2002.

Figure 5.8
Coastal cliff west of Albufeira (Castelo), consisting of Miocene sedimentary rocks.
Photo by Delminda Moura, 26/03/2018.

Figure 5.9
Microfossils from the Mem Moniz Spongoliths. A: *Reticulofenestra minuta* (cocosphere); B: *Coccolithus miopelagicus* (cocosphere); C: *Coscinodiscus tuberculatus* (diatom); D: *Microscleva* (sponge). Note: 1µm=0,01 mm. Source: Moura, 1998.

Table 5.1
Synthesis of the formations exposed on the Escarpão Plateau, paleoenvironments and geo-bioindicators. Produced by Delminda Moura.

Chapter 6

Figure 6.1
Examples of geodesic vertices (GV) on the elevated hills on the outskirts of the Escarpão Plateau. C: Photograph of the old mill that hangs on the wall of the current mill. Photographs by Delminda Moura, 08/09/2020.

Figure 6.2
Location of the hills and geodesic vertices mentioned in the text. The base on which they were marked is the geological map of Portugal, scale 1/100 000, Folha Ocidental, Serviços Geológicos de Portugal. Figure produced by Sónia Oliveira.

Figure 6.3
Limestone layers of the Escarpão Formation at the margin of the valley of the Quarteira stream. Photograph by Rui Gregório, 23/07/2021.

Figure 6.4
Schema of a thrust. Produced by Delminda Moura.

Figure 6.5
Cerro Monchina. Schema produced by Delminda Moura, Sónia Oliveira and Gabrielle Descamps. Field photographs, by Delminda Moura, 08/09/2020.

Figure 6.6
Schema of the geometric relations between Cerro do Ouro and Cerro de São Vicente, from the Late Jurassic, and the clays from the Early Cretaceous. Schema produced by Delminda Moura.

Figure 6.7
View of the outcrops of Cretaceous clays, observed from Cerro de São Vicente (A) and Cerro do Ouro (B). Note the chimneys of FACEAL in both photographs. Photographs by Delminda Moura, 21/10/2021.

Chapter 7

Figure 7.1
Alteration in the limestone of the Escarpão Formation. Photograph by Delminda Moura, 05/07/2019.

Figure 7.2
General schema of the chemical weathering of a rock. Schema produced by Delminda Moura.

Figure 7.3
A: *Terra rossa* resulting from the dissolution of limestone. Photograph by Sónia Oliveira, 20/01/2020;
B: Soil typical of limestone regions, this one on the Escarpão Plateau;
C: Quartz pebbles that broke loose from the carbonate matrix due to its dissolution;
D: Detrital residual phase.
Author of the photographs:
C and D: Luís Pereira, 06/05/2020
B and E: Delminda Moura, 06/05/2020.

Figure 7.4
A: Ponta da Piedade, Lagos, Algarve. Photograph by Delminda Moura; B: Photograph by an unmanned aerial vehicle (drone) of the gullies of Albandeira (Algarve), taken by Sónia Oliveira, 25/03/2014.

Figure 7.5
Schema of a karst system. Schema made by Delminda Moura, Sónia Oliveira and Gabrielle Descamps.

Figure 7.6
Field photographs on the Escarpão Plateau, showing examples of karren (epikarst). Authors of the photographs: A: Luís Pereira, 25/05/2020; B and C: Luís Pereira, 14/12/2019; D and E: Luís Pereira, 07/07/2020; F: Rui Gregório, 23/07/2021 G: Luís Pereira, 13/12/2019.

Figure 7.7
Aspects of karst related to water drain into the subsoil. Authors of photographs: A, B, D, E, F: Delminda Moura, March, 2019 to 17/08/2021; C and G: Sónia Oliveira, 20/01/2020.

Figure 7.8
Lapies on the Escarpão Plateau. Photographs by Luís Pereira, 28/12/2019.

Figure 7.9
Chãs on the Escarpão Plateau. Photographs by Delminda Moura, 26/03/2021 to 17/08/2021.

Figure 7.10
A: Public washhouse, at Fonte de Paderne; B: Channeling of water to be afterwards transported by dikes and water channels to irrigate the floodplains: C. Photographs by D. Moura, 31 May, 2021.

Figure 7.11
A and B: Quarteira stream riverbed. Photographs by Luís Pereira, 31/12/2019; C: Meanders of Quarteira stream, well embedded in the plateau. Photograph by Rui Gregório, 23/07/2021.

Figure 7.12
View of the landscape from Cerro Monchina. Photographs by Delminda Moura, 20/12/2020.

Figure 7.13. A and B: Ribeira de Algibre on 20/12/2020; C: Ribeira de Algibre on 26/12/2020. D and E: View of Quarteira stream facing south from the Purgatório Bridge (Paderne) on 20/12/2021 and 26/12/2021, respectively. Photographs by Delminda Moura.

Figure 7.14
Coastal cliff between Olhos de Água Beach and the mouth of Quarteira stream (extreme right). Photo by Delminda Moura, 02/04/2016.

Figure 7.15
Two generations of fluvial terraces more than 270 meters away from Ribeira de Algibre Sand and raised 12 meters from the current bed. Photograph by Delminda Moura, 26/12/2020.

Figure 7.16
A - E: Fluvial terraces. Photographs by Delminda Moura, 26/12/2020 to 31/05/2021.
F: Fossils of small *Triops vicentinus* trapped in the mud of a temporary pond, property of Delminda Moura, courtesy of Margarida Cristo, a Temporary Mediterranean Ponds researcher.

Each place contains within itself the history of the time that preceded it and that of the world it involved. The authors of this book adopted that idea as the starting point for this glance over the Escarpão Plateau. They chose a place where the rocks tell us about more than 150 million years of geological events and where the world of plate tectonics dictated the rules and left its traces. On a journey through time and space, this work explains how this plateau was formed, from the rocks we find there to the valleys that fit into them.

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