

# MESSEL

## An Ancient Greenhouse Ecosystem

Editors:  
Krister T. Smith  
Stephan F.K. Schaal  
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SENCKENBERG

Krister T. Smith, Stephan F. K. Schaal, Jörg Habersetzer (Eds)

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# **MESSEL – An Ancient Greenhouse Ecosystem**

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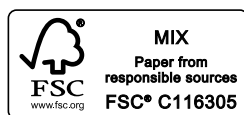
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## This book is dedicated to the memory of

### **Dr. Gerhard Storch**

May 21, 1939 – August 11, 2017



The paleobiologist Gerhard Storch dedicated a significant portion of his working life at Senckenberg to different mammals from Messel, such as pangolins, bats and rodents. These interests are reflected in numerous publications. For many years he was a valued colleague and for many of us a good friend as well. He always respected his colleagues on a personal level, and it was always easy to engage with him.

### **Dr. Gregg F. Gunnell**

July 19, 1954 – September 20, 2017



The paleontologist Gregg Gunnell was internationally known for his worldwide studies of Eocene mammals, particularly primates, carnivores and bats. These studies attracted considerable scientific attention to these groups, even outside paleontology. Visits to the Department of Messel Research and Mammalogy were a customary part of his work over the last 20 years, where he never failed to inspire and motivate us.

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The years of pleasant collaboration on common interests and their calm and pleasant demeanor bound these exceptional researchers to many of us as friends, nor were they neglectful of younger colleagues. Their friendship, personal enthusiasm and professional expertise will be sorely missed even as they remain in respectful memory.



## Foreword



Since 1995, the oil shale deposits of the Messel Pit have been included in the UNESCO World Heritage List – and for a good reason. With the Messel Pit, the State of Hesse is in possession of a unique window into geological history, a site that today offers a fascinating look into the world 48 million years ago. Nowhere else in the world can there be found a quantity and quality of fossils from that epoch that will reveal such a wealth of detail to the experienced observer.

Therefore, the now petrified habitat at Messel is a significant treasure for the State of Hesse. Today, our state owes its high quality of life in no small part to the widely protected natural landscapes, which make up one third of the state's land area. Does it thus not stand to reason to also protect the valuable fossil habitat of "Messel" – in particular, since it is of such global scientific significance?

After a tumultuous history that, for several decades, was marked by the clashing interests of various user groups, the spectacular paleontological research findings from the Messel Pit played a significant role in favor of the pit's preservation for science, and thereby the recultivation of the former oil shale surface mining. The State of Hesse supported the preservation by purchasing the mining operation in 1991, along with the permit rights for the extraction of oil shale.

Now it is up to us to preserve this magnificent piece of natural history. Together with the Senckenberg Gesellschaft für Naturforschung, the Hessian State Museum in Darmstadt and the Visitor Information Center Messel Pit GmbH, the State of Hesse pursues this challenging task. Today, exhibitions in Frankfurt, Darmstadt and Messel as well as in major natural history museums abroad display fossils from our Hessian world heritage. In this context, we are particularly pleased with the intensive civic involvement. I extend my heartfelt thanks to all of you for your commitment to the preservation and exploration of the Messel Pit.

For several decades now, scientists of the Senckenberg Gesellschaft für Naturforschung have been conducting research at the Messel Pit, frequently in conjunction with national and international experts. They perform extensive paleontological detective work, thereby helping to open a large window for the public into the history of our earth and its life. With impressive images of rare fossils and with varied and exciting texts, the present book draws a vivid picture of the world in Messel.

My thanks go to all who contributed to this book. I hope the readers will find enjoyment and, above all, many new insights while perusing this volume.

A handwritten signature in blue ink, which appears to read "Volker Bouffier".

Volker Bouffier  
Minister President of the State of Hesse

## Foreword



When the discovery of a fossil crocodile was reported near Messel in the year 1876, nobody could foresee that this location would one day become an important World Heritage Site. More than 100 years had to pass before this status was achieved. Oil shale surface mining for the production of fuel gas was established and later abandoned, followed by almost 20 years of discussions regarding the future use of the mine. At the same time, efforts began to extract the real treasure of Messel: unique fossils, 48 million years old and of high scientific value. These fossils and their history form the content of the present book.

On 9 December 1995, the Messel fossil site was added to the UNESCO World Heritage List, which currently includes 1052 sites in 165 countries, among them 41 World Heritage Sites in Germany. This is impressive proof of the great universal significance of the Messel site as a heritage for humanity and its worldwide recognition. Since 1975, Senckenberg has been conducting research in the oil shale deposits, taking over the surface mining operation at the Messel Pit on 1 July 1992. That same year, a special department was established for this purpose. Senckenberg decided to make the Messel Pit a research focus and, together with the Hessian State Museum in Darmstadt, another Hessian institution, to open a window for the general public into the history of our earth and its life.

But why is Messel so valuable for science? With its uniquely preserved, 48-million-year-old fossil remains, the site offers an unusually complete insight into a long vanished ecosystem, which existed under conditions very different from those encountered today. Back then, the area was dominated by a greenhouse climate with extremely high atmospheric carbon levels far in excess of 1000 ppm, with high precipitation and mean annual temperatures of  $18 \pm 2.5^\circ\text{C}$  – i.e., conditions we are approaching once again today, due to the anthropogenic carbon dioxide emissions. And of equal importance: Messel offers us a unique look at the early evolution of mammals, including our own ancestors, which was only made possible by the extinction of the dinosaurs 66 million years ago.

The year 2017 marks a special anniversary of the Senckenberg Gesellschaft für Naturforschung: We look back at 200 years of exciting nature research and are very pleased to discover that there were many high points, to which the Messel research contributed greatly in the past decades. This is impressively documented by the large number of scientific publications by German and international Messel researchers, and we have been successful in our attempt to make these results available to the public by all suitable means. In the context of our museum construction project in Frankfurt, a new, expanded Messel exhibition is in the works for the near future.

Following the 25th anniversary of the Department of Messel Research and Mammalogy, this second, popular-scientific book about Messel is being published by Senckenberg. With impressive images of rare fossils from public and private collections and with diverse texts, it demonstrates the impressive advances in Messel research, while at the same time pointing out the potential yet to be tapped.

With this book, published in English and German, we attempt to live up to our goal of imparting this knowledge in an understandable and adept manner. At the same time, we would like to increase the interest in the world heritage and offer fascinating insights into our prehistoric world.

I wish our readers much enjoyment when immersing in the Eocene epoch, a heartfelt “Glück Auf!” to the excavation and preparation team of the Messel surface mining operation, and exciting findings and lively discussions for all Messel researchers. And if reading this book whets your appetite for more, simply stop by the Visitor Information Center at the Messel Pit, which is always worth a visit.

Prof. Dr. Dr. h.c. Volker Mosbrugger  
General Director of the Senckenberg Gesellschaft für Naturforschung

## Foreword



The Messel Pit, one of the world's most important cultural and natural monuments, was added to the World Heritage List on 9 December 1995 as Germany's first UNESCO Natural Monument. Since the fossil site's discovery in the late 19<sup>th</sup> century, outstanding fossils have been recovered in southern Hesse.

If you look at the outstandingly well-preserved fossils, it is hard to imagine that they owe their preservation to the destructive force of a volcanic eruption. But it was this very force that created the deep crater in which the Messel Lake formed. Thus, a basically horrible event created the perfect environment for allowing this diverse primeval forest habitat to endure throughout the ages, to be unearthed again 48 million years later, intact with its entire original inventory. And the discovery of this unique fossil habitat was again connected to an act of destruction – in this case by the hand of man. For it was the mining for lignite and, later, oil shale that enabled the uncovering of this treasury in historic times.

Following Rudolf Ludwig's notice in 1876 regarding the first discovery of crocodile bones, it became increasingly clear that the Messel Pit carried a significant scientific potential. The Hessisches Landesmuseum Darmstadt started the first scientific excavations in 1966, but they were only conducted on a regular basis since 1971, after cessation of the mining operation. In the early years, a number of other museums and university institutions were involved in the digs, e.g., Karlsruhe, Tübingen, and Brussels. Currently, the excavations are primarily run by the Hessian State Museum in Darmstadt and the Senckenberg Gesellschaft für Naturforschung in Frankfurt. The rich, globally unique fauna and flora unearthed in the process has provided such a wealth of data that the time has come to summarize the latest findings.

Thankfully, with the present book, the colleagues at the Senckenberg Gesellschaft für Naturforschung direct the focus back to the unique archive of geological history. Together with numerous other researchers, they present the new scientific results regarding the fossils, their habitat and the living conditions in and around the Messel Lake as well as the climate and evolution, based on a number of outstanding examples.

Dr. Gabriele Gruber

Head of the Department of Natural History at the Hessisches Landesmuseum Darmstadt

## Preface

This second Messel book by Senckenberg, published simultaneously in German and English, will introduce readers with an interest in nature to the results of the research conducted since the 1970s by biologists and geo-scientists on the unique fossils from the Messel oil shale deposits. Alternatively, you can simply peruse the illustrations and take pleasure from the beauty of the 48-million-year-old fossils.

Most of the illustrated fossils are part of the Senckenberg collection and thus primarily originate from our own research excavations. Additional fossils illustrated here come from the Hessian State Museum in Darmstadt as well as other museums and private collectors. We are extremely grateful to them for making their fossils and photographs available. A complete list of the institutions and collections can be found in the image captions and sources.

We would like to pay tribute to all who were involved in the campaign to permanently preserve the Messel Pit, from the cessation of the mining activities until its purchase by the State of Hesse, and who helped to unearth the traces of a buried world and make them widely available for future generations. Besides volunteers and honorary fossil hunters, this also includes hundreds of interns who supported the institutes during their annual digs. Our technical assistants and taxidermists always assured the required care and quality during the excavations and preparation. We express our heartfelt thanks to all of the authors who, with their respective chapters, contributed to the book's success. The large number of contributions adds a personal touch to each individual chapter and impressively demonstrates the international co-operation. The up-to-date, first-hand information makes the topics accessible to the discerning, interested layperson without abbreviating the scientific content. In the two editions of this book, the change of primary editor represents the competency of the respective native speaker.

Twenty-five years ago, the Department of Messel Research was established at the Senckenberg Research Institute in Frankfurt am Main. For Senckenberg, which had already been conducting scientific excavations in the pit since 1975, this solidification represented an important step and an acknowledgement of the Messel research. The research, carried out in conjunction with many German and international scientists, produces exciting results but also illustrates that the species diversity at the site has only been incompletely recorded to date. Based on extrapolations, it is likely that there are still many species of invertebrates waiting to be discovered, and that the known diversity of seed-bearing plants and several groups of vertebrates may increase significantly. Therefore, it stands to reason that several future generations will continue to be involved in exploring the fossil site.

New methods established in paleontology during the past decades, e.g., 3-D computer tomography for non-destructive analysis of bone structures, have significantly improved the examination of Messel fossils in regard to both qualitative and quantitative data. Accordingly, more exciting research findings can be expected in the future, which will further increase our understanding of the Messel ecosystem.

The inclusion of the Messel Pit Fossil Site in the UNESCO World Heritage List in 1995 represents a global acknowledgement and appreciation of the work done by many involved persons. In the year 2020, the Messel Pit will celebrate its 25-year anniversary as a World Heritage Site. This success story gives all of us a reason to be proud.

Krister T. Smith

Stephan F. K. Schaal

Jörg Habersetzer

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# Chapter 1

## Messel – Eventful Past, Exciting Future

Stephan F. K. Schaal

**About 48,270,000 years ago** Volcanism in Europe causes the formation of maars – differently shaped craters of variable depth – thereby creating space for maar lakes and the deposit of lake sediments. According to the plate tectonic model by Scotese (2013), at the time of its formation, the Messel Maar was located at the current geographic latitude of the Alps. The crater quickly filled with water and sediments began to accumulate as Messel drifted northward with the European continental plate (Chapter 2).

**About 47,300,000 years ago** Over a period of about 1 million years, the Messel oil shale was formed. Upon filling up with sediments, the maar is silted up and from now on holds the fossilized remains of animals and plants from paratropical habitats (Chapter 3).

**About 30,000,000 years ago** The lifting and folding of the Alps begins. Central Europe – an island archipelago at the time – becomes dry land as the Antarctic binds significant amounts of water as ice and sea level drops. The Alpine region as well as the area including the Messel Maar located farther north are affected by tectonic uplift; this is followed by erosion (continuing to the present day). Several hundred vertical meters of material are eroded in the Messel region.

**Start of modern chronology** The Messel Maar has reached its current position, now located farther to the north. From the time of its origin until today it moved approximately 500 km northward, due to the shift of the European continental plate (Fig. 2.2; Chapter 2).

**18th century** Oil shale is discovered south of the village of Messel, located between Frankfurt am Main and Darmstadt in the state of Hesse.

**19th century** The first fossil crocodylian is recovered from the oil shale layer in 1875, and the discovery is described shortly afterwards (Ludwig 1877). The first paper offering an overview of the fossil site's geology and paleontology is published (Wittich 1898). Following the awarding of the Messel claim, the Messel Union is founded in 1884 for the exploitation of ironstone and lignite. In addition, a pyrolyzation plant is operated for the production of mineral oil and paraffin from the oil shale.

**1912** A contractual agreement with the mine owner transfers the sole rights of the Messel fossils to the Grand Ducal Museum at Darmstadt (the future Hessian State Museum Darmstadt). Henceforth, until 1973, all fossils recovered in Messel find their way into the Darmstadt fossil collection.

**1945–1959** The production facilities are destroyed during World War II, but are immediately rebuilt after the end of the war. The facility is seized by the American military government and, until 1953, is under the auspices of the I.G. Farbenindustrie AG, Frankfurt am Main. The facility is converted into a paraffin and mineral oil factory. A mining and extraction agreement is entered into with the state of Hesse.

**1959** The YTONG concern, an aerated concrete manufacturer from Sweden, takes over the paraffin and mineral oil factory Messel GmbH (Beeger in Schaal & Schneider 1995).

Fig. 1.1: View into the Messel Pit, summer of 2017.

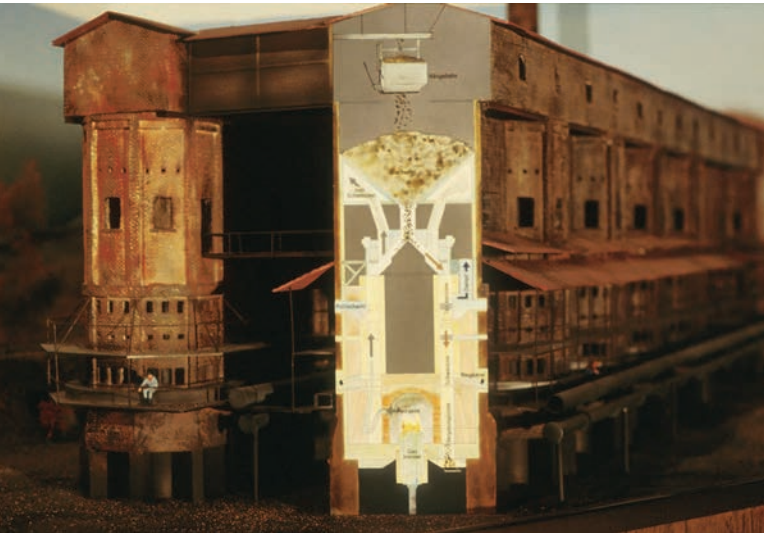


Fig. 1.2: Model of the carbonization plant with the circular kilns at Messel.

**1961** For the first time it is possible to successfully transfer the highly delicate Messel fossils to synthetic resins. A scientist from Berlin uses various materials in order to fixate the original bones in a way that allows subsequent examination at any time and permanent storage (Kühne 1961). The transfer method described by him is later regularly applied and individually developed by private fossil collectors and the preparators of research museums active in Messel.

**1966–1967** Initiated by the Hessian State Museum in Darmstadt, the first two systematic fossil digs are conducted in Messel (Kuster-Wendenburg 1969).

**Late 1960s to late 1980s** Still tolerated to a certain degree, private collectors continue to successfully search for fossils in the oil shale (Behnke et al. 1986), unearthing significant specimens in the process. Thus, the work of private collectors also led to an important contribution toward the exploration of the now world-famous fossil site.

**1971** Final cessation of the industrial oil shale extraction. The fossils' remarkable state of preservation and the synthetic resin transfer method developed in the 1960s cause a renewed increase in digging activity by private collectors. These activities take place within a "gray zone" without proper permits by the mining authority, yet they are tolerated by the responsible parties.

Upon the announcement of initial plans to fill the Messel Pit with garbage from the region of Darmstadt, Dieburg, Offenbach and Frankfurt, citizens of Messel organize a citizens' initiative against the planned landfill. At the same time, scientists caution against the loss of the fossil site and the consequences for paleontological research.

**1975** Upon receiving the official excavation permit, the two large Hessian institutions – the Hessian State Museum (Hessisches Landesmuseum) Darmstadt (HLMD) and the Senckenberg Natural History Society (Senckenbergische Naturforschende Gesellschaft) in Frankfurt am Main – begin conducting regular scientific digs at Messel. In addition, there are short-term activities by various other institutions, in particular during the 1980s.

The "Citizens' Initiative for the Prevention of a Landfill at the Messel Pit" founds an association and, according to its bylaws, "...makes it their mission to preserve the natural and social environment of the citizens of Messel, the citizens of Darmstadt and other municipalities, therefore working decisively against the establishment of a major landfill in the Messel Pit."

**1977** The Senckenberg Museum in Frankfurt puts on a special exhibition entitled "Prehistoric Horses and Crocodiles" in close co-operation with participating private collectors.

**1980** Two years after its foundation, the Museumsverein Messel e.V. (Messel Museum Association) opens a fossil and local history museum in the old city hall. An impressive model of the pyrolyzation plant with circular kilns, built especially for the exhibition, brings the local industry of the past back to life (Fig. 1.2).

**1981** Upon receiving the planning approval decision for the conversion work and the filling of the pit with garbage, the Higher Mining Authority orders the immediate implementation. Since legal remedies do not have a suspensory effect, the conversion of the surface mine into a landfill may commence despite the pending appeal to the Administrative Court in Darmstadt. The "Citizens' Initiative for the Prevention of a Landfill at the Messel Pit" and the municipality of Messel file a suit against the decision. The ensuing years are characterized by legal disputes and continuing construction work in the abandoned mining pit.

**1983** Based on its successful digs, the Senckenbergische Naturforschende Gesellschaft establishes a research station in Messel.

**1984** Following an order of immediate implementation by the Administrative Court of Kassel, the construction work continues. In the course of the ongoing conversion from surface mining to a landfill, from 1984 until the end of the 1980s an access road, a drainage system with pump shaft and water treatment plant, a garbage transfer station and administrative buildings are constructed.

**1988** Compiled by formerly active Messel researchers, the first book is published that presents all important research results known by then in a popular scientific fashion (Schaal & Ziegler 1988; English version 1992).

**1990–1991** Following the initiation of a planning permission procedure for a pile landfill next to the pit in 1988, which was later abandoned, the final out for the landfill in Messel does not arrive until 1990. Subsequently, the Environmental Ministry in Wiesbaden orders the Hessian Higher Mining Authority to cancel the planning permission decision. The appeals pending at the Federal Administrative Court are halted as a consequence. After a decade, the legal battle surrounding a landfill at the Messel Pit is finally over.

**1992** Following the purchase of the Messel Pit, in 1991 the State of Hesse concludes a contract with the Senckenbergische Naturforschende Gesellschaft regarding the operation of the Messel Pit. According to the Federal Mining Act, effective immediately, Senckenberg becomes responsible for the surface mining operations. Its takeover as operator in 1992 heralds a new era for Messel research at Senckenberg (Schaal & Schneider 1995). And after many years of oil shale mining for the production of crude phenols, for the first time the extraction of fossils takes priority. On the occasion of the 175<sup>th</sup> anniversary of the Senckenbergische Naturforschende Gesellschaft, a new permanent Messel exhibition is opened in Frankfurt am Main.

**1993** Establishment of a scientific advisory board for the Messel Pit and founding of a Messel Administrative Association. A specimen from the Senckenberg dig, a bat, accompanies the German Spacelab Mission D-2 as the mascot of German astronaut Ulrich Walter (Fig. 1.3).

**1994** The high number of significant fossil discoveries and the popular scientific presentation of the Messel research results in radio and television have created a public awareness for paleontology – in particular since the first special exhibition and the publication of commemorative postage stamps. The scientific results and the fossils' uniqueness lead to an application for acceptance of the Messel oil shale deposits into the UNESCO's World Heritage List.

**1995** The mining rights to the "Messel Pit" are transferred into the ownership of the State of Hesse, which may immediately begin with the extraction of the natural resources. On 9 December, the UNESCO decides to accept the Messel oil shale deposits onto the World Heritage List as "Messel Pit Fossil Site" (Fig. 1.4).

**1997** It becomes possible for anyone to take a look inside the Messel Pit: the Messel Administrative Association builds a viewing platform for visitors (Fig. 1.5).

**1998** By decision of the general assembly of the "Citizens' Initiative for the Prevention of a Landfill at the Messel Pit e.V.," after more than 25 years the association self-dissolves in accordance with its by-laws (Mößle & Pagnia 2000), once the association's purpose has been achieved.



Fig. 1.3: A reminder of the D 2 Spacelab mission with bat SMF-ME 10 (NASA Space Shuttle flight STS-55).

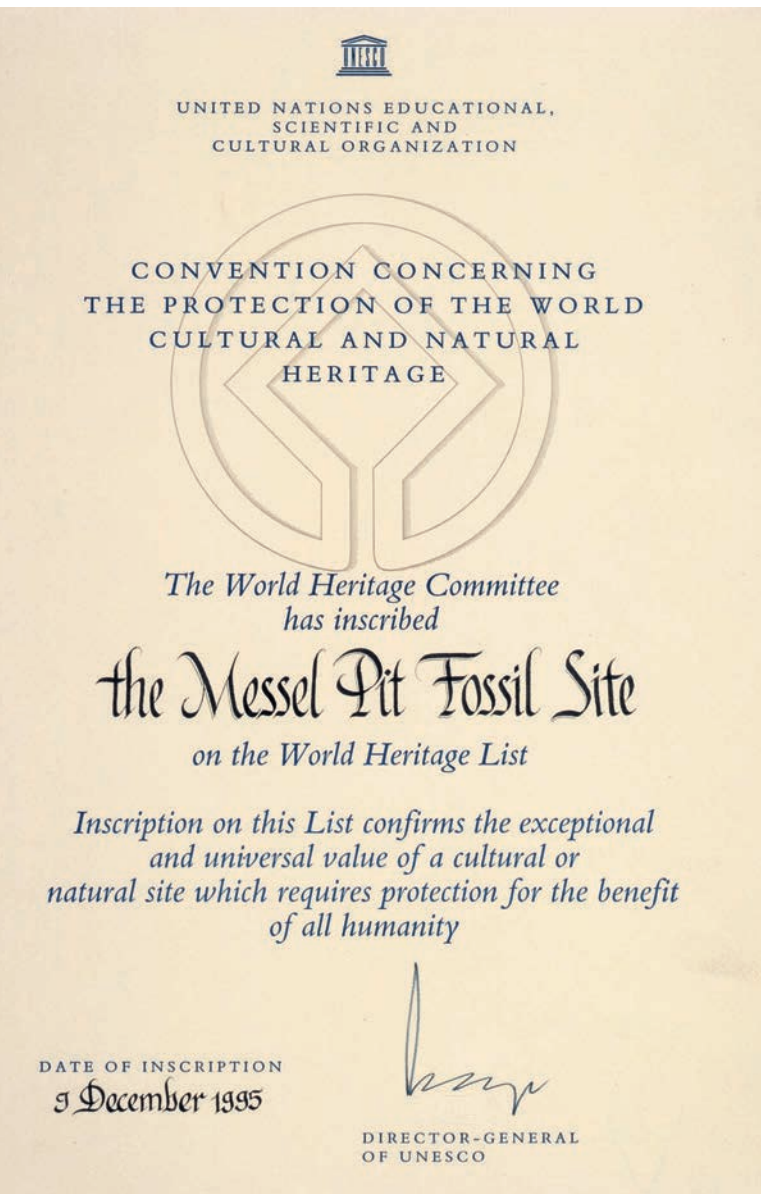


Fig. 1.4: UNESCO certificate dated 9 Dec 1995: the Messel Pit fossil site becomes a World Heritage Site.

**2001** An exploration drilling to a depth of 433 m is conducted. It aims at answering questions about the origin of the oil shale deposit. By means of corresponding rock samples, it can be shown that the oil shale deposits formed in a maar lake, and that the volcanism in Messel dates back to an age of  $47.8 \pm 0.2$  million years (Mertz & Renne 2005). The age is

currently given as  $48.27 \pm 0.22$  (Lenz et al. 2015). In addition to the Senckenberg Research Institute, the Institute for Geoscientific Joint Tasks and the Hessian State Authority for the Environment and Geology participate in the joint project.

**2002** Designs and studies for a visitor and information center at the south edge of the Messel Pit mark the kickoff for the planning of the future center. It is commissioned by the Hessian Ministry for Science and the Arts.

**2010** Opening of the visitor and information center at the Messel Pit. Fig. 1.6 shows a view toward the north, including the visitor center, molded into the never-used garbage transfer station in a step-like design (right), with the Messel Pit in the background. To the left is the access road to the pit, with the observation platform at the pit edge.

**2011** World-famous Messel fossils travel to China as part of a Chinese-German Senckenberg project, where they will be on display as a permanent exhibition in the Paleontological Museum of Liaoning, China's largest paleontological museum.

**2014** The Hessian State Museum in Darmstadt is reopened after several years of extensive renovation. This marks the end of the special exhibition "Messel on Tour" (Hessian State Museum Darmstadt 2007), which becomes an impressive new permanent exhibition in the museum.

**2017** The Department of Messel Research and Mammalogy of the Senckenberg Institute celebrates its 25-year anniversary.

**Future perspectives** The overall success of research on Messel becomes apparent based on the large number of scientific publications. To date, there are almost 2,000 publications, plus intensive public relations work by all involved institutions.

By now, original Messel fossils are on display in national and international special exhibitions as "world heritage ex situ."

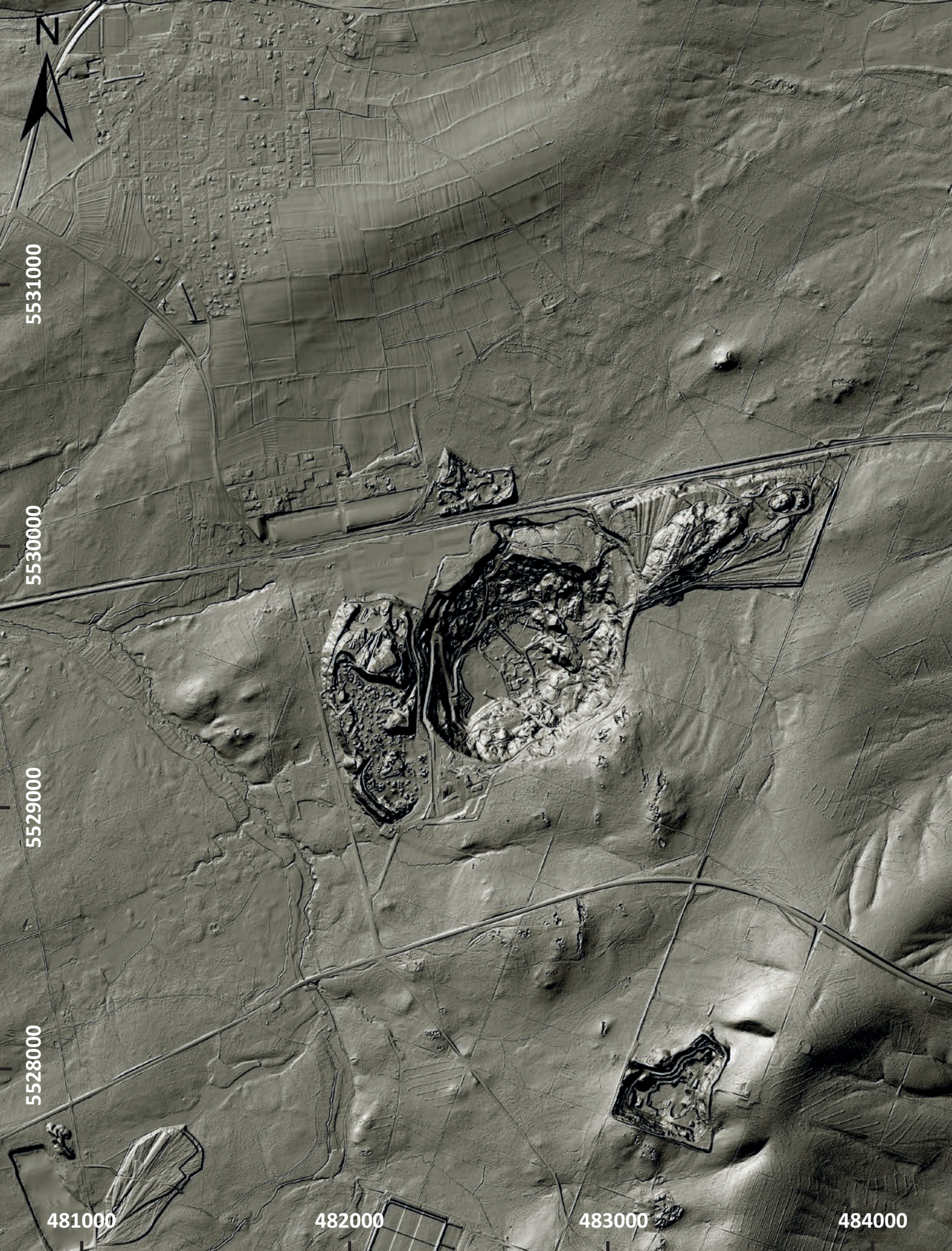
Worldwide, about one hundred biologists, paleontologists and geologists are involved in Messel research. Using the latest methods, they explore old, already known as well as brand-new fossil discoveries. Thus, to date there is no end in sight for the exciting history of the Messel fossil site.



Fig. 1.5: Visitor platform at the southern edge of the Messel Pit.



Fig. 1.6: Visitor and information center at the Messel Pit.



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## Chapter 2

# The Formation of the Messel Maar

Georg N. Büchel & Stephan F. K. Schaal

The Messel Pit is embedded in a topography with a shallow relief, which rises 80–120 m above the Upper Rhine lowlands. The gentle gradients are indicative of the strong Cenozoic geochemical weathering and erosion (denudation) that led to a leveling. Volcanic deposits only remain in the vents, where they were protected from erosion and survived until today.

The Messel Pit at the center of the map section in Fig. 2.1 originated as a maar volcano, which was significantly larger than the present-day pit. A maar volcano consists of a large crater that has formed into the past land surface. The crater is surrounded by a shallow embankment consisting of loose volcanic materials. Shortly after its formation, the crater fills with water above a deep-reaching tuff vent (diatreme). At the time of its origin, the maar lake was situated at approximately 46° latitude N, corresponding to a modern location in the French part of the western Alps. Since then – according to the reconstruction by Scotese (2013) – the Messel Pit has been carried by continental drift some 500 km northward (Fig. 2.2).

At the time of the maar formation in Messel, Europe constituted an island archipelago (Fig. 2.3), similar to modern-day Indonesia. Large parts were covered by shallow water zones. The Atlantic already separated North America from Europe, and the ocean to the south, named after Tethys, the Greek goddess of the sea, was slowly closing due to the collision with the African plate. In addition, this collision led to the formation of the Alps, which during that time were likely only visible as a chain of islands. There is a

strong indication that the Tethys Sea was connected to the Polar Sea via the Turgai Strait (Scotese 2013). The extent to which this separation between Europe and Asia served as a barrier for faunal interchange is subject to discussion (e.g., Solé et al. 2016). The primeval North Sea extended up to the modern-day low mountains.

A faunal and floral interchange between the African, Asian and North American continents was largely precluded during the formation of the Messel fossil site. The European island archipelago was clearly demarcated from other land masses, allowing for the development of a fauna with an endemic character, i.e., without external influences. The De Geer route from Canada across Ellesmere Island and Svalbard was only temporarily available as a land bridge for the spread of organisms during the early Eocene (McKenna 1983). Until the early Eocene, another land bridge, the so-called Thule Bridge, formed a connection between Canada and Europe. For several millions of years, this served as a path that enabled a faunal interchange via Greenland, Iceland and the Faroe Islands, which were otherwise separated by oceans (Brikiatis 2014).

Due to the movements of the earth's crust and the associated continental drift, Europe moved noticeably from southwest to northeast, eventually assuming its current position. The oceans to the south, east and north were displaced, and a new land bridge once again enabled the immigration of animals and plants.

Fig. 2.1: Modern land surface in the area around the Messel Pit following extensive erosion (denudation). The digital elevation model is based on LIDAR data.

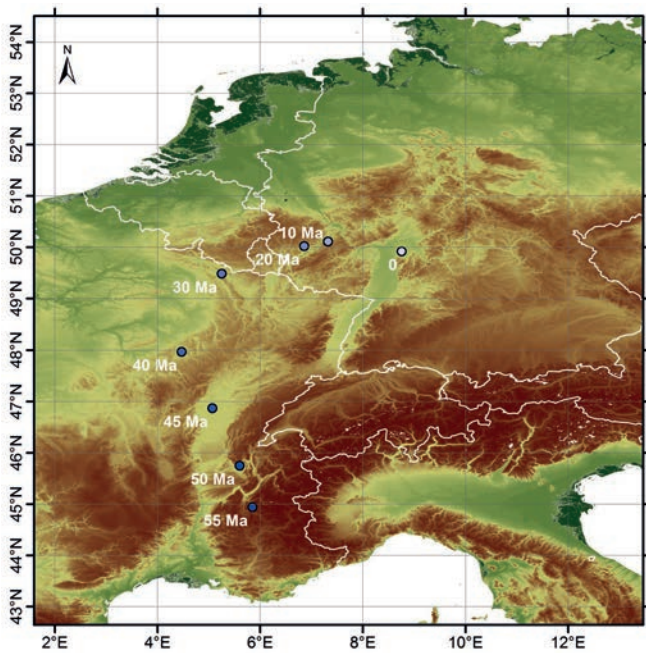


Fig. 2.2: Shift of the geographic position of the Messel fossil site during the Cenozoic.

### The volcano and the maar at Messel

The Messel Maar is located in the southeastern part of the Sprenslinger Horst, which is covered by a loose association of additional Eocene volcanoes extending toward Frankfurt (Fig. 2.4). These likely involve 20 former cinder cones, approximately four additional maar volcanoes and three trachyte deposits, whose volcanic rocks buckled upward to form dome-like protrusions (Negendank 1975, Lippolt et al. 1975). All of these volcanic phenomena were formed 50–45 million years ago (Mertz & Renne 2005).

The age of eruption of the Messel volcano was determined to be 48.2 million years ago by means of  $^{40}\text{Ar}/^{39}\text{Ar}$  dating (Mertz & Renne 2005, Fig. 2.5). Based on pollen analyses and the correlation with the astronomical time scale (periodic change in the earth's orientation relative to the sun), the length of the sedimentation period of the Lower Messel Formation and approximately two-thirds of the Middle Messel Formation is estimated at roughly 0.74–0.94 million years (Lenz et al. 2015). Adding the sedimentation period for the upper part of the Middle Messel with an average sedimentation rate of 0.14 mm per year assumed for the lower part results in a time

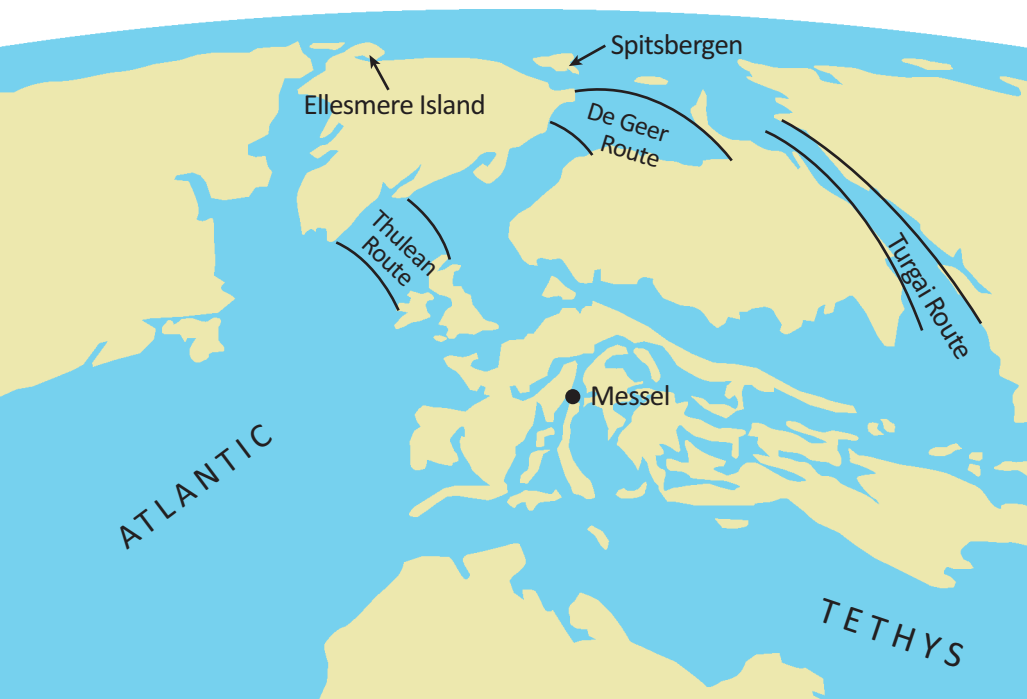


Fig. 2.3: European island archipelago and the land-sea distribution 48 million years ago. Simplified geological reconstruction including the occasionally present land bridges.

period of clearly more than one million years during which the Messel Maar is assumed to have existed.

Prior to the formation of the Messel Maar, there existed a massive sequence of breccia, conglomerates and sandstone from the Upper Rotliegend (Permian). Today, all that remains is a sediment layer of 66 m thickness near the pit's eastern edge (Felder & Harms 2004, Marell 1989). The crystalline Odenwald to the south served as the delivery area. Below the Rotliegend layers, the Sprenlinger Horst consists of igneous rock such as granites of the Hercynian bedrock. Chronologically, they can be correlated with the Upper Devonian/Lower Carboniferous (Stein 2001, Mezger et al. 2013, Ogg et al. 2016, Fig. 2.5). It is in these Rotliegend and granite rocks that the crater and vent of the Messel Maar were formed. The three-part sediment layers that formed in the crater during the early to middle Eocene are referred to as Lower, Middle and Upper Messel Formation.

#### Almost gone: the Upper Messel Formation

At the end of the 19th century the "oil shale" was discovered, which was mined for crude oil production until 1971 by means of surface mining down to a depth of 60 m (Matthess 1966). In the process, approximately 55 m of laminated black pelites were removed from the Middle Messel Formation as well as the sediments of the Upper Messel Formation, except for a few remnants. The basis of the Upper Messel Formation, with a maximum thickness of 40 m, is located at a depth of approximately 120 m above sea level. The depressions occur in the eastern and southeastern area around the pit's outcrop. The Upper Messel Formation consists of black clay with lignite seams and colorful claystones, overlain by clayey sands. Using the existing dating methods, they are indistinguishable from the underlying laminated black pelites of the Middle Messel Formation.

At this point, the description of the Middle and Lower Messel Formation is augmented by the research drilling conducted in 2001 (position: R 3482757.75, H 5531296.42), which at 105.9 m above sea level was located centrally at the lowest point of today's pit. The reconstructed former land surface above the drilling showed an elevation of approximately 162 m above sea level. Accordingly, this re-

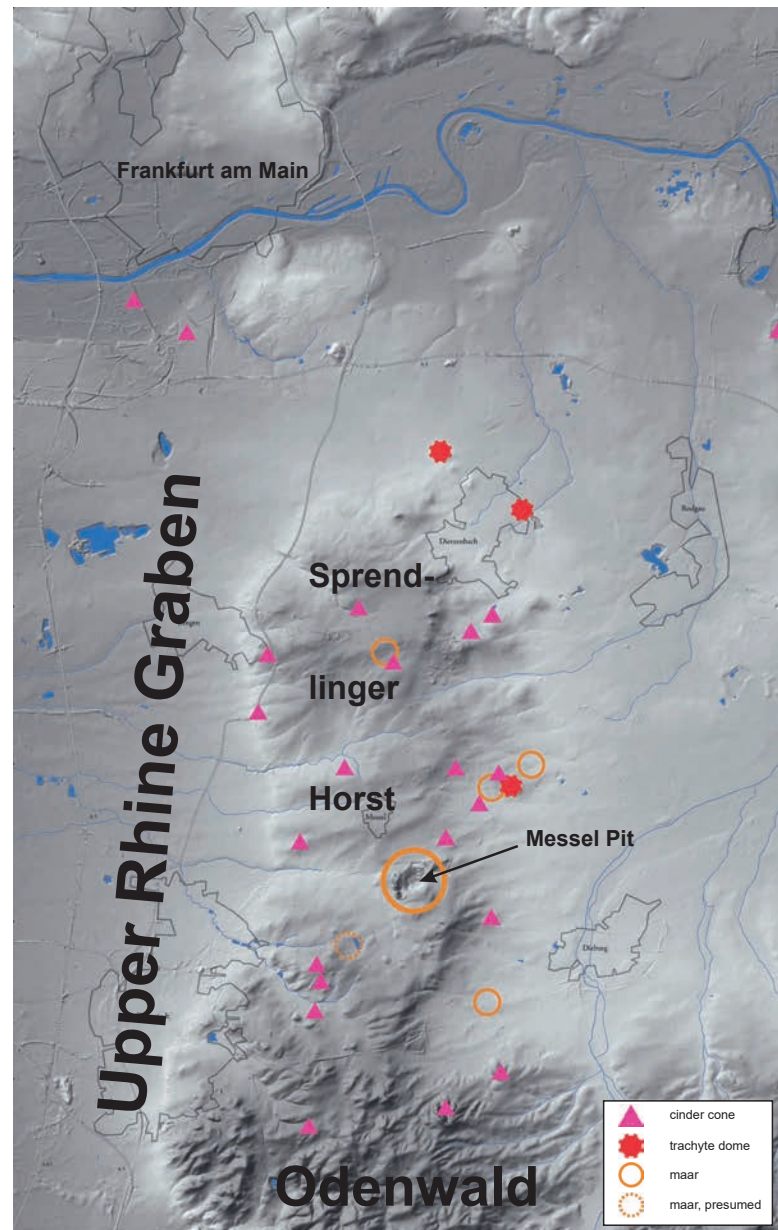


Fig. 2.4: Location of the Messel Pit within Germany.

sults in the presence of a 54 m thick oil shale layer, after subtracting the thin layer of Quaternary wind-blown sand overlying the Rotliegend layers.

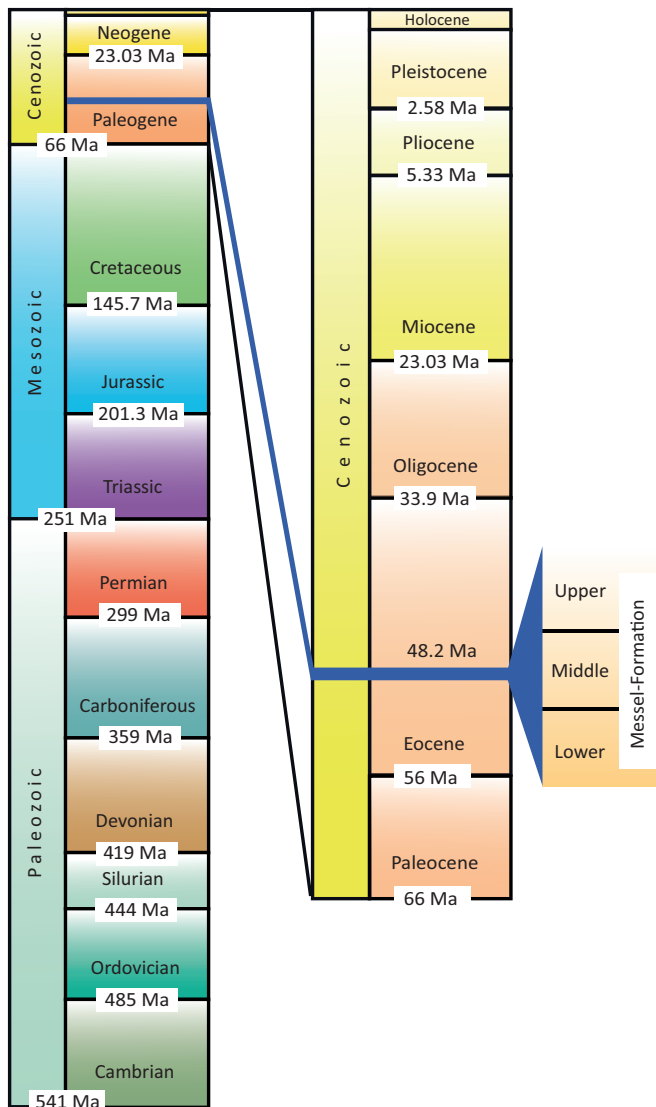


Fig. 2.5: Position of the Messel Formation in the geological time table.

### The Middle Messel Formation with oil shale

The layer between 0–94 m (106–12 m above sea level) shows the presence of dark, bituminous, often finely laminated dark olive-gray to dark brownish-gray clay- and siltstones with a high water content (Fig. 2.6 top). These clay- and siltstones are referred to as “oil shale” by the miners, since they can be split like roofing slate, and crude oil can be extracted by means of pyrolysis. The sequence of black pelite

consists of finely laminated areas alternating with coarsely laminated layers up to 20 cm thick. Closer to the edges, the grain size increases, while the organic components decrease at the same time (Pirrung 1998). These sandy-gravelly inclusions represent volcanic (pyroclastic) sediments that slid into the lake from the maar’s tuff embankment.

Due to its high content of organic substances (crude phenols up to 25 % by weight), for many years, oil shale was considered worth mining. The majority of these so-called kerogens originates from green algae of the species *Tetraedron minimum* and from other plants. Animals played no role in the formation of kerogens. The green algae are the product of algal blooms, and their sedimentation was interrupted by clay particles introduced during seasonal rainy periods. The resulting double layers are interpreted as an annual event, based on which the lake’s lifespan can be determined. Due to its large water depth, the Messel maar lake was a meromictic lake, i.e., subject to partial mixing. Its body of water was layered, and only the lake’s upper 10 to maybe 30 m were subject to temperature and oxygen fluctuations (Chapter 13). Below this and at the lake’s bottom there was no circulation and mixing with the surface water. The oxygen contained in the water was used up during the decomposition of dead organisms, creating ideal conditions at the lake bottom for the formation of crude phenols and the preservation a fossilized fauna and flora (Chapter 4).

The finely laminated sections of the Middle Messel Formation frequently show eyelet-shaped drainage structures, rip marks and faults (Fig. 2.6 top). The edge areas show an increasing extent of slippage structures (Pirrung 1998) that indicate settling phenomena of the underlying diatreme and the hardening (diagenesis) of the black pelites themselves. According to Rullkötter et al. (1988), the thickness of the overlying sediments of the Upper Messel Formation must have been less than a few hundred meters.

The oil shale primarily consists of smectite (up to 35 % by weight), an expandable clay mineral formed during the weathering of volcanic rocks, and of water (up to 40 % by weight). Components such as iron, calcium and phosphate are only present in minute amounts. They are occasionally concentrated in layers and can be easily recognized when cutting the rock. Fig. 2.6 shows a drill core half from the drilling



in 2001 with striking yellow and brown siderite layers (iron carbonate) in the oil shale. A high iron content in the sludge may have led to an increased propagation of microbes, which can explain the occasional formation of extremely thin to several millimeter-thick siderite layers (Felder & Harms 2004). Phosphate minerals such as messelite and montgomeryite can also be found irregularly distributed, e.g., in the marker horizon m (Schaal et al. 1987). In addition to other marker horizons (Alpha, Beta and Gamma), this horizon makes it possible to relate the discovery locations within the fossil site to each other.

**Sand and ash: the Lower Messel Formation**

The noticeably sandy Lower Messel Formation was explored by drilling between 94–228 m (12–122 m above sea level) (Schulz et al. 2002). The base of this formation shows the first layered, subaquatic sediments, which contain a significantly lower amount of erupted magma components (juvenile components) than the underlying lapilli tuffs (Fig. 2.6, center top). The sequence of the Lower Messel Formation can be divided into three parts. The lower part consists of sand layers, breccia and xenoliths (secondary rock clasts) up to block size from crystalline and Rotliegend rocks. The middle part consists of finely stratified sand, silt and clay layers interspersed with two layers containing lapilli tuffs. The upper lapilli tuff layer (162.6–159 m) contains black pelites and coaled wood remnants (Felder & Harms 2014).

Between 373–228 m, a total of 145 m of ash and lapilli tuff layers can be found, which only contain a small number of crystalline and Rotliegend fragments. The lapilli contain few bubbles and are frequently of a spherical and zoned design, with a diameter between 0.1–2 cm (Fig. 2.6, center bottom). Moreover, this layer contains slightly larger, drossy lapilli. Wood remnants in the lapilli’s core are not uncommon. The high proportion of juvenile, rounded lapilli with single pieces of dross indicate that the eruptions near the

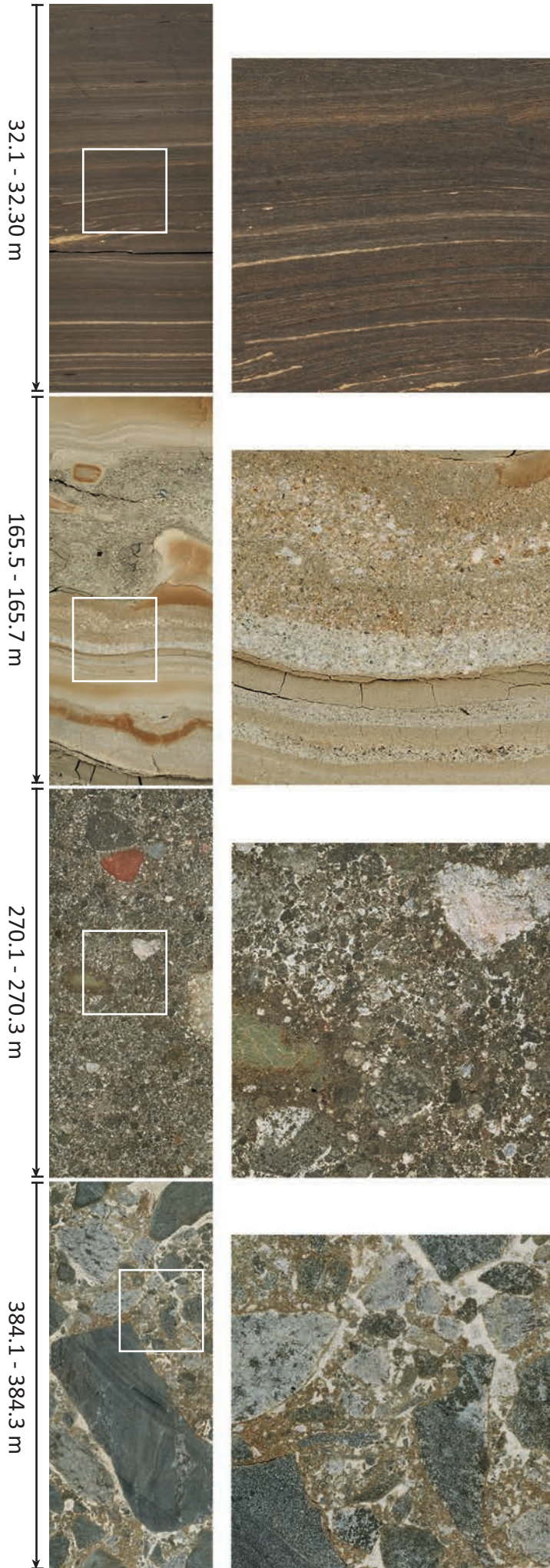


Fig. 2.6: Drill core halves of the Messel drilling in 2001. Top: oil shale, center top: sandy-gravelly sediments, center bottom: lapilli tuff, bottom: volcanic clastic rock; length of frame edges 5 cm. The three bottom units originate from the Lower Messel Formation, the top unit from the Middle Messel Formation.

end of the eruption activity in the Messel Maar took place closer to the earth's surface. Similar phenomena can also be identified in the Ranu Agung Maar in the eastern part of the island of Java (Pirrung et al. 2004) and in the Laach Maar (Büchel 1988) in the Eifel.

The lowest layers explored by drilling (433–373 m) consist of diatreme breccia with crystalline and bleached Rotliegend sediment blocks (Fig. 2.6, bottom). There is no reliable information regarding the extension of the diatreme toward the Rotliegend past the final depth at 433 m. The geomagnetic and gravimetric investigations by diploma students in W. Jacoby's working group at the University of Mainz in the 1990s were unable to unravel this deep area (oral communication W. Jacoby). The reflection-seismic investigations by Bunnell et al. (2004) lead to the expectation of a stratified diatreme structure for an additional 150 m below the final exploration drilling depth after approximately 50 m of breccia, at least down to these depths. Based on the examination of deeply cut diatremes, e.g., from the diamond industry, or from cuttings of deeply eroded diatremes in Cenozoic volcano fields, it may well be expected that the unlayered diatreme tephra extends to a depth of an additional kilometer (Lorenz 2000).

Fig. 2.7: The 80 m-deep Chinese maar lake Dalongwan (approximately 1 km diameter) with ring wall in cross-section; the enlarged section shows the typical layers.

### What did the Messel Maar look like?

In order to give an idea of the Messel Maar's original shape, Fig. 2.7 illustrates the Dalongwan Maar (China) with its maar lake and the cut tuff embankment. The outwardly inclined ash- and block-bearing lapilli tuffs, which are abruptly cut off toward the maar lake, are clearly visible. The edge of the maar thus intrudes rather steeply into the lake and surrounds the body of water on all sides. This steepness and seclusion likely existed for some time at the Messel Maar, as well. The reconstruction of the Messel Maar is based on an assumed thickness of the tuff wall of 80 m. The Laach Maar in the Western Eifel, with a diameter of 1,000 m and a tuff wall with a total thickness of approx. 40 m, may serve as an indicator for this estimate. In all likelihood, the wall at Messel was at least twice as thick.

This leaves the question about the diameter of the original crater lake, and to what extent the relief was lowered by the Cenozoic denudation. Based on the pool of existing data regarding the Messel volcano, some of which we have introduced here, and the comparison of old and young maar volcanoes around the world, we have attempted to visualize the former Messel volcano. In the process, the more strongly structured volcano landscape was simulated by means of a twofold super-elevation of the topography. The extensive amount of erosion was assumed to be approximately 300 m (Fig. 2.8). To arrive at this



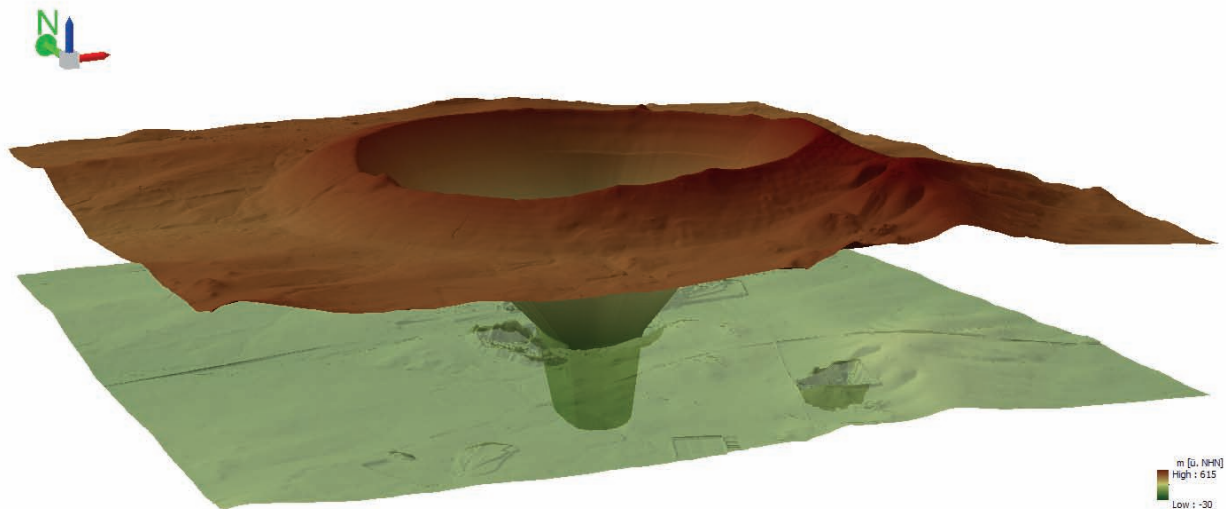


Fig. 2.8: Reconstruction of the Messel ring wall at the time of the maar's formation 48 million years ago (top), in comparison to the present land surface at Messel (bottom).

amount, and thus the elevation of the immediate surroundings of the original crater, a post-sedimentary reduction of the diatreme tephra's pore volume and the crater lake sediments from 30 % to 20 % was assumed. The diatreme's depth was calculated at 1 km below the base of the lapilli tuffs. The total thickness of the Lower, Middle and Upper Messel Formation was extrapolated at approximately 360 m (80 m Upper, 156 m Middle und 127 m Lower Messel Formation). In addition, it was assumed that the sediments of the Upper Messel Formation completely filled the crater, thus extending to the level of the surrounding land surface. This results in an elevation of the previous land surface during the time of eruption of the Messel Maar of 460 m, as opposed to 162 m above sea level today.

The preservation of the potentially almost complete crater sediments is therefore due to an elevator-like shift of the depth from the crater to the upper part of the vent (diatreme), based on the compaction of the formerly loose diatreme tuffs and breccia, as demonstrated by Suhr et al. (2006) at the maars of Baruth and Kleinsaubernitz. This depth shift of a central part of the formerly far-reaching crater sediments into a much smaller diatreme narrowing downward in a funnel shape was associated with a bowl-shaped

alignment of the crater sediments. Thus, at the modern excavation level there is a centrally directed inclination of black pelites of  $2^{\circ}$ – $13^{\circ}$  at the pit's center, with an inclination of  $20^{\circ}$ – $30^{\circ}$  near the edges. Based on drilling results at the north edge, the modern-day rim of the diatreme shows an inclination of approximately  $60^{\circ}$  (Pirrung 1998). According to the seismic examinations, the rim of the diatreme appears to become steeper towards the bottom (Buness et al. 2004). On the other hand, for the crater walls of the original maar crater we have considered an inclination of  $30^{\circ}$ – $40^{\circ}$  in the crater's reconstruction.

### The crater's history

Magma rises through the crystalline rocks of the Sprenglinger Horst, repeatedly encountering groundwater-filled fractures on its way to the top. Due to the pore water's high pressure, groundwater comes into contact with the rising magma, where it spreads out and creates water vapor films due to heating by the magma (Fig. 2.9, step 1). From a certain depth on, perhaps a few hundred meters, the vapor films from the water intrusions collapse. This leads to immediate contact between the magma and the water

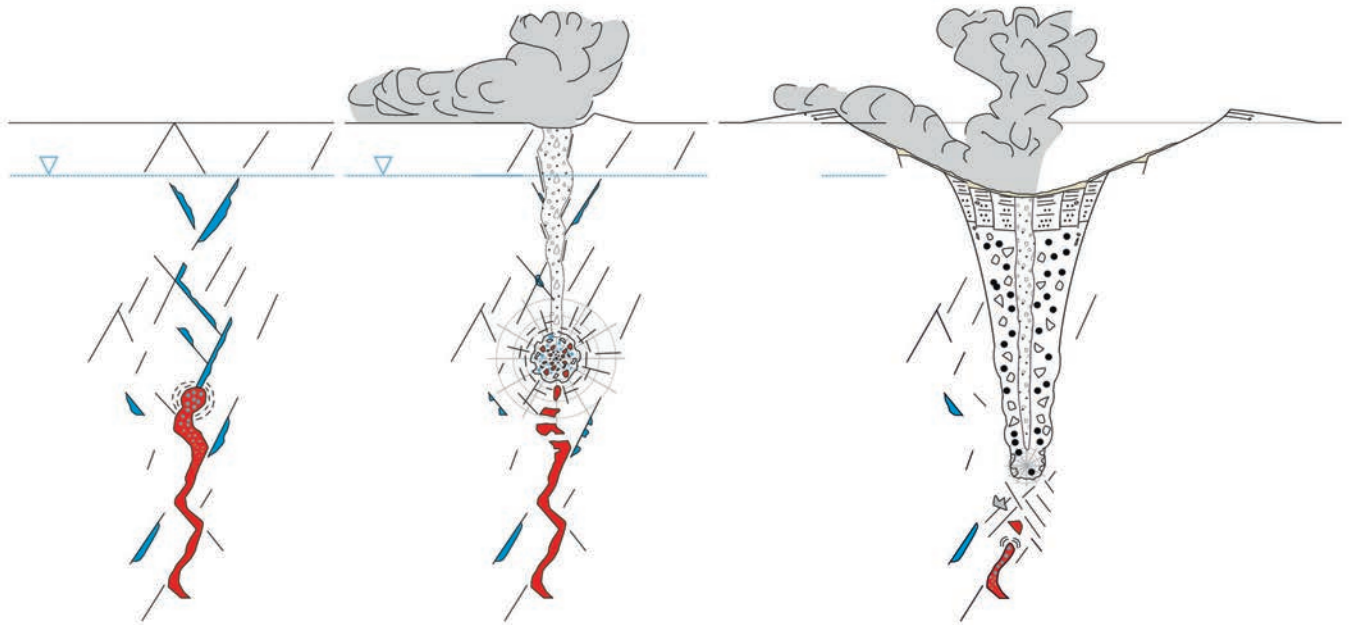
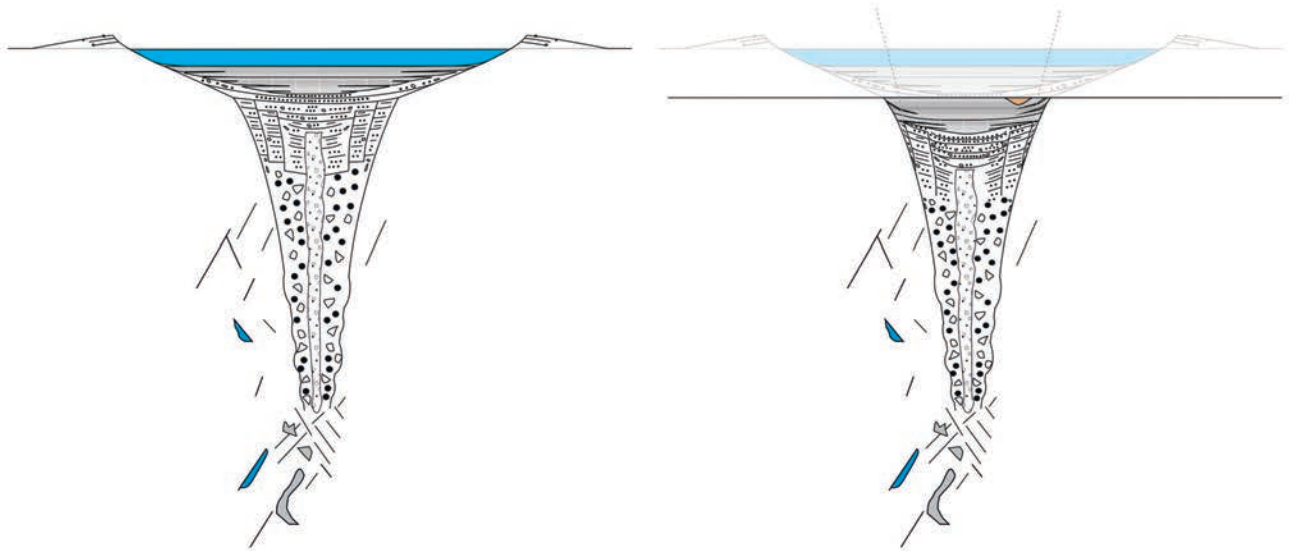


Fig. 2.9: The main steps in the formation of the Messel Maar (from left to right).

Fig. 2.10: Hopi Buttes volcano field (Arizona) with feeder dike exposed by erosion in the foreground and tuff vents at middle distance.

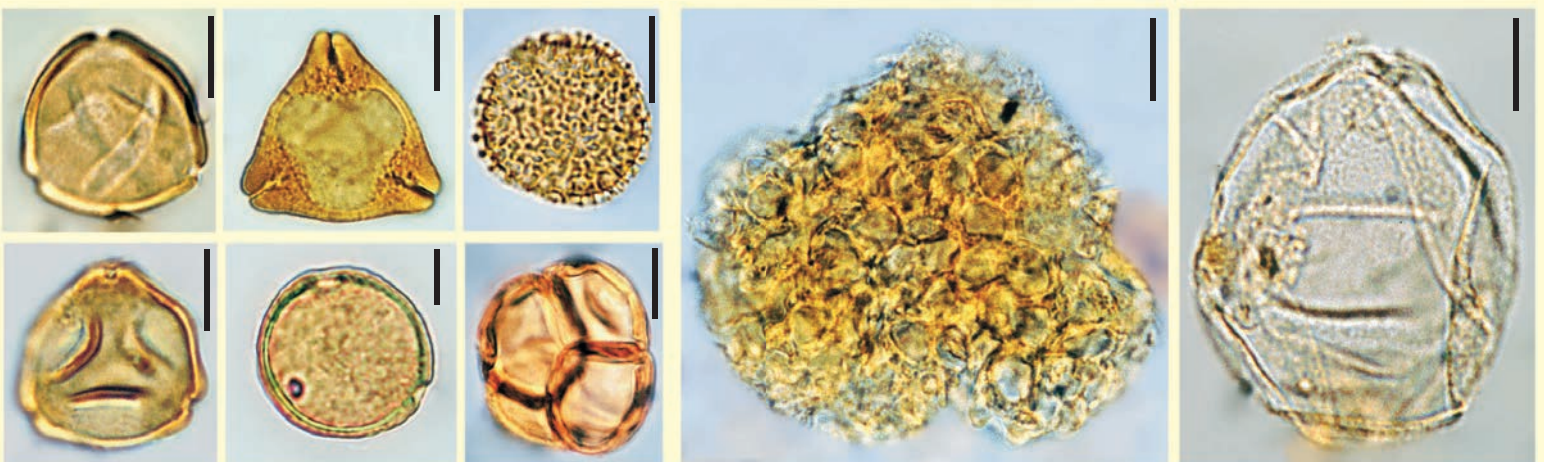
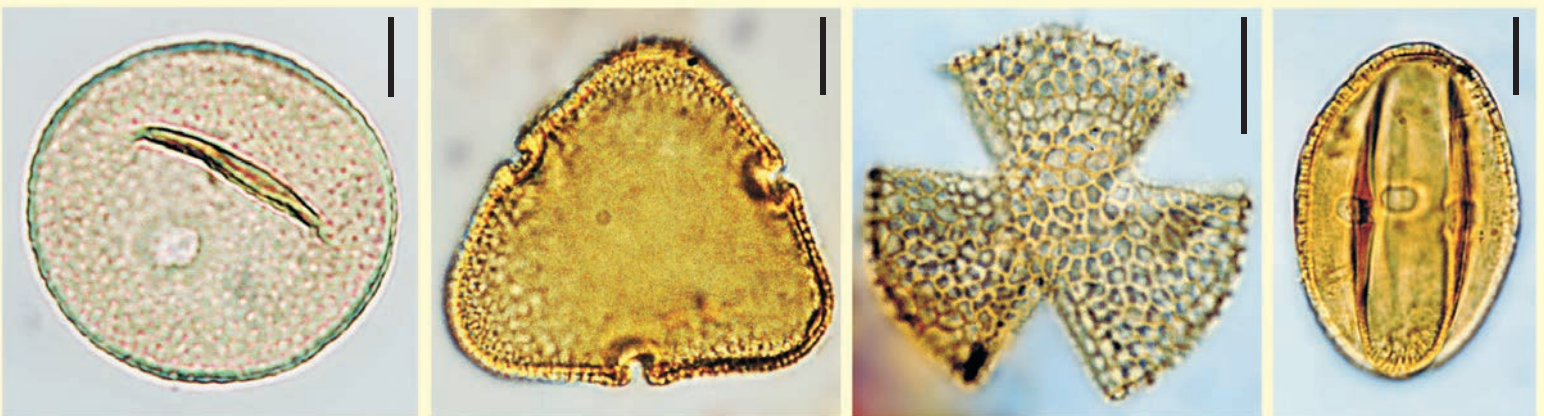
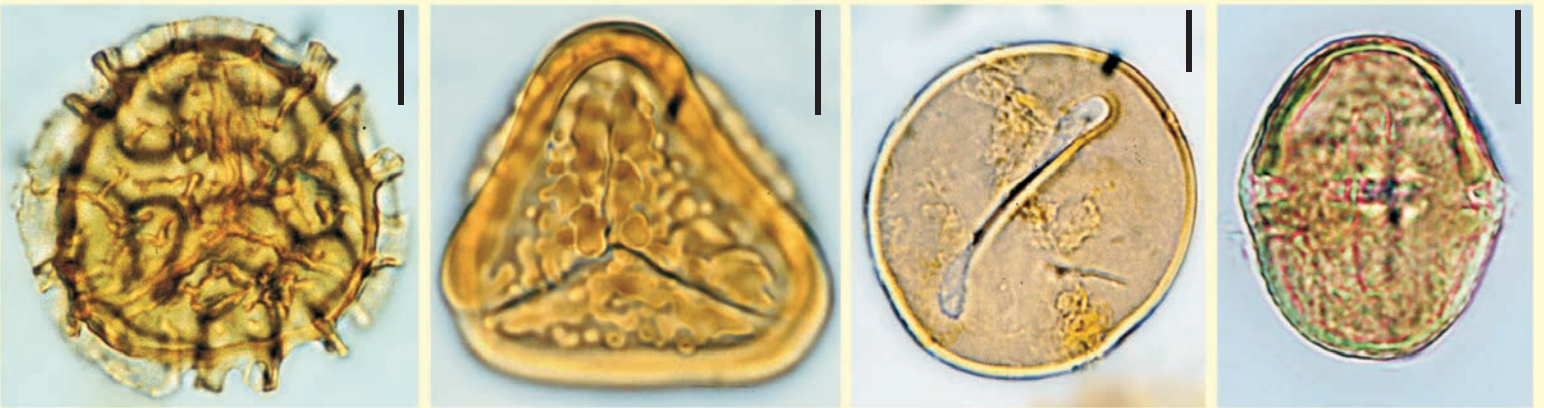
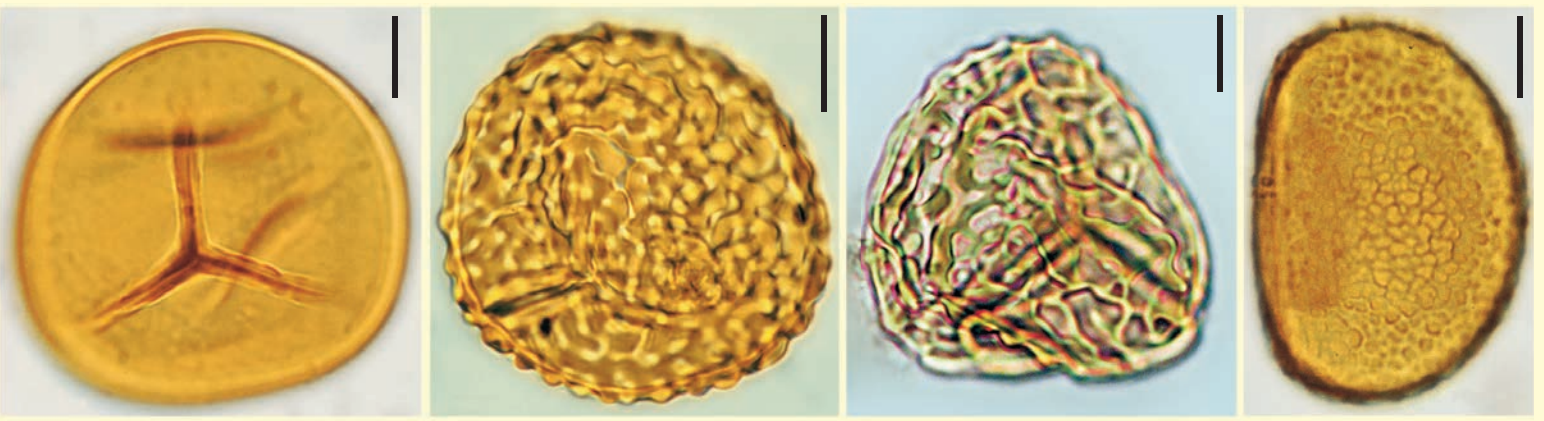




introduced from outside, an immediate crushing of the bedrock stones due to shock waves, and a subsequent expansion of the superheated water vapor. In volcanology, these recurring events are called phreatomagmatic eruptions (Fig. 2.9, step 2). Through a narrow vent, the bedrock that falls into the explosion chamber is fragmented, and the turbulent eruption system unloads in a large, strongly expanding eruption cloud. This so-called “base surge” races across the densely tree-covered land surface at supersonic speed, tearing down the giants of the primeval forest in the vicinity of the crater’s rim. At the same time, large expelled bedrock blocks crash down onto the freshly deposited pyroclastics. Higher air currents move ash particles over many kilometers. Additional eruptions ensue, and in the process, the events keep shifting farther downward (Fig. 2.9, step 3). An increasing number of bedrock slabs falls into the hollow spaces caused by explosions and eruptions, widening the vent. The expelled pyroclastics fill up the resulting hollow spaces from above. This leads to a deepening and widening of the vent and a widening of the crater. Several weeks later, the eruption activity finally ceases. Over time, the large crater’s

lower part fills with intruding groundwater (Fig. 2.9, step 4). At the same time, sedimentation sets in. The lower part of the crater is filled with clastic sediments, while bituminous clays are deposited higher up under still water conditions. Meanwhile, the tuff wall is eroded. The upper part of the crater contains sediments from the time when the crater was almost completely filled up. Over time, the surrounding areas of the crater also become subject to intense geochemical weathering. Several hundred meters of the Rotliegend sediments and the crystalline rocks are eroded. Simultaneously, the middle part of the crater sediments collapses into the diatreme, since the loose volcanic rocks located in the vent become compacted (Fig. 2.9, step 5).

In the case of Messel, no information is available to us regarding the lower part of the diatreme. The diatreme in the volcano region of the Hopi Butte, shown in the background in Fig. 2.10, is a known example of compacted diatreme rocks. Via the chute-like intrusion visible in the foreground, the magma reaches the upper region of the crust, where it made contact with the groundwater.



# Chapter 3

## Paleoclimate – Learning from the Past for the Future

Olaf K. Lenz, Volker Wilde, Walter Riegel

Throughout its history, the earth has been subject to steadily alternating glacial periods and greenhouse phases. In order to make reliable predictions regarding the future global climate change and its effects on our species and our environment, it is necessary to develop an understanding of the processes that took place over periods of time far beyond the instrumental record of climate data during the past decades.

With the aid of numerous deep sea drillings, scientists in recent years developed an oxygen isotope curve that reflects the development of deep sea temperatures in the past 65 million years (Zachos et al. 2001, 2008; Fig. 3.2). In the meantime, it has also been accepted as a global temperature development curve. It shows a warming trend since the middle Paleocene, which reached its high point with the “Early Eocene Climatic Optimum” (EECO) approx. 50–52 million years ago. This was followed by a gradual, initially very slow cooling, until the occurrence of a drastic drop in temperature around the turn from the Eocene to the Oligocene. This started the transition from the Paleogene greenhouse climate to the glacial climate of the Oligocene and Neogene (Zachos et al. 2001).

The long-term climate development was only interrupted by a few short-term fluctuations. The most prominent of these warming events (“hyperthermals”), the “Paleocene-Eocene Thermal Maximum” (PETM; McInerney & Wing 2011), occurred at the Paleocene-Eocene boundary, approx. 56 million years ago. The total duration of this event is estimated to have lasted about 170,000 years (Röhl et al. 2007). It was caused by a short-term massive input of greenhouse gases in the atmosphere and was accompanied by an average temperature increase of 5–6°C. This increase was felt most noticeably in the high latitudes, where, with a rise of 7–10°C, it far exceeded these average values.

The Eocene – the time when the Messel oil shale was deposited – thus falls into a period when the earth was dominated for the last time by a greenhouse climate not caused by man. For example, the report of the Intergovernmental Panel on Climate Change (IPCC 2014) predicts a CO<sub>2</sub> level for the year 2100 that is comparable to the levels in the Eocene (Parrish & Soreghan 2013). The Eocene is thus particularly well-suited as a reference period.

During the Eocene, the area around Messel was covered by a forest characterized by a subtropical to

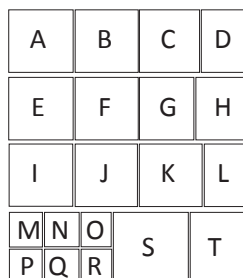


Fig. 3.1 Examples of pollen and spores from the scientific drilling at Messel in 2001.

A: spore of a climbing fern (Schizaeaceae), B and C: different types of fern spores, D and F: spores of polypod ferns (Polypodiaceae), E: spore of a club moss (Selaginellaceae), G: pollen grains of a water lily (Nymphaeaceae), H: pollen grain of a sapotaceous plant (Sapotaceae), I: pollen grain of a restio plant (Restionaceae), J: pollen grain of a plant from the kapok family (Bombacaceae), K: pollen grain of a witch hazel plant (Hamamelidaceae), L: pollen grain of a vine plant (Vitaceae), M, P and Q: pollen grains of extinct walnut plants (Juglandaceae), N: pollen grain of an unknown extinct plant, O: pollen grain of an oleaceous plant (Oleaceae), R: pollen grain of a heather plant (Ericaceae), S: colony of the “oil alga” *Botryococcus*, T: shell of the dinoflagellate *Messelodinium* (Dinophyceae). Scales: 10 µm.

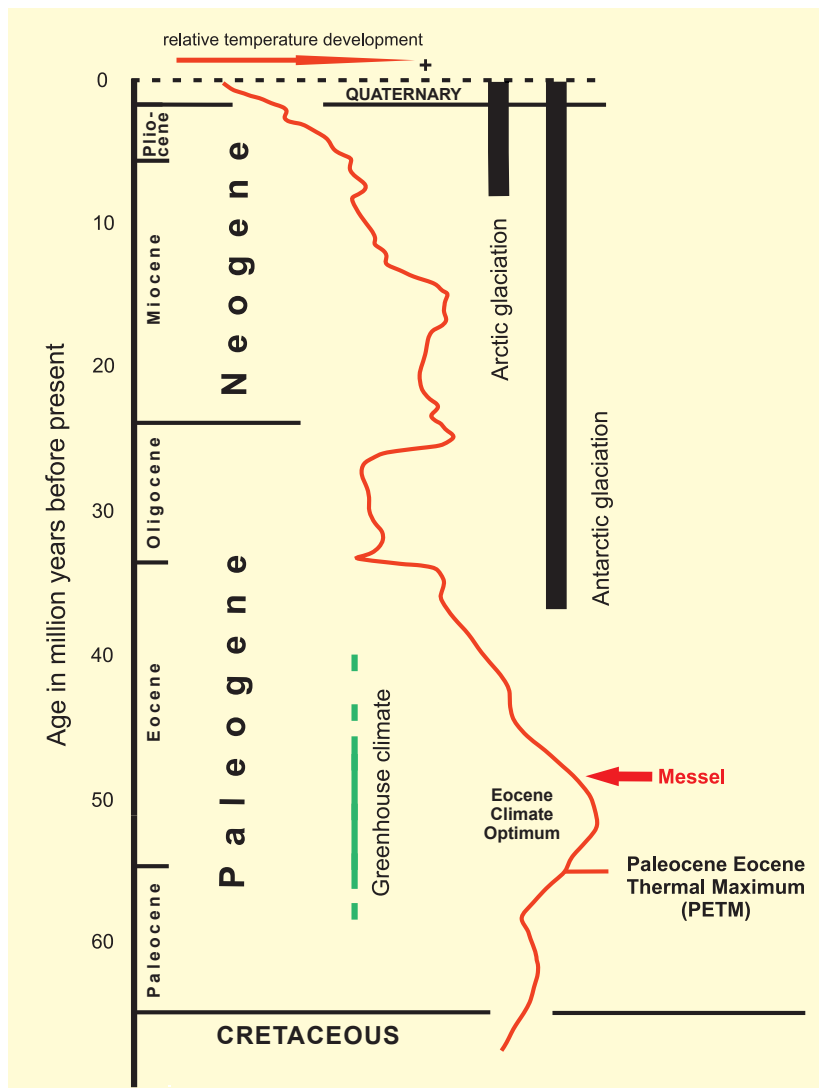


Fig. 3.2: Temperature development in the deep sea during the Cenozoic. The Messel oil shale originates from the time of the Paleogene greenhouse climate.

tropical vegetation. However, it contained a diversity of deciduous trees and shrubs primarily found in the temperate climate zones today (Wolfe 1979). At annual mean temperatures between 20–25°C, this vegetation grew in the Northern Hemisphere in the transitional zone between the globally dominating tropical rainforests and the temperate mixed deciduous forests widespread in the polar region. With the predominance of mammals and flowering plants, the flora and fauna of that time already resembled that of today, and many of the plants existing at that time can easily

be assigned to modern families. Since a particularly species-rich fauna and a paratropical flora from the Eocene have been preserved in the Messel Pit, this fossil site plays a key role in the exploration of the Eocene paleoclimate in Europe. With the aid of floristic macro- and microfossils, and taking into account the plant families' modern climatic requirements, it was possible to calculate a mean annual temperature of 16.8–23.9°C (Grein et al. 2011). Measurements of oxygen isotopes in vertebrate bones led to almost identical values, at  $18 \pm 2.5^\circ\text{C}$  (Tütken 2014). Even during the coldest month, the temperature did not drop below  $10^\circ\text{C}$ . This is also confirmed by the presence of warmth-loving crocodylians (Grein et al. 2011; Markwick 1998) that inhabited the surface water of the Messel lake, which reached temperatures of  $25 \pm 3^\circ\text{C}$  (Tütken 2014). In addition, with an annual precipitation between 803 and 2,540 mm, the climate was very wet (Grein et al. 2011). The characteristic, finely laminated deposits of the oil shale even reflect seasonal fluctuations. Thus, in regard to their temporal resolution, these deposits show close similarities to the so-called varves (sediments deposited in thin annual layers) from glacial meltwater lakes or the growth rings of trees. Both count among the climate archives that can be analyzed by measuring their thickness and counting their frequency. Besides these varves, pollen and spores of plants serve as particularly important climate proxies, since plants are highly sensitive indicators for the continental paleoenvironment and the paleoclimate (Traverse 2007).

### Pollen and spores – A means for documenting climate fluctuations

The flora surrounding the maar lake at Messel during the Eocene can be reconstructed by means of embedded remnants, such as leaves, fruits, seeds, flowers, and occasionally, wood (Wilde 2004; Collinson

et al. 2012; Chapter 6). Contrary to macrofossils, floristic microfossils can be found in each rock sample from the Messel oil shale. These are microscopic pollen grains and spores or algae, which, after chemical treatment, can be extracted in large numbers from the sediment and subsequently be analyzed under the microscope (Thiele-Pfeiffer 1988).

By means of statistical analysis, it is possible to recognize and analyze changes in the frequency of individual taxa over the time that elapsed during the deposition. While the initial deposition rate was still very high and no oil shale was formed in the beginning (Fig. 3.3), seasonally layered oil shale was later deposited very slowly and continuously, thereby showing an unusually high temporal resolution. At an average sedimentation rate of 0.14 mm per year, determined on the basis of various methods (Irion 1977; Goth 1990; Lenz et al. 2010), it was possible by means of the scientific drilling at Messel in 2001 (Chapter 2) to continually analyze a time period of about 640,000 years (Lenz et al. 2011). With the deposition of oil shale, which also housed the macrofossils, the maar had stabilized, and a climax vegetation had replaced the pioneer vegetation from the recolonization phase in the crater area (Chapter 13). This led to the central question in the investigation regarding whether and to what extent the climate cycles that are predominant during the current glacial period of the Quaternary are also reflected by the vegetation under the greenhouse conditions of the Eocene (Lenz et al. 2011, 2015).

Following a successful preliminary study on the basis of old data from a drilling in 1980 (Thiele-Pfeiffer 1988; Lenz et al. 2005), the section of the 2001 Messel drill core that lay above 94.60 m was therefore sampled at regular intervals (every 10 cm). This is the section that contains the continuous oil shale that was deposited without major disturbances.

Subsequently, the samples, which were taken at every 20 cm – corresponding to a time interval of about 1,400 years between samples – were examined for the presence of plant microfossils. As a result, it could be clearly demonstrated that regular vegetation changes occurred in the early Middle Eocene at Messel, which apparently correspond to Milankovitch

cycles (Box 3.1). However, the climate changes were always so small that they did not lead to a complete displacement or immigration of new plants within the climax community, but only to shifts in the spatial distribution and spread of individual plant species or communities (Lenz et al. 2011).

Next, the sample density was increased to 10 cm in a 10 m-long segment of the drill core, thereby reducing the time interval between two samples to 700 years. In addition, an oil shale block of 1 m thickness was extracted from the pit (Fig. 3.4). In the laboratory, samples were taken from this block at 1 cm intervals, so that the time period between samples was reduced to 70 years. The statistical analyses of these time series led to the conclusion that cyclic vegetation changes also occurred in the range of centuries to a few millennia. Such sub-Milankovitch cycles precisely correspond to the short-term periodicities known from the glacial period of the Quaternary.

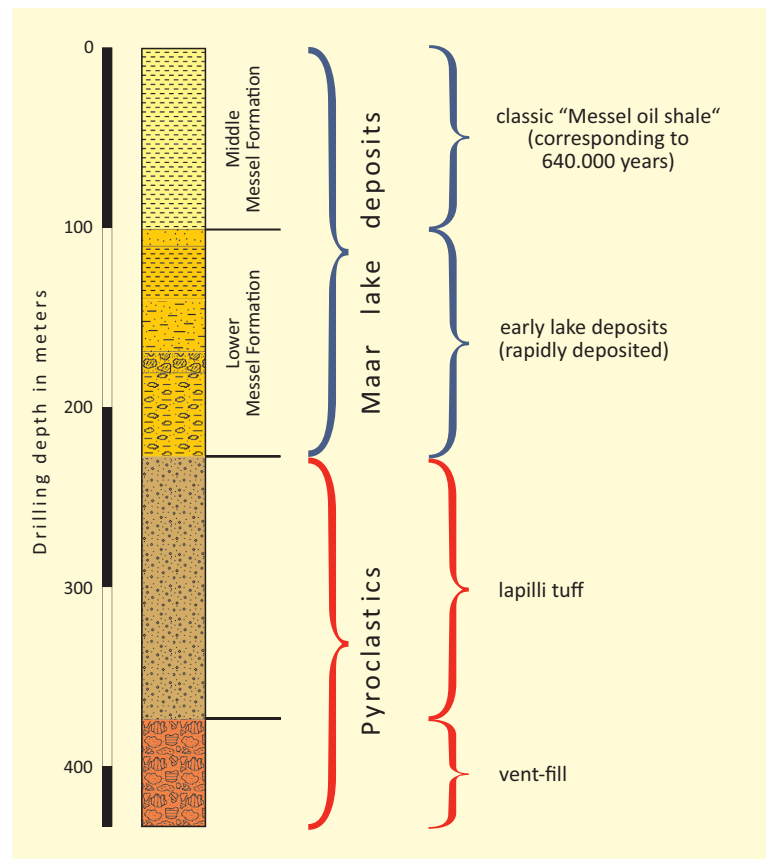
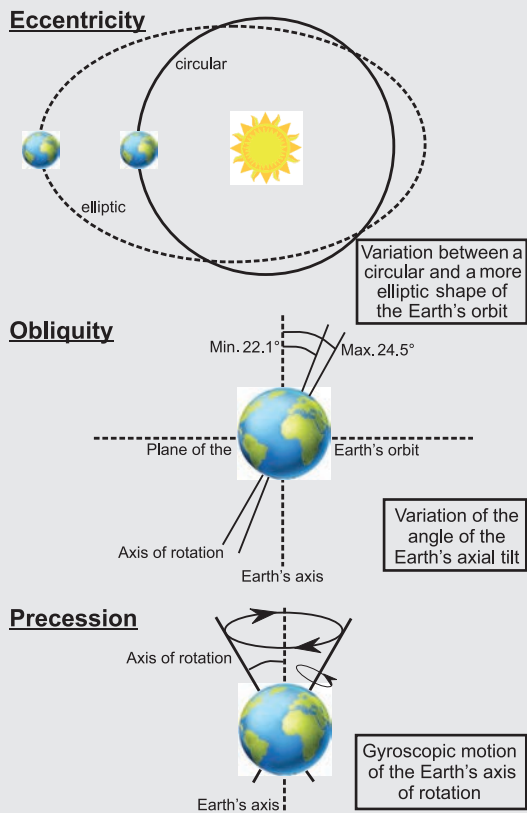


Fig. 3.3: Schematic profile of the Messel scientific drilling in 2001; the examined deposits of the maar lake are shown in the upper section.

**Box 3.1: Milankovitch and sub-Milankovitch cycles**

Even without human impact, the earth's climate undergoes changes and follows regular cycles. Long-term periodic climate fluctuations are particularly characteristic for the glacial period of the



Quaternary and cause alternating glacials ("ice ages") and interglacial periods. At the end of the 1940s, the Serbian mathematician Milutin Milankovitch correlated these cycles to cyclic changes in astronomical ("orbital") parameters; in honor of their discoverer, these are referred to as "Milankovitch cycles." Thus, the earth's orbit around the sun changes within approx. 100,000 and 400,000 years from almost circular to slightly elliptical and back to circular ("eccentricity"). The tilt of the earth axis in relation to the level of the earth's orbit ("obliquity") fluctuates over a cycle of approx. 40,000 years between 22.1° and 24.5°, and the rotation of the earth's axis, which rotates like the swaying axis of a spinning top on the level of the earth's orbit ("precession"), also fluctuates in a cycle lasting about 21,000–26,000 years. All of these cyclic processes lead to changes in solar radiation and thus ultimately to climate changes. Through the overlapping of individual cycles, these effects can be additionally strengthened or weakened.

Even below the Milankovitch cycles, there are obvious cyclical climate changes, which fluctuate in a range between a few decades to several thousand years. These so-called sub-Milankovitch cycles are primarily due to changes in sun spot activity. An immediate consequence is changes in the ozone content, the temperature, cloud formation or circulation within the stratosphere. This may result in noticeable effects on the vegetation, e.g., during the so-called "Little Ice Age," which lasted from the 14<sup>th</sup> to the early 19<sup>th</sup> century.

Thus, it could be documented for the first time that even the greenhouse regime of the Eocene was subject to fluctuations, e.g., regarding solar activity, that are comparable to the recent geological past, and that these fluctuations had an effect on the vegetation even under the stable greenhouse climate (Lenz et al. 2017).

**Varves – "Annual rings" in the lake sediment**

The quantitative analysis of pollen and spores has a lower limit in regard to the temporal resolution. That is because there is a minimum amount of material in individual samples that is required for the statistical analysis. It is not possible to take a sufficiently large sample size below a layer thickness of one centimeter, since this results in an insufficient number of pollen grains and spores for an analysis.