Paleozoic Rocks of Tunisia

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Concept, nomenclature, and their relationship with North Africa

By

Mohamed Soua

Cambridge Scholars Publishing

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PREFACE

Between approximately 541 and 252 million years ago, there was a period of Earth's history known as the Paleozoic Era. It was also during this period that plants started to generate seeds and the earliest creatures with backbones appeared. It begins with a few simple animals, followed by several interesting plants that have seeds, mountain ranges, oceans, and other unique things, much like in a narrative book!

There was a lot of evolution going on at this time, which implies that plants and animals were evolving into the various species that exist today. At that period, a wide variety of flora and fauna, including early fish and trilobites, that are now extinct, were in existence. The Earth was going through exciting times, and it was a fantastic time to study its past. For the most part, it was a warm, humid climate. During this time, life on Earth was beginning to grow more varied and complex, which paved the way for the evolution of more sophisticated organisms.

The book in question is an edited collection of the author's many published works on North Africa's Paleozoic history, with a particular concentration on southern Tunisia. Southern Tunisia was undoubtedly a part of the overall north African system at that time. Examining this geological section will surely solve the region's mystery. The goal of the book is to give readers a thorough understanding of the geological history of the area as well as the events that occurred throughout the Paleozoic era's many stages.

The author has brought together many articles to produce a comprehensive resource that describes the southern Tunisian region's geology. The purpose of this book is to provide readers a deeper understanding of the history of the rocks and soil in the area. It also discusses the instruments created by humans to investigate and learn about it.

Shale is a form of oil and gas that is discovered in unconventional areas. It is one of the book's key topics. These materials date back to the Devonian and Silurian eras, which are quite distant times. The author describes the rocks and other subsurface materials that contain these resources and provides an overview of the methods and equipment utilised to locate and extract them.

The sediments that formed as a result of glaciers during the Ordovician period are another topic we are researching. The author examines in detail the rocks and formations and the ways in which scientists have investigated and comprehended them.

It also provides an overview of the events that took place in the Carboniferous, Permian, and Cambrian periods. The author provides readers with a detailed account of the events that took place during those eras by discussing various objects that formed in the earth during that time.

All things considered, this could provide readers a thorough and in-depth understanding of the Paleozoic geological history of southern Tunisia. The published articles contain a wealth of valuable material that the author has compiled for the benefit of scholars, students, and anybody else interested in learning about the local geology.

ACKNOWLEDGEMENTS

I would like to thank Dr. Sebastian Lüning who kindly provided a thorough review on an early draft of the paper "Paleozoic oil/gas shale reservoirs in southern Tunisia: An overview. Journal of African Earth Sciences, 100, 450-492", generously opened fruitful discussion and provided numerous suggestions, which improved the text. I would like to thank Prof. David Lloydel (University of Portsmouth) and Pr. Omer Bozkaya (Pamukkale University) for reviewing an earlier draft of the last chapter (Mineralogical Characterization of the Early Silurian Shales as Encountered in Southern Tunisia).

I am indebted to the people with whom I had several discussions on the paleozoic of the Tunisian subsurface since I joined the "Entreprise Tunisienne d'Activites Petrolieres" (ETAP) on 2007, where I have been assigned to work on Real-time drilling data analysis of a couple of "Pioneer Natural Resources Company" wells and then to join the team "Gas from shale" as the principal geologist. This provided me the opportunity to work jointly with SITEP (Société Italo Tunisienne d'Exploitation Pétrolière) on well EB-407 and assist the coring of the Silurian "Argiles Principales" Formation. I deeply thank Jalel Smaoui, Ali Trichelli, Oussema Echihi and Sofien Haddad for several discussions on the subsurface and the Permian outcrop during fieltrips.

I am also obliged to the extensive discussions with Prof. Dalila Zaghbib-Turki (University of Tunis-El Manar) who helped me to further my education about the "Paleogeography of Tunisia" with emphasis to the Paleozoic period.

My respects go to the numerous researchers, authors of publications and articles, without exceptions, from whom I have learned a lot through the richness and quality of their work.

I cannot conclude these acknowledgments without a heartfelt and grateful thought for my little family, and particularly for my wife, Amira, and my beloved daughters, Roua and Riyem. Their patience, support, and love throughout these past years have been invaluable, and without them, I would not have been able to complete the writing of this book.

My thanks are also due to Cambridge Scholars Publishing, particularly Alison Duffy (Commissioning Editor) for her dedication and support during the process of producing this volume.

About the Author

Mohamed Soua, PhD, is specialized in mineralogy and chemostratigraphy. His professional experiences have provided him the background in geological research, specifically stratigraphy and mineralogy. with expertise is being covering full spectra of chemostratigraphy, mineralogy, sequence stratigraphy, regional geology, logging interpretation, cylostratigraphy, micropaleontology and petrophysics.

He received a Bachelor of Science in 2003, followed by a Master of Sciences in 2005, and then a Ph.D. in 2011 all in the field of Geology from the University of Tunis-El Manar, Tunisia. Since graduation he has started his professional career as an Exploration Geologist at the Entreprise Tunisienne d'Activités Pétrolières (ETAP) from 2007 to 2012. After a brief period in academia as an Associate Professor in the Department of Geology at his alma mater, He joined Saudi Aramco in 2014. Starting as a Chemostratigrapher, he has since held positions of increasing responsibility.

He is an editor for the Arabian Journal of Earth Sciences and the Journal of Open Transactions on Geosciences. He is a member of the American Association of Petroleum Geology (AAPG) and the International Centre for Diffraction Data (ICDD). He has published extensively in diverse geological subjects.

CHAPTER 1

GROWTH OF THE CONCEPT: BACK TO THE EARLY EXPLORATION OF TUNISIA

The Carthaginian knowledge

Around 440 BCE, the widely celebrated ancient Greek historian and geographer from Halicarnassus named Herodotus released his renowned book, "Histories" (Figure 1.1). He captivated his audience by detailing the lifestyle and possessions of the Carthaginians, emphasizing the magnificence of their civilization. Among the many aspects he highlighted about those residing in southern Tunisia was their coastline, which stretched from present-day Gabes to Sfax, and included an island called Cyraunis (now known as Kerkennah).

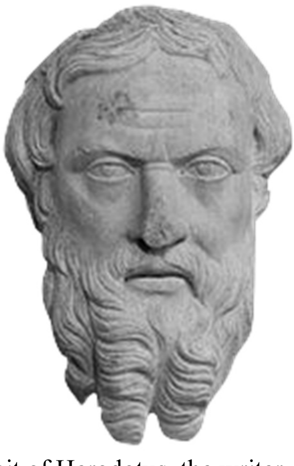


Fig. 1-1 A famous portrait of Herodotus, the writer of the book History (ca. 484 BC-425 BC), a Greek historian.

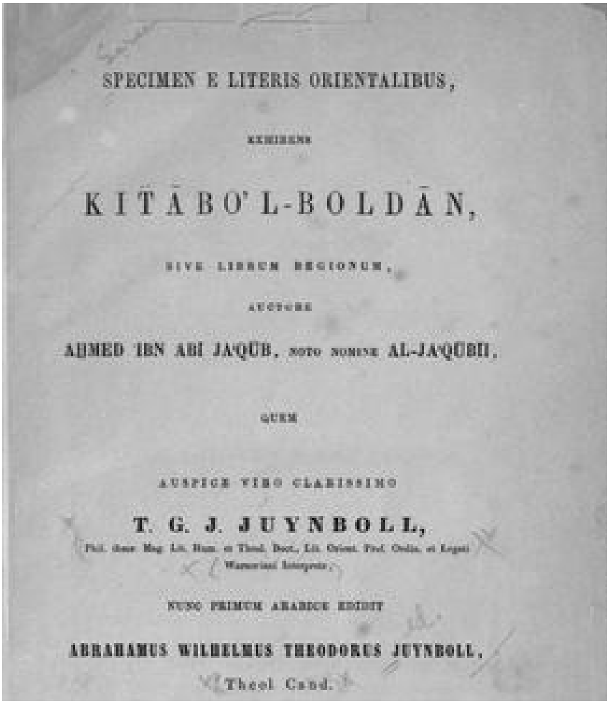
As reported by the Carthaginians, the island had a length of two hundred furlongs (equivalent to 40km, and accurately reflecting the true length of the archipelago) and a width of just over 11 km. It was easily accessible from the mainland and was covered in vines and olive trees. In the center of the island was a lake that contained golden dust. The young women of the area used birds' feathers coated in bitumen or oil to extract the dust from the mud.

The island was dotted with small lakes, but one was larger than the others, measuring seventy feet and two fathoms deep. The locals would dip a pole with a bunch of myrtles into the water, and upon pulling it up, they would find a pitch-like substance stuck to it. This substance had a better aroma than the bitumen found in Pieria. They would then channel this substance into a trench near the lake and collect it in jars. Any debris that fell into the lake would move underground and reappear around four furlongs away in the sea.

Antiquity and older times

As mentioned before in this book, the Carthaginians were good at getting bitumen, mining, and quarrying in places about 30 to 60 km away from their main city, like at Jebel Ressas. After Carthage was destroyed, the Romans used these quarries and mines again for themselves.

Later, some Arab writers like Abu Abd Allah Muhammad al-Idrisi (1100-1165) and Abd al-Rahman ibn Khaldun (1332-1406) start to give impressive descriptions of the country. Other explorers like Ahmad ibn Waḍiḥ al-Yaʿqubi (died on 897/898) and Abdullah ibn Amr Al Bakri (1040–1094) cited the various mines of Majjana (nowadays Jerissa) near the Algerian-Tunisian border including iron, silver, lead and galena ores (see Kitāb al-buldān of Al-Ya'qubi for more details, Figure 1.2), centuries before the discovery of these mines.


SPECIMEN E LITERIS ORIENTALIBUS,

KITĀBO'L-BOLDĀN,

AHMED IBN ABI JA'QŪB, NOTO NOMINE AL-JA'QŪBII,

QUEM

T. G. J. JUYNBOLL,

ABRAHAMUS WILHELMUS THEODORUS JUYNBOLL,

Theol. Cand.

Fig. 1-2 A cover of Kitāb al-buldān of Al-Ya'qubi.

Early journey: acquiring knowledge

Table 1.1 provides a summary of the initial explorers who visited Tunisia in the centuries mentioned, along with their academic qualifications and the time period in which they lived. However, for more extensive information on explorers who visited Tunisia, please refer to the subsequent paragraphs.

Name	Life	Remarks
Thomas Shaw	1692-1751	English Anglican priest, stayed in Tunisia (Barbary)from 1720 to 1732
Jean-Andre Peyssonnel	1694-1759	French physician and naturalist, travelled to the regency of Tunis in 1724-1725
Rene-Louiche Desfontaines	1750-1833	Doctor and naturalist, travelled to Tunisia from 1783 to 1785
Christian Tuxen Falbe	1791-1849	Danish naval officier, diplomat and archeologist, stayed in Tunisia from 1821 to 1838
Edmond Pellissier de Reynaud	1798-1858	French soldier then diplomat, was French consul in Sousse from 1843 to 1848

Table1-1. Summary of the historical explorations in Tunisia

The first known geological journey to Tunisia was done by Peyssonel in 1724-1725. During his journey, Peyssonel observed rocks that were advantageous for quarries and mines, along with the historical modifications in the coastlines. At around the same time, Shaw (1738) wrote about his trip to Central Tunisia (Sbeitla). He talked about fossils and minerals, like the Cenomanian coral *Aspidiscus cristatus*, and included pictures and explanations.

Peyssonel's letters were not made public until 1838, over a hundred years after he travelled to eastern Tunisia. The book called "Voyages dans les régences de Tunis et d'Alger," included reports from Desfontaines, which were initially published in 1798. The first volume of the work was dedicated to Peyssonel's letters, titled "Relation of a trip to the Barbary Coast, made by order of the king, in 1724 and 1725."

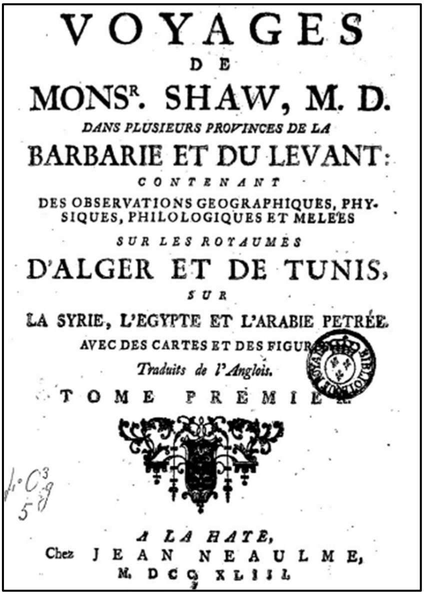

VOYAGES
DE
MONSR. SHAW, M. D.
DANS PLUSIEURS PROVINCES DE LA
BARBARIE ET DU LEVANT:
CONTENANT
DES OBSERVATIONS GEOGRAPHIQUES, PHYSIQUES, PHILOLOGIQUES ET MELÉES
SUR LES ROYAUMES
D'ALGER ET DE TUNIS,
SUR
LA SYRIE, L'EGYPTE ET L'ARABIE PETRÉE.
AVEC DES CARTES ET DES FIGURES.
Traduits de l'Anglois.
TOME PREMIER.
A LA HAYE,
Chez JEAN NEAULME,
M. DCC. XLIII.

Figure 1-3 A cover of Shaw's 1738 trip book

PEYSSONNEL ET DESFONTAINES.

VOYAGES

DANS LES RÉGENCES

DE TUNIS ET D'ALGER,

PUBLIÉS

PAR M. DUREAU DE LA MALLE,

Membre de l'Institut
(Académie des Inscriptions et Belles-Lettres).

TOME PREMIER.

PARIS,

LIBRAIRIE DE GIDE,
ÉDITEUR DES ANNALES DES VOYAGES,

1838.

Figure 1-4 A cover of the journey of Peyssonnel and Desfontaines published on 1838.

Adolphe Dureau de la Malle, a member of the Institute, took the lead in initiating this publication. The goal was to fix the problem that had been around for a hundred years, which was that Shaw's book was the only source people used to find information about North Africa. Peyssonnel and Desfontaines (Figure 1.4) published their voyage so that people could check if the British traveler's claims were true.

Acquisition of global knowledge

The German Mannert wrote about the Gulf of Gabes in his book "Old Geography of the Barbary States," which was translated into French in 1842. He connected the Gulf of Gabes to the ancient Lake Triton mentioned in old books.

Then, British geographers have given accounts of their exploration to Tunisia, such as Sir Grenville Temple in 1835 and Spratt in 1846.

The Consul of France in Sousse from 1843 to 1848, Edmond Pellissier published in 1853 a description of the Regency of Tunis where physical geography plays a significant role.

Charles Tissot, a diplomat who was very interested in ancient history and studying the Earth's features, was stationed in Tunis during the 1850s. He went to visit and wrote about the chotts in 1857.

Doctor Guyon, military specialist, examined and depicted in 1864 the thermo-mineral sources of Tunisia. Amid a trip from Philippe ville to Mourzouk by means of Tunis and Tripoli, Adolf Overweg to begin with specified the conch beds of the Tunisian Sahel. Vatonne skimmed the Tunisian South during a reconnaissance from Tripoli to Ghadames then from there to El Oued, in Algeria (1863).

In 1868, Bourguignat published in Paris a Malacological History of the Regency of Tunis. Finally, let us note the oceanographic cruise of the Narval, directed in 1873 by Commander Mouchez, which enabled Ch. Velain to describe certain points of the Tunisian coast, the Galite and the Ile Plane. Issel then carried out a study of the Galite in 1877 and told the story of the Crociante cruise. In 1914, after studying in Sardinia, he was to create the Tyrrhenian floor.

In 1876, Belluci traveled through Tunisia and made rich discoveries of prehistoric industry in particular in the region of Oudref and Metouia. Tchihatchef, naturalist and geographer, explored many countries including the Maghreb and published in 1880 an important work Spain, Algeria, Tunisia with a route map. His story includes many geographical descriptions with reflections on the inhabitants; it focuses above all on the wild flora of the sites visited. He reports that the palaces of Mohammedia were already ruined. He cites the work of Professor Guido Stache published in Austria in 1876 with mention of Rudistes near Bou Kornine. Tchihatchef reports limestone with corals in Zaghouan but he does not attribute an age to them. He attributes to a recent tectonic upheaval the disappearance of the communication between the Chott Fejedj and the Gulf of Gabes: it was already the discussion about the inland sea according to the reconnaissances of Roudaire.

Launched in southern Algeria, the myth of the inland sea has caused much ink and saliva to flow. F. de Lesseps initiated at some points this project, supported by Roudaire in 1874, to flood the depressions by opening a passage through the gulf of Gabès. The most delirious intervention was that of P. T. Virlet d'Aoust in 1845 which confirms the ancient existence of the inland sea; for the author, the uprising of the Tritonian hills, comparable to the system of Etna and Vesuvius of Elie de Beaumont, would be posterior to the expedition of the Argonauts (in Morin and Memmi, 1972).

Perpetua, italian geographer, published a detailed description of the Regency with all the information necessary for travelers in 1882 “Geografia della Tunisia”. He gave precise descriptions of the coasts, the relief, the islands, the chotts and the sebkhas. He underlined the absence of an active volcano but considered Bou Kornine as an extinct volcano, an error that standstill with more recent authors. He commented on the earthquakes as well. He described the marble of Chemtou and the Roman quarries of Pleistocene stone in the region of Mahdia; he mentioned the iron ores of Jerissa and Jebel Onk and some lead sites including Jebel Ressas. He also cited the thermo-mineral sources including Korbous, Hammam Lif, Jedidi, etc. as well as the beautiful sources of Gafsa, Nefta, Sbeitla, etc.

The mining engineer Edmond Fuchs had explored Tunisia in 1874; he cited the Middle Lias rocks in Zaghouan and pointed out the major fault that borders this massif; he then became interested in southern Tunisia and after a study on the isthmus of Gabès confirmed in 1874 and 1877 the conclusions of an Italian mission by opposing the Roudaire project of an inland sea. This position was also adopted by Nicolas-Auguste Pomel, whose work in Algeria was considerable. He studied in detail the coastline of the Little Sirte and the sector of the chotts in 1877.

The Austrian geologist and paleontologist Guido Stache had also travelled to Tunisia; he had also been attracted by the discussion on the inland sea and pointed out the Turonian near Gabès; he described the coast and the Kerkennah Islands; his publications between 1875 and 1876 (in Burollet, 1995) recount his travels, to Ressas, along the Gulf of Gabès where he comments in particular on the Quaternary deposits.

The Scientific Exploration of Tunisia

According to Burollet (1995), the Scientific Exploration of Tunisia mission was an essential step in the description of the country, from the beginning of the 1880s. the following description and references have been provided in Burollet (1995). The botanist Ernest Cosson had already studieed flora of Algeria and with collaboration of Krakil he published some new botanic information on southern Tunisia around 1957. The botanist Paul-Napoléon Doûmet-Adanson, who in 1874 had carried out a mission to study the thorny gum trees of Bled Thala, led the teams from 1882 to 1884 (cited by Cosson, 1881). At the request of Cosson, supported by Alphonse Milne-Edwards and Albert Gaudry, it was enriched in 1884 with a geological section entrusted to Georges Rolland with the help of Philippe Thomas from 1885 and Georges Le Mesle in 1887. Rolland has covered central Tunisia, Thomas worked further south and Le Mesle was responsible for the north of the country, as well as the Far South exploration. They gave good descriptions of the Zaghouan Jurassic and Eocene of the Maktar and Kairouan regions; the mission's research attracted the Commander Marchand who showed Le Mesle the fossiliferous Neocomian near J. Ressas. As early as 1885, Rolland underlined the regional importance of the great fault of Zaghouan, which a more complete story was shaped a century after by Turki (1985).

Philippe Thomas, a military veterinarian and geologist, had acquired experience in Algeria before commencing work in Tunisia at the age of forty-two. On April 18, 1885, he discovered a phosphate deposit at Jebel Tselja, after identifying the "Suessonian" in the Gafsa chain, which was comparable to the Mfatah deposit in Algeria. This was discovered in the El Haria shales and clays.

On December 7 of the same year, he announced the discovery of phosphates to the Academy of Sciences. This breakthrough was the result of Thomas's meticulous analysis, which confirmed the predictions of Jules Tissot, a mining engineer in Constantine (Morin, 1972).

Valéry Mayet's account in 1887 provides valuable insights, detailing a journey to the South in 1884. The most efficient mode of transportation from Sousse to Sfax was still by sea, as the journey on land with horses, mules, and camels was cumbersome. The observations made during the expedition were primarily focused on botany and zoology, but some geological observations were also noted. These included the gypsums of Oued Leben south of Jebel Meheri, the Cretaceous of Bou Hedma, the small Cenomanian exogyras east of Orbata, and the Miocene fossils located west of Jebel Chemsi.

These early explorations also led to the discovery of prehistoric sites and the description of the Roman wall of Bir Oum Ali, known as Clausurae (fortification) or Limes (pronounced Leem-ez). The Roman wall of Bir Oum Ali was known as Clausurae or Limes due to its function as a fortification or boundary line, respectively. Clausurae is derived from the Latin word "clausus," meaning "closed," and refers to the wall's purpose of enclosing or protecting a particular area. Limes, also derived from Latin, refers to a boundary or limit, and was used to describe the fortified boundary lines of the Roman Empire. The wall of Bir Oum Ali was likely named by Roman conquerors who constructed it as part of their military strategy to protect their territories and control the movement of people and goods. Some of the most well-known examples of these walls include: Hadrian's Wall: A fortification built across the north of England; Antonine Wall: A turf fortification built across Scotland; Limes Germanicus: The border of the Roman Empire in Germania, stretching from the Rhine River to the Danube River; Limes Arabicus: A fortified boundary protecting the Roman provinces of Arabia and Palestine; and Limes Tripolitanus: A defensive boundary separating the Roman Empire from the Garamantes in the Sahara Desert.

Later on, Francis Aubert, a mining engineer, conducted geological research in 1884, which he combined with the findings of the members of the mission, to produce the first comprehensive geological map at a scale of 1/800,000 in 1892. He also published notes on the Berriasian of Central Tunisia, Cretaceous of the Extreme Southern, and the Eocene of Northern Tunisia. To accompany the 1892 geological map, he wrote a 91-page report.

This map is an exceptional document, considering the limited time available for surveys and the lack of adequate topographic data. However, only a few geologists have had the opportunity to study it, as very few copies of the map existed. In 1911, Ginestous reported that the map was out of stock and untraceable, with copies held by the Geological Service of Tunisia and the Geological Society of France having disappeared. Fortunately, a color copy was found by Burollet, which was forwarded to the Geological Service of Tunisia by BRGM (as mentioned in Burollet, 1995). During the aforementioned scientific exploration of Tunisia, frequent gypsum-salt extrusions had been noticed and described. Both Philippe Thomas in his note on ophitic rocks (1890-91) and Aubert in the note on the map, and in particular in the appendix on the eruptive rocks, observed the extrusive style, bipyramid quartz and mineralization, however, with the lack of advanced conceptional tools, they wrongly linked these formations to the lower Cretaceous whose lagoon layers were known south of central Tunisia. It was necessary to wait for Léon Pervinquière for the Triassic age of the extrusions to be recognized.

In 1902, at the request of the Ministry of Public Instruction, Rolland was offered to write all the results of the Scientific Exploration mission, but he declined the offer due to health reasons and this task was entrusted to

Philippe Thomas, then he retired. He therefore wrote the Essay of a geological description of Tunisia with the support of Gaudry, by Péron and Paul Bursaux, technical director of Phosphates de Gafsa. In 1907, the first part appeared: Outline of physical geography, followed by the second in 1908: Stratigraphy of Paleozoic and Mesozoic terrains. The drafting of the third part ended with the death of Ph. Thomas in 1910. It was Léon Pervinquière who took up the torch and he was putting the finishing touches to it when he too died in 1913. At the end, Emile Haug published the book, and it is moving to see the two successive prefaces marking the deaths of the two geologists.

Moving towards 1912 and 1913, Spath, published first Jurassic ammonites description from Zaghouan with great skill and precision, in which certain observations including ammonites from the Callovian in the Ammonitico rosso were confirmed by Biely and Rakus much later, in 1969-70.

Gerest travelled through southern Tunisia from Gabes to Souf and a note published in 1889 attributes an upper Cretaceous age to Jebel Tebaga. Hamy made a trip to Matmata in 1891 with the geologist Errington de la Croix who had already described the Jebel Cherichera a few years earlier. Jourdy, carrying out topographic campaigns in the South, surveyed sections described by Le Mesle. The fossils were studied by Lambert and by Robert Douvillé in 1905.

Preceded in 1897 by Blanchet in Matmata and in Douiret, Cornetz stayed in the South from 1891 to 1894 and he published in 1896: The Tunisian Sahara, structure and morphology. Joly made a trip to the South in 1906/07 and he proved for the first time the existence of fossiliferous Triassic at Jebel Rehach; he attributed the lower part of the sandstones to the Permian (which is unfortunately still recognized as permo-triassic sandstones by some researchers), an interpretation taken up by Ginestous, meteorologist, who wrote in 1911 a Geological sketch of Tunisia with a geological map at 1/800,000 deduced from the Aubert map and supplemented by more recent, in particular by the map of central Tunisia at 1/200,000 due to Pervinquière (1903). Although less detailed, the map of Ginestous therefore marks a clear improvement over that of Aubert. The extrusions are attributed to the Triassic, but there are still many missing, especially in the north of the country where they still wait for the upcoming work of Joleaud (1913-1914). The geological sketch is an already modern work, with paleogeographic and hypsometric maps and numerous structural sections. Ginestous had published in 1906 a treatise on Tunisian climatology which remains a classic, confirmed by the systematic recordings made during the following 90 years.

Henri Douvillé determined the Jurassic fossils of the Tataouine region and published several articles on the Southern Jurassic from 1904 to 1908. In 1910 and 1911, he gave with Roux an excellent description of the links west of Gafsa.

Gevrey, in 1910, raised a large part of the sheet to 1/200,000 of EI Ayacha; this document was to be completed in 1932 by Solignac during the printing of the geological maps at 1/200,000.

Tunisian prehistory also experienced a real development with Jacques de Morgan, creator of the term 'Capsien'.

The Tunisian Atlas is the object of the interest of geologists from various countries: the Hungarian Janko in 1890 with a study of Bou Kornine, the Frenchman Mares around Le Kef in 1884, the Swiss Baitzer in 1893- 95 with the discovery of Liassic fossils in the Zaghouan limestones (determinations helped by Ch. Mayer-Eymar) and the German Koken near Gafsa in 1909. C. de Stefani described Jurassic fossils at Jebel Aziz (1907).

Léonce Joleaud had particularily identified the Lower Cretaceous at Jebel Bou Kornine (1901). He describes in 1914 the great alignments of the extrusive Triassic and he mentions a geological map at 1/500,000 due to Vanney, published in Tunis by the Saliba printing press; Unfortunately, this document has never been found according to Burollet (1995).

In 1910, Paul Nicou gave a summary of iron deposits in Tunisia (Jerissa, Slata, Hameima, Nefza).

In 1927, Marcel Solignac conducted research in Northern Tunisia, which he published two years later in 1929 as a book that included a map of the region at a scale of 1:200,000.

In 1932, Egene Berkaloff uncovered the late Paleozoic strata, and in early 1933, he collaborated with Henri Douville and Marcel Solignac to release a brief description of the Permian rocks of Southern Tunisia and a list of their fossils.

The first significant research on Tunisian geology was conducted by Mathieu (1950), who incorporated local geological terms into his work.

C. Castany (1951-1955) then concentrated on the Central region of Tunisia. In 1956, oil exploration commenced in the area, and Burollet (1956) provided the initial stratigraphic terminology for the country, partly based on the work of Burollet et al. (1954).

Castany (1962) further expanded the International Stratigraphic Nomenclature, particularly focusing on the stratigraphic terms that were in use in Tunisia at that time.

In 1964, Glaçon and Rovier discovered limestone microbreccia in Kroumirie. Jauzein and Rovier identified Adissa and Ed Diss formations at the same location in the following year. In 1967, Busson did a survey of Southern Tunisia. Later, Rakus and Biely categorized the Lower Liassic rocks in the Tunisian Dorsal as the “Formation calcaire de l’Ouest”. Furthermore, Bajanik et al. recycled the terms for Miocene formations such as Beglia and Saouf, and gave new nomenclature including Mahmoud Formation, Cap Bon Group, Sehib Formation, and the Bou Sefra Facies. In 1973, an honorary book was published in honor of Solignac, introducing many new formations. This included the Tithonian Ressas Formation, Haffouz Facies, Korbous Limestone, and Oued Hamman Formation. In the following year, Biely and his colleagues revised the Neogene stratigraphy in Northern Tunisia. They named the Bejaoua Group, Medjerda Group, and the Oued Mellegue Group with its two formations: Tessa and Oued Djouana. Back in 1975, Turki discovered the Grija Formation of the Aptian age in Jebel Bargou. Khessibi, on the other hand, introduced the continental Kebar Formation of the mid-Cretaceous age in Jebel Kebar. For many years since the 1960s, Dominique Massa has done considerable research on the Paleozoic of both Libya and Southern Tunisia. In May of 1964, the El Borma oil field was discovered in Triassic reservoirs near the Algerian border, launching Tunisia's oil industry. Subsequently several other fields have been found, namely Ashtart, Bouri, El Biban, Ezzaouia, Sidi El Kilani, El Menzah, Cercina, Miskar, and Tazarka. To manage exploration and production operations throughout the country, the “Entreprise Tunisienne d'Activités Petrolières” (ETAP) was founded in March 1972. The underestimated Isis Field of Tunisia was discovered in 1974, but didn't get developed until December 2001. Bishop wrote an article in 1975 about the geology of Tunisia and its bordering countries, followed by second paper in 1988 on the hydrocarbon geology of East-Central Tunisia. Burollet (1976) contributed a review of Tertiary geology and Fournié (1978) was responsible for the “Lithostratigraphic Nomenclature of the Upper Cretaceous and Tertiary Series of Tunisia”, introducing 10 new formations.

Ben Ferjani et al. (1990) later reviewed the petroleum geology of Tunisia under the support of ETAP.

A brief oil exploration history

Oil Exploration in Tunisia began in 1894, with the first license being granted in northern Teboursouk next to Ain Guetrane located in northern Tunisia. This has been dated as the first prospecting license for hydrocarbons. The first wells were drilled in 1909 in the vicinity of Ain Ghelal, located about some 50 km northwest of Tunis; several of them went to about 100 meters. Before and immediately after the first World War, exploration drilling was done around other surface shows, but all wells were dry. The first hydrocarbon discovery, gas in Lower Cretaceous sandstones, was made in the Jebel Abderrahman structure of the Cap Bon region in 1948.

An overall survey of northern Tunisia was undertaken in 1924-1925 by geologists from Royal Dutch-Shell and Standard Oil. In 1924 the latter company drilled the surface anticline of Cap Bon to a total depth of 1,585 meters (5,200 feet); the only result was the evidence of some gas and bitumen in the Lower Cretaceous.

This well, which represented the only deep exploration undertaken during this period, was at that time considered to be ill-advised, and the well-known geologist Pierre Termier, Inspector-General of Mines and Technical Adviser to the Tunisian Government, wrote in 1928 that it had been located.

In 1931 SEREPT was created by French and Tunisian states and it was founded to explore for petroleum in the country.

Exploration activity was based on surface geology and surface seeps, with the available primitive technology. Six wells have been drilled, two of them showing strong indications of gas and oil Kebir-1 near Bizerte and El Haroun-1 south of Bizerte Lake.

During the period between 1949 and 1950, seismic activity was focused on the Cap Bon and northcentral region, and the first discovery of gas was made in the Jebel Sidi Abderrahmam structure. In 1950 began the exploration of Eastern Tunisia: Shell and Gulf in association with SEREPT: CPDT and SNAP explored the Sahel and Central Tunisia and later NW Tunisia. Several wells have been drilled, bringing informations on the stratigraphy of Eastern Tunisia and indicating oil shows as in Ktitir-1 and 2, Chorbane-1, Sainte Juliette-1, and so on.

Hydrocarbons laws were progressively changed. The permits became less large and numerous new operators acted successively. Exploration activity increased between 1956 and 1960 with the drilling of 20 wells.

During this period an extensive exploration program was carried with progressive introduction of new techniques, particularly the magnetic record of seismic and the first commercial oil production was made in Middle Triassic Sandstone of the El Borma structure on the Algerian border in 1964.

Stimulated by this discovery, exploration extended into Central Tunisia and the eastern offshore of Sfax-Gabès and was rewarded in 1966-67 by the discovery of the Douleb and Semmama oil fields, Sidi El Itayem oil field in 1970 and Ashtart offshore oil field in 1971.

The 1964 El Borma discovery in the northeastern part of the Ghadames Basin was followed up with only limited success. Its western extension into Algeria was established in 1969 and a number of small accumulations were subsequently made nearby, over the next 10 years.

Among these, Chouech Essaida (1972), Larich (1979), and Debbech (1980) identified in southern Tunisia as well as Hassi Keskessa (1969) in Algeria. With the modest El Franig, Sabria Nord, and Baguel discoveries between 1980 and 1983, Amoco decided to expand exploration of the Palaeozoic successions further to the north, into central Tunisia. Despite the fact that they demonstrated the existence of a Palaeozoic petroleum system on the northern face of the so-called Talemzane Arch (see new definitions in the upcoming chapters of this book) and raised the prospect of additional discoveries there, they were incredibly small.

The high price of oil encouraged offshore exploration later in the 1970s. As a result, new oil was discovered in the Miocene Sands (Birsa and Yasmin fields in 1976; Tazerka field in 1979) in the Gulf of Hammamet. On the other hand, gas was tested at Hasdrubal and Miskar in 1975 and 1974, respectively, but at that time it was thought to be non-commercial.

The major discoveries conducted during the early eighties in new targets, such as oil from the Jurassic M'rabtine sandstones and the Cenomanian Zebbag dolomites (Ezzaouia and El Biban oil fields in 1980) along with gas and condensate from the Ordovician quartzite (El Franig gas field in 1981), were rewarded by the use of modern exploration techniques and the introduction of more flexibility in permit granting and acreage.

In addition, the oil and gas fields of Zarat and Baraka, Hasdrubal, and the Chargui gas fields, as well as Sidi El Kilani (1989), Belli and Cercina (1991), Oued Zar 1 and 2 (1996-1998), Laarich 2 (1997), and Hamouda-1(1998), as well as other fields, were all discovered (1998).

Starting from 2002, Pioneer Natural Resources played a significant role in the discovery of crucial Paleozoic findings in southern Tunisia, either in part or entirely responsible. The aforementioned discoveries include the concessions Jenein Nord-Cherouq (50 %), Mona/Durra (30%) and Adam (20%), as well as discoveries made into the permits of Jenein Nord, Anaguid, El Hamra and Borj-El-Khadra up to 2010. Example of a discovery within the Silurian Acacus sand can be mentioned in well Adam-1 which was drilled in 2002 by Pioneer together with Eni. This announcement encouraged a successful drilling succession. In the beginning of 2011, OMV declared the purchase of all Pioneer's subsidiaries, thereby gaining ownership of the previously mentioned concessions and production permits.

The paleozoic discoveries included the Silurian and Ordovician reservoirs. This acquisition completed in reality OMV’s Jenein Sud and Nawara production. A discovery has been announced in 2015 by Mazarine Energy and ETAP while drilling well CAT-1 (Chouchet El Atrous-1) regarding the Ordovician El-Hamra and El-Atchane formations.

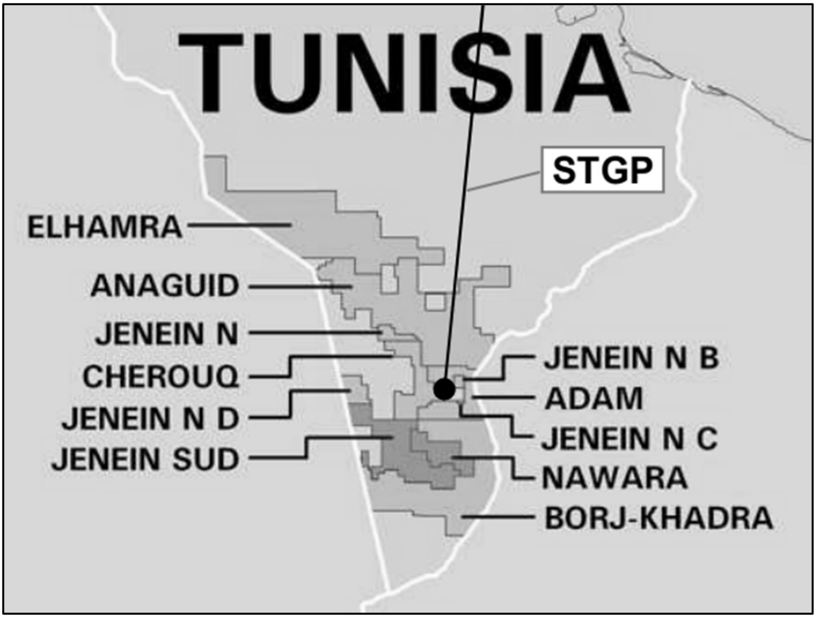


Figure 1-5 2011 concessions/permits distribution in southern Tunisia inclusing subsidiaries of Pioneer Natural Resources (orange colour) and OMV (green colour). (Source: https://www.omv.com/en/our-business/upstream/portfolio-and-locations)

The Paleozoic, age and definitions

The Paleozoic is a significant period of geological time that began around 541 million years ago with the Cambrian explosion, which saw a remarkable diversification of marine life. The end-Permian extinction, the largest biotic extinction in Earth history, occurred about 252 million years ago. It was much more significant than the Cretaceous-Tertiary Event (occurred around 66 million years ago), which wiped out among other species the dinosaurs. Long before the dinosaurs were on the scene, a variety of plants and animals inhabited our planet throughout the Paleozoic, but they were essentially wiped off by a series of severe volcanic eruptions in Siberia.

However, the Paleozoic era was a comparatively young time in geological terms, having just started 541 million years ago. Orogeny is the term used to describe the process of creating mountains over tens or hundreds of millions of years as a result of various geological occurrences. There are collisions between continents. Converging with continents are islands and microcontinents. Together, these occurrences raise mountains. Long before the Paleozoic, a supercontinent by the name of Rodinia existed. At the start of the Neoproterozoic period, Rodinia was a supercontinent that contained the majority or all of the Earth's landmass. It existed between 1.1 billion and 750 million years ago.

It formed from parts of an older and poorly understood supercontinent, and broke up during the Tonian period, with its continental fragments eventually re-assembling to form Pangaea 300-250 million years ago. The exact position and history of Rodinia is not well-known compared to Pangaea. The breaking up of Rodinia may have triggered the extreme cooling of the global climate around 700 million years ago, known as the Snowball Earth of the Cryogenian period, as well as the rapid evolution of primitive life during the Ediacaran and Cambrian periods.

During the early Paleozoic era, the supercontinent, known as Rodinia, began to disintegrate. Its different fragments were randomly spread across the globe in the north and south. As Laurentia, a continent that included much of what is now North America, joined the northern continents, it underwent more orogenies, or mountain-building processes. In contrast, Gondwana was created by the union of the southern continents.

The formation of Pangaea, the most recent supercontinent, occurred when the collision between Laurentia and Gondwana took place. The process of Pangaea's formation began approximately 300-250 million years ago and continued until around 200 million years ago when it was fully formed.

Figure 1-6 Approximative reconstruction of the supercontinent Rodinia (Dalziel, 1997)

The Paleozoic is substantially more well-known because, compared to the Precambrian epoch, it is a more recent time period. Another factor is that Paleozoic creatures possessed hard parts that were well preserved in fossil form. The Paleozoic fossil record sheds important light on the diversity and evolution of early Earth life, including the birth of sophisticated living forms like fish, amphibians, and reptiles.

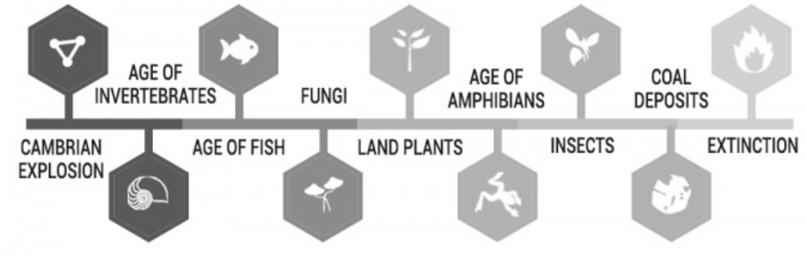


Figure 1-7. Paleozoic Era timeline.
(source:https://earthhow.com/paleozoic-era)

The major divisions of the Paleozoic Era are the Cambrian (541 million to 485.4 million years ago), Ordovician (485.4 million to 443.8 million years ago), Silurian (419.2 million to 419.2 million years ago), Devonian (419.2 million to 358.9 million years ago), Carboniferous (358.9 million to 298.9 million years ago), and Permian (298.9 million to 252.2 million years ago) periods.

One may say that the Paleozoic started is when Africa first began to take shape. Tillites that were widely deposited during the Ordovician period can be found in southern Morocco, much of western Africa, and sub-equatorial Africa as far south as Namibia. The end of the Precambrian Period and the start of the Cambrian Period are separated by that tillite series. Southern Morocco, the Western and Mauritanian Sahara, and Namibia are the locations where marine fossils from the Cambrian Period (about 541 to 485 million years ago) can be found. Southern Tunisia, the Tanzanian coasts, and the Mozambique Channel all have Permian Period marine fossils that date from about 299 and 252 million years ago. The Karoo System in South Africa has Permian remnants that are continental rather than marine origin.

Brief definition of the Paleozoic era

The Cambrian is the Paleozoic era's first epoch, lasted roughly from 541 to 485 million years ago. The Cambrian Explosion, a relatively brief period of rapid evolution of sophisticated living forms that took place around 540 million years ago, is what makes it most famous. Many of the important animal groups, such as trilobites, brachiopods, mollusks, and arthropods, make their first appearances in the fossil record at this time.

As opposed to the soft-bodied animals that predominated earlier times, the hard-shelled organisms that emerged during the Cambrian epoch left behind a more significant fossil record. As the foundation of the marine ecosystems that still exist today, these species were essential to the evolution of life on Earth.

Figure 1-8. Paleogeographic reconstructionof the Earth at the Cambrian. Recostruction modified after Cocks and Torsvik (2002); Torsvik and Cocks (2004)

Significant geological occurrences, such as the dislocation of the Rodinia supercontinent and the subsequent development of the new supercontinent of Gondwana, occurred during the Cambrian epoch. As a result, new oceans formed and ecological niches were created, which the rapidly evolving Cambrian fauna swiftly filled.

The Cambrian period is distinguished in terms of geology by the extensive deposition of marine sediments, such as sandstones, shales, and limestones, which are frequently abundant in fossils. These sediments were deposited in a range of marine habitats, including reefs, deep ocean basins, and shallow coastal regions.

The Cambrian epoch was a crucial time in the development of life on Earth and had a big impact on the geological and biological history of our planet.

Geologically speaking, the Ordovician period followed the Cambrian and lasted from roughly 485 to 444 million years ago. It is so named in honour