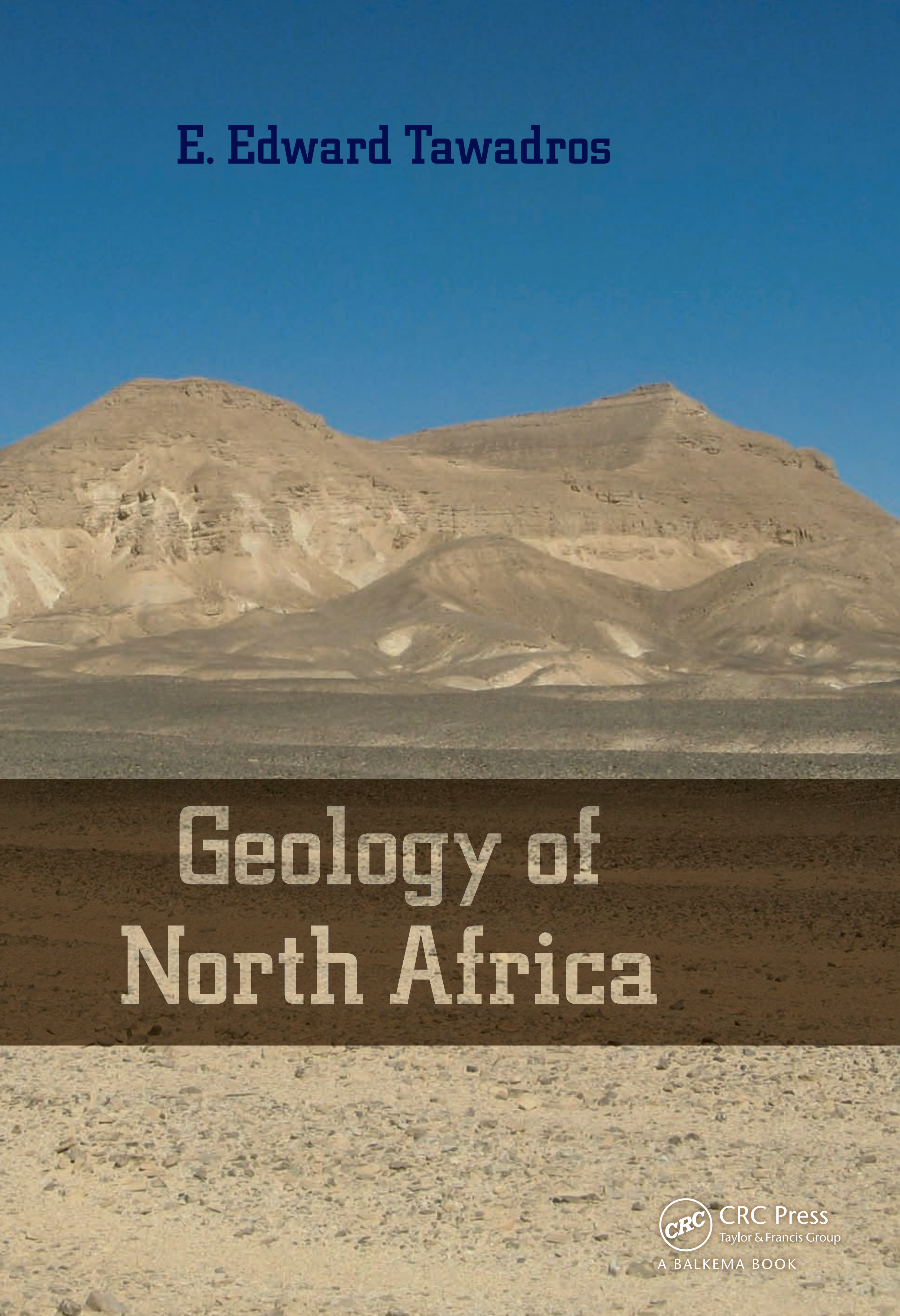

E. Edward Tawadros

Geology of North Africa

CRC Press
Taylor & Francis Group
A BALKEMA BOOK

Geology of North Africa

"*No limit may be set to art, neither is there any craftsman that is fully master of his craft*."

(Instructions of Ptahhotep, XXIV Century B.C.)

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E. Edward Tawadros

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Preface

This book is a revised and expanded new edition of the Geology of Egypt and Libya (Tawadros, 2001). It follows the same structure as the first edition. New chapters covering the geology of Algeria, Tunisia and Morocco have been added to cover the geology of all of North Africa. The petroleum systems of North Africa are discussed in a new chapter. In addition, a new chapter dedicated to the history of geological ideas and oil exploration in North Africa has been included. The book reviews the tectonic elements, the geology of the Pan-African Shield, and Phanerozoic geological evolution of the five North African countries, and gives a description of most of the lithostratigraphic units in the region. It includes a bibliographic list of more than 2500 references, which will guide the interested reader to further information. The main objective still remains the same; to give a quick reference to the geology of North Africa that can be useful to both professionals and students. The first edition contains more than 20 tables that show stratigraphic nomenclature used by various authors for different areas. These tables are not reproduced in the present edition. The present work is an attempt to compile a large portion of the published data to summarize the geology of North Africa.

The thickness of the rock-stratigraphic units is expressed in both Imperial and SI units. However, distances are expressed in the SI units only.

This compilation does not contain proprietary data. It is based entirely on published data. However, in writing the book, the author was guided by the many years of experience gained while working in and on North Africa.

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Acknowledgements

I thank Sebastian Lüning who supplied me generously with copies of his publications, videotapes, and pictures from his fieldtrips. I am indebted to the people who provided me with photographs of outcrops in many parts of North Africa. Prof. Jochen Kuss (University of Bremen) kindly provided the picture for the book cover. Prof. Baher El Kaliouby (Ain Shams University) contributed pictures from Sinai and read the chapter of the Pan-African basement. Steven Aitken (Calgary) provided the picture of the Hamar Laghdad buildups of Morocco. I am also obliged to Kent Wallace and John Harper for the thorough reviews of the first edition. I am grateful to the late Prof. Manuel S. Pinto (INHIGEO) who invited me to write two chapters on the history of geological ideas and oil exploration in Egypt and Libya for a planned publication, which form the basis of the history chapter in this edition. I am also grateful to Dr. A.A. Ismail (Ain Shams University) for providing me copies of his publications that otherwise would not have been available to me. Andras Zboray drew my attention to the photograph of the Staff of the Desert Survey Department, and Peter Clayton kindly gave me the permission to reproduce it here. Extensive discussions with the staff of Nexen in Calgary helped me to further my education about the geology of North Africa. Two positive book reviews of "Geology of Egypt and Libya" by Richard Moody and A.J. Reedman pointed out some of the short comings of the first edition, which I tried to rectify in the current edition. Initial correspondence with A. Michard and D. Frizon de Lamotte put my unrealistic ambitions into check and helped me to restructure the chapter on the geology of Morocco.

My thanks are also due to CRC Press, particularly Germaine Seijger and Lukas Goosen for their dedication and support during the process of producing this volume.

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About the author

Ed. Tawadros, *Ph.D., P. Geol.*, is an international geological consultant based in Calgary, Alberta, Canada. He received a B.A.Sc. degree in geology from Ain Shams University, Cairo, in 1968, followed by a post-graduate Diploma in applied geology from Cairo University, a M.Sc. degree in geology from Université de Montréal, Canada, and a Ph.D. in geology from the University of St. Andrews, Scotland. He also holds a BA Major in Spanish from the University of Calgary, Alberta. Since graduation he has worked for a number of consulting and major oil companies, including the General Petroleum Company, Cairo, Egypt, Géophysique France-Québec, Montreal, Robertson Research Company, Canadian Superior Oil, Mobil Oil Company, and Nexen, Calgary, Canada, and Sirte Oil Company, Libya, and more recently in Argentina. He has authored and co-authored a number of papers dealing with the geology of parts of Canada and Libya. He also co-authored papers on the comparative geology of North Africa and the Caucasus with colleagues from Russia and Azerbaijan. He is a member of the Canadian Society of Petroleum Geologists (CSPG) and the Association of Professional Engineers, Geologists and Geophysicists of Alberta (APEGGA).

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PART 1

History of geology and hydrocarbon exploration in North Africa

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Chapter 1

Introduction

The history of geological and petroleum exploration in parts of North Africa has been treated by Gentil (1902), Demoulin (1931), Desio (1967, 1968), Meckelein (1975), Said (1990b), EGPC (1992, 1994, 1996), Klitzsch (1994), Legrand (2002), Bettahar (2007), and Missenard et al. (2008), in addition to brief reviews of the history of specific geological points in the numerous publications on the geology of North Africa. The history of geological research in Egypt and Libya is treated in detail by (Tawadros, in preparation). The five North African countries treated here share many aspects in their geological make up, yet the pace and timing of the development of the geological ideas vary widely.

1.1 EGYPT

In the 1700s, Egypt was visited by many famous travellers, such as Thomas Shaw (1692–1751), Fredric Hasselquist (1722–1752), Richard Pococke (1704–1765), and James Bruce (1730–1794).

The end of the 18th and the beginning of the 19th Centuries were the most significant times for the development of scientific research in Egypt. The results of the French Expedition led by Napoleon Bonaparte in 1798–1801 were included in the monumental publications of the "*Description de l'Egypte*" and the "Memoirs relative to Egypt" (1799, 1800). Napoleon also established the *Institut d'Egypte*, which was probably the first truly scholastic institute in North Africa since the Ancient Library of Alexandria. The Expedition also produced the first two reliable maps of Egypt; one at the scale of 1:100,000 in 47 sheets; the other at the scale of 1:1,000,000 (published in 1828). One of the earliest descriptions of *Nummulites* in Egypt was that by Monge (1746–1818).

In 1820, Hemprich and Ehrenberg from the Zoological Museum in Berlin collected land animals and plants from the Gulf of Suez, Sinai, Nubia, and Lebanon. In 1824–1825, Klunzinger and Ehrenberg collected marine animals from the Red Sea. Ehrenberg wrote on coral reefs of the Red Sea in 1832 and 1834. Cailliaud (1826) described Eocene fossils in Egypt. Eduard Rüppell from the Senkenberg Museum, Frankfurt, began his work in Egypt in 1826. In 1837, Russegger introduced the term "Cataract Sandstone" in Upper Egypt, which he subsequently changed in 1842 into the "Nubian Sandstone" to initiate one of the most enduring controversies in the history of geology in North Africa. In 1841, D'Hericourt made a few geological observations on the Red Sea in Egypt and the Gulf of Aden. Other geological observations were made by Orlebar (1845). Bellardi (1851 and 1854) described and catalogued the Egyptian *Nummulites* collection at the Mineralogical Museum of Turin. Lieutenant Newbold (1848a) wrote a brief note on the geology of Egypt. O. Fraas (1867) described the Eocene outcrops between Assiut and the Pyramids.

In 1868, the first shafts and wells for oil were dug at Gebel Zeit in the Southern Gulf of Suez. During that time, H. Bauerman (1869) discovered the Carboniferous in Sinai. Schweinfurth discovered the Carboniferous sediments at Wadi Araba (Schweinfurth, 1885) (described by Walther in 1890), studied the Mokattam Hills (Schweinfurth, 1883), fossil vertebrates in Fayium (Schweinfurth, 1886), and the Cretaceous at Abu Roash (Schweinfurth, 1889), He compiled his observations in Egypt in a book (Schweinfurth, 1921). E.T. Hamy (1869) wrote on the Quaternary of Egypt. Owen (1875) described a Sirenian mammal (*Eotherium aegyptacum*) from the Eocene Nummulitic Limestone of the Mokattam Hills near Cairo. Duncan (1869) described echinoderms, molluscs, and other fossils from the Cretaceous rocks of Sinai.

A number of Expeditions were sent by the Khedive of Egypt and the Royal Geographical Society to explore for the sources of the Nile, which led to the discovery of the sources of the Nile in 1862 by John Speke (1827–1864) and James Grant (1827–1892). An expedition to Sinai and Palestine in 1871 was sponsored by the Palestine Exploration Fund and led by officers of the Royal Engineers (Major C.W. Wilson, 1872–1873). Another expedition was sent to the Eastern Desert in 1874–1876; the result of which was a geological and mineralogical reconnaissance of the region carried out by Mitchell (War Office, 1876) between Rudeis and Qoseir on the Red Sea coast and Qena on the Nile. A report on the geology and petroleum occurrences of Ras Gemsah and Gebel Zeit was published (Mitchell, 1887). Many samples were collected during that expedition and the final report included a geological map and a profile. The southern part of the Eastern Desert between Aswan and Qena in the Nile Valley and Berenice and Qoseir on the Red Sea coast was visited by the Scientific Expedition dispatched by the Khedive of Egypt in 1891 under the leadership of E.A. Floyer (1893) who made a few geological observations in the area. Felix (1884, 1904) carried out detailed studies of Egyptian corals. Antonio Figari Bey (1804–1870) summarized his observations in his book (Figari, 1864) and collected many Tertiary and Cretaceous fossils samples that were described several decades later by Greco (1915, 1916, 1917, 1918) and Stefanini (1918).

The last quarter of the 19th Century saw another turning point in the development of geological research in Egypt with the accomplishments of the Rohlfs Expedition in 1874–1876. The Expedition was the first comprehensive and multidisciplinary work on the Western Desert and included, in addition to Rohlfs, many other renowned scientists, such as Ascherson (botanist), Jordan (geodesist and astronomist), Zittel (geologist and paleontologist), and G. Remelé (photographer). The results of the Expedition were produced in three volumes of the "*Expedition zur Erforschung der libyschen Wüste*" (1875–1883). The results were also published by Zittel (1883a, b) in Palaeontographica, volume 30 "*Beiträge zur Geologie und Paläontologie der libyschen Wüste und der angrenzeden Gebiete von Aegypten (unter Mitwirkung mehrerer Fachgenossen herausgegeben von Karl A. Zittel*), along with contributions from Jordan, Ascherson, Schenk (1883), Mayer-Eymar (1883, 1886, 1898), Schwager (1883), de la Harpe, Quaas (1902), Wanner (1902), de Loriol (1864, 1881, 1883), Pratz (1883), Fuchs, Dacqué, and Oppenheim (1903, 1906). This work also produced the first map of northern Egypt at a scale of 1:300,000.

In 1882, the British occupied Egypt, but apparently the occupation did not slow down geological exploration activities. In 1883, Zittel subdivided the Cretaceous and Tertiary rocks in Egypt into units that persist until today. Meyer Eymer conducted many studies on the paleontology of Egypt from 1883 until 1903. Dames (1883, 1894) examined Tertiary vertebrates in Fayium which were housed in the Berlin Museum of Natural History. Dawson, J.W. (1884) discussed the Geology of the Nile Valley in a brief note, and in 1888 he published the book "Modern Science in Bible Lands". Von Nötling (1885) studied Tertiary crustacean. In 1893, Suess introduced the name Tethys, which was followed by many discussions, debates, and controversies that continue until today (e.g. Ball, 1910, 1911). In 1894, Schellwein identified Upper Carboniferous brachiopods in exposures along the Gulf of Suez. Seward (1907, 1935) identified fossil plants from Egypt. Osborne & Granger (1907) made an expedition to Fayium and collected vertebrate samples for the American Museum of Natural History.

In 1886, the discovery of the Gemsa Field in the Southern Gulf of Suez in Miocene dolomitic reefal carbonate (later Nullipore Limestone) reservoirs signalled the beginning of oil exploration in Egypt. Ardagh (1886) made the first attempts to explain the origin of the oil seeps in Gebel Zeit.

Egypt entered the 20th Century with a giant step for geology. In 1896, the Geological Survey of Egypt was founded by Colonel Henry George Lyons (1864–1944). Hume, Beadnell, and Barron joined the Survey. Since that time the Geological Survey played a crucial role in the development and advancement of Egyptian geology and the development of the mineral wealth of Egypt. Barron discovered phosphate in Gebel Qurn near Qift in Upper Egypt 1896 and in Wadi Hammama in 1897. During that time, Gregory (1896) introduced the "African Rift Valley" concept and the debates the ensued about the origin of the Gulf of Suez (Hume, 1901, Ball, 1910, 1911, 1920, Gregory, 1920a, b, 1921). The celebrated Edward Hull (1896) wrote the "Geology of Nile Valley". E. Fraas (1900) constructed a cross-section across the Eastern Desert from the Nile to the Red Sea, and reported a new whale (Zeuglodon) species from the Middle Eocene of the Mokattam Hills in Cairo (Fraas, 1904).

In 1901, Hume wrote "Rift valleys and geology of Eastern Sinai" for the International Geological Congress in response to Gregory's arguments. Barron & Hume (1900, 1902) studied the geology of the Eastern Desert. Ball (1900) published "Topography and Geology of Kharga Oasis". Blanckenhorn joined the Survey in 1900 and published on the geology of Egypt and the origin of the Nile, where he introduced the term "Urnil" to define an ancestor of the Nile. Blanckenhorn (1900) described fossils collected by Schweinfurth from Tubruk and Porto Bardia in Libya and correlated them with Miocene rocks in Egypt. Douvillé (1900, 1901a, b) studied the foraminifera collected by Fourtau (1902) and reported the discovery of *Orbitolina* at Gebel Genefe. In 1902, Beadnell described Cretaceous rocks in Abu Roash west of Cairo and divided them into lithostratigraphic units that are still in use today, albeit under different formational names. Ball (1902) published "Gebel Garra and the Oasis of Kurkur" in Southwestern Egypt. C.W. Andrews accompanied Beadnell on two expeditions (1902 & 1903) to the Fayium where he identified new species of vertebrate fossils. Ball & Beadnell (1903) published the treatise on the "Baharia Oasis". Their findings were only surpassed by those of Ernst Strömer von Reichenbach almost thirty years later. Strömer made the most significant discoveries of vertebrate fossils in Egypt (from 1910 until 1936). His collection was sent to the Berlin Museum in 1922, but was destroyed when the Museum was bombed by the allies in 1944. Strömer was accompanied by Markgraf in 1910. Strömer introduced the *Baharijhe Stufe* (Baharia Formation) (1914) and confirmed its marine origin. The fossil plants collected by Strömer were described by Hirmer (1925). At the same time, Harding King (1916, 1918) made an expedition to the Dakhla Oasis in the Western Desert.

In 1905, Beadnell published the results of his studies on the Eocene-Cretaceous systems in the Esna-Aswan areas in Upper Egypt, and introduced the Esna Shale for a succession that straddles the Cretaceous-Tertiary boundary, which triggered an enduring controversy (reviewed by Tawadros, 2001). In 1907 Ball examined the first Cataract at Aswan following the pioneering work by Hawkshaw (1867). In 1906, Barron mapped the western portion of Sinai, and Hume & Beadnell mapped Southeastern and Central Sinai. In 1908, Weill published "La Presqui'ile du Sinai" which included descriptions of sedimentary and igneous rocks.

Cairo (Fouad I) University, the first university in Egypt, was established in 1908.

In 1909, Hume became head of the Geological Survey (Fig. 1.1), and systematic geological studies and mapping of Egypt began. In 1910, Schweinfurth produced independently the first modern map of Egypt.

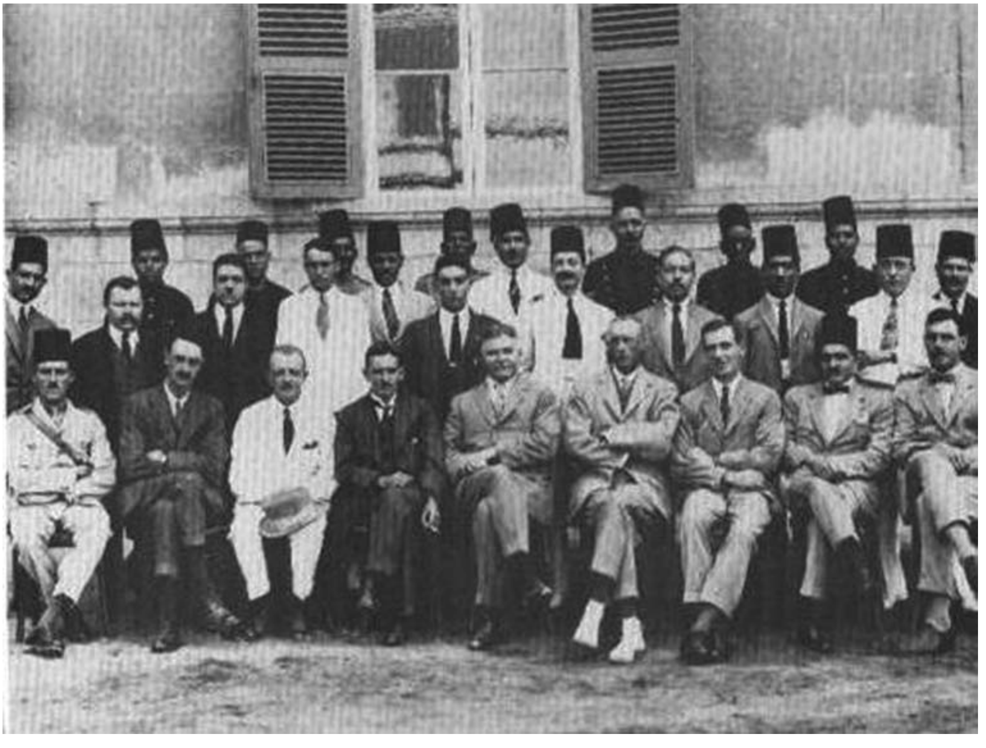

Figure 1.1 Photograph of members of the Geological Survey of Egypt in 1925. Front row: Patrick Clayton, George Murray, John Ball, W.F. Hume, H.L. Beadnell, O.H. Little, Hassan Sadek, George Walpole (Courtesy of Peter Clayton).

In 1911, the Nakhla Meteorite fell in Egypt; Hume collected samples and Ball (1912) described them in "The Meteorite of El Nakhla el Baharia". Recently, samples of this meteorite were subjected to various analytical tests and were subject of numerous debates, including the origin of life (Jull et al., 2000, Meyer, 2004).

Edward Hull joined Kitchner's Expedition (1892–1895) and carried out geological mapping in Sinai. Hull (1886) regarded Lower (Northern) Egypt and Sinai as traversed by a series of north-south-oriented folds. He postulated that the Gulf of Suez was formed due to faulting along folds (the Syrian Arc folds).

In 1911, Production started from the Gemsa Field (depleted in the 1930s after producing 1.4 mmbbls of oil). Shell entered Egypt, with the Anglo Egyptian Oil Fields Company "AEO" (50% with BP). In 1913, the Hurghada Field was discovered by Shell in Carboniferous "Nubian" sandstones by drilling a surface anticline, which constituted the first major oil discovery in Egypt. The field was put on production the following year and produced nearly 48 million barrels by the time it was depleted in 1996. In 1918, the Abu Durba Field (depleted in the early 1940s) onshore the Gulf of Suez was discovered in Nubian Sandstone near oil seeps by the Egyptian Government. No trap or seal were detected in that field (EGPC, 1992). Reserves were small and the Government handed over operations to the Egyptian Oil Syndicate in 1923 after drilling 10 wells.

The Petroleum Development Committee was formed in 1913 following the discovery of the Hurghada Field and Hume and Ball became members. Barthoux & Douvillé (1913) discovered Jurassic sediments at Maghara in Northern Sinai (Douvillé, 1916). Ball (1913) wrote "Topography and Geology of the Phosphate District" and "A Brief Note on the Phosphate Deposits of Egypt". Eck (1914) described the cephalopods collected by Schweinfurth from the Cretaceous chalks.

In the period 1914–1918, WWI interrupted the geological exploration activities in most of North Africa. However, new information was added during that time thanks to the efforts of the soldiers/scientists who participated in the war. In 1916, the British Light Car Patrol was formed, of which Claude H. Williams and John Ball were members. The use of motor cars for reconnaissance in the Libyan Desert contributed to a better understanding of the Egyptian deserts and the distribution of sand dunes. Hassanein Bey reached the Kufra Oasis accompanied by Rosita Forbes in 1920 (Forbes, 1922); one of the earliest female travellers in Egypt.

Moon, Madgwick and Sadek joined the Survey in 1917, and in 1920, Hassan Sadek became head of the Petroleum Research Board. In 1922, Egypt gained independence from Britain, and Fouad I became king of Egypt. In 1923, Schweinfurth compiled his works in Egypt in "*Auf unbetreten Wegen in Aegypten*". Hassanein Bey (1924) crossed the desert from Sallum to Kufra and Sudan. The samples collected from Kufra and Oweinat during that expedition were described by Hume (1924) and Moon (1924). The Anglo-Egyptian Oil Company (AEO) introduced the Eöstöv torsion balance into Egypt for the first time, and Gemsa and Hurghada fields were surveyed. Moon & Sadek (1923) carried out a study on the Gulf of Suez and introduced the name Nullipore Rock for a Middle Miocene *Lithothamnion* Limestone unit. Hume (1924) wrote "The Egyptian Wilderness". In 1925, Hume published his monumental work, the "Geology of Egypt" in three volumes, which was completed in 1945. Barthoux (1922) gave a detailed account of the Precambrian basement in Sinai.

In 1927, Beadnell published an account of his studies in Central Sinai in "Wilderness of Sinai", which was preceded in 1909 by a review in the Geographical Journal.

In the meantime, H. Sadek and P.A. Clayton studied the Northern Galala Plateau and Gebel Ataqa on the western side of the Gulf of Suez and George Walpole (1927) discovered the Qattara Depression in the Western Desert. Debates on the origin of the desert depressions and their potential for power generation started (Serry Bey, 1929, Anderson, 1947, Pfannenstiel, M., 1953, Gindy & El-Askary, 1969, Albritton et al., 1990, 1991, Gindy, 1991). In 1927, Ball published his article "Problems of the Libyan Desert" in The Geographical Journal. Bagnold traversed the Western Desert from Cairo to Siwa in motor cars. Beadnell surveyed the Western Desert south of Kharga Oasis and drilled the Bir Missaha well. In 1928, the Geological Survey of Egypt made a new geological map of Egypt, which was included in the "Atlas of Egypt" presented to International Geographic Congress in Cambridge. Gebel Oweinat (Uweinat) was shown on that map for the first time.

Bagnold led another expedition in 1938, during which Tomkeief & Peel (1942) described the igneous rocks at Gebel Oweinat. In 1978, a multidisciplinary group, led by Farouk El-Baz (El-Baz et al., 1980), Vance Haynes and William McHugh retraced Bagnold's 1938 expedition to Gilf Kebir and Uweinat (Bagnold et al., 1939).

In the 1930s, a group of scientists-soldiers, that included Beadnell, Ball, Bagnold, and Clayton, as well as members of the royal family, including Prince Kamal el-Din Hussein (1875–1932) (1928), the son of Sultan Hussein Kamel and grandson of Khedive Ismail, and Hassanein Bey (another member of the royal family), ventured into the heart of the Western Desert. They were joined by Sir Clayton-East-Clayton (1908–1932)[1] and his wife Lady Dorothy (nicknamed Peter) Clayton (1908–1933), as well as the controversial Ladislau Almàsy. Rosita Forbes, who accompanied Hassanein Bey (1924), disguised herself as a Bedouin woman in order to achieve her mission. Their enthusiasm was also fired by the desire to locate the legendary Oasis of "Zerzura", the first mention of which was in the Arabic fiction book, "Book of Hidden Pearls".[2] Its existence and location made the subject of long discussions in the Journal of the Royal Geographical Society, which involved Almàsy (1936), Harding King (1928), Wingate (1934),[3] and Ball (1928). In addition, Almàsy was occupied with the search for Cambyses army, believed to have vanished in a sandstone storm. In 1929, Almàsy drove from Wadi Halfa to Selima Oasis and along Darb el Arbain in the Eastern Desert. The same year (1929), Bagnold explored the Sand Sea in the Western Desert. Bagnold made another expedition in 1930 to continue his study of the desert sands (Bagnold & Harding King, 1932).

In 1932, Almàsy, Sir Robert Clayton, P.A. Clayton, and Penderel explored the western side of the Gilf Kebir in the southwest corner of Egypt. The same year,

1 Sir Clayton died of polio, and Lady Clayton died a year later in a plane crash after her return to England.

2 According to Ahmed Bey Zaki (1907) (cited by Ball, 1927b), this book has been the cause of more damage to the Ancient Egyptian monuments since the Arab invasion of Egypt than all the ravages of war and the and of time.

3 Wingate (1903—1944) was a Lieutenant with the British army in the Sudan when he left to Egypt in January of 1933 in search of Zerzura. His fame came after he left Egypt and was transferred to Israel (before its foundation), then to Ethiopia, where he led the force against the Italians. He then worked in Burma, organizing the Chindits, the commandos who operated behind the Japanse lines. Wingate died in an air crash in Burma and was buried in the United States.

Bagnold led another expedition to Gebel Uweinat, and P.A. Clayton achieved the first east-west crossing of the Great Sand Sea (Clayton, 1933). In his trip, P.A. Clayton discovered the enigmatic Libya Desert Glass, which was the subject of a number of studies (Clayton & Spencer, 1934, Cohen, 1959, Jux, 1983, Bigazzi & de Michele, 1996, Barrat et al., 1997, Osterlund et al., 1997, Müehle, 1998, Frischat et al., 2001, Koeberl et al., 2003). Interestingly, the desert glass was used by prehistoric inhabitants and the Ancient Egyptians (Roe et al., 1982, George, 2000). In 1933, Wingate crossed the Sand Sea from Abu Mungar to Dakhla on camelbacks. An Italian mission led by Marchesi mapped Gebel Uweinat.

In addition to these desert exploration missions, other key scientific studies were published in the early 1930s. MacFadyen studied the coral reefs of the Red Sea (1930) and Miocene foraminifera from the Gulf of Suez and Sinai (1931). Vadasz (1933) studied iron ores in Egypt (re-examined by Nassim, 1950, and assigned an Upper Cretaceous age by Attia, 1955). Cuvillier (1930) published his treatise "*Nummulitique Egyptien*", in which he treated the geology of Egypt in precise details. Gardner & Caton-Thompson (1926) Caton-Thompson & Gardner (1932), the first female geologists to work in Egypt, published the results of their combined geological-archeological studies in the early 1930s; thus establishing the geoarcheology discipline in Egypt. Caton-Thompson (1952) published her work on the Kharga Oasis.

In 1935, King Farouk succeeded his father Fouad, and the Alexandria (Farouk I) University; the second in Egypt, was established in 1938. Cayeux (1935) described the Egyptian phosphates and compared them with those of Palestine and Jordan. Bagnold published his results in "Libya Sands".

In 1937, the South Mediterranean Oil Co. (Catex or SOMED), Anglo Egyptian Oil Co. (Shell or AEO), and Standard Oil of Egypt (Standard Oil of New Jersey) acquired several concessions in the Western Desert west of the Nile Delta.

The first refraction seismic survey in Egypt was carried out at Abu Shaar in the Gulf of Suez by the Egyptian Government in 1929. Seismic surveys in Egypt were made by Socony (later Mobil) in Northern Sinai and by SOMED in the Western Desert. The Ras Gharib Field was discovered in the Miocene Nullipore Carbonates with original oil in place (OOIP) of 290 mmbbls oil.

In 1938–1945, WWII was another period when geological exploration was interrupted. On the other hand, thanks again to a group of scientists who participated in the war continued their scientific investigations. Bagnold formed the Long Range Desert Group (Bagnold, 1945, Clerk et al., 1945) and in the meantime examined the desert sands.

Scientific interest in sand dunes probably started in Egypt by V. Cornish (1897) who discussed extensively their shapes and formation modes in "On the formation of sand dunes", followed by Johannnes Walther (1900) in "*Das Gesetz der Wustenbildung*". H.J.L. Beadnell (1910) and John Ball (1927a, b), officers of the Geological Survey, wrote on the sand dunes of the Libyan Desert. Harding King (1916), a member of the British Light Car Patrol suggested that the dunes "have a curious power of collecting sand" and explained the origin of the seif and barchan sand dunes. R.A. Bagnold (1941) published his classical book "The Physics of Blown Sand and Desert Dunes", based on his observations in the deserts of Egypt. Other studies of sand dunes were made by Ladislas Kádár (1934) in Egypt and di Caporiacco (1934) in Libya.

In 1944, exploration for hydrocarbons in Egypt entered a new phase with the Dabaa-1, the first well to be drilled in the Western Desert by Anglo-Egyptian Oil Company (AEO), followed by the Khatatba-1, the second well in the Western Desert, spudded by SOMED, and the Abu Roash-1 (1946) and Abu Roash-2 wells (1947).

In 1945, the Sudr Field was discovered by Mobil in Miocene reservoirs in two onshore fault blocks east of the Gulf of Suez. In 1947, the Asal Field in the onshore of the Gulf of Suez was discovered in Miocene sands and fractured Eocene limestones by Mobil. Stainforth (1949) studied the foraminifera of the Oligocene, Miocene and Pliocene in the Gulf of Suez. In 1949, the Feiran Field, onshore the Gulf of Suez, was discovered in Miocene and Turonian-Cenomanian sands by Standard Oil. The Ras Matarma Field was discovered in the Rudeis Formation and fractured Eocene carbonates. In 1946, Awad gave the first description of Triassic rocks at Arif el Naga, and Eicher (1946) described the conodonts in the same succession. Spath (1946) described Middle Triassic cephalopods in Sinai. In 1951, the first mention of the Brown Limestone as a major source rock for hydrocarbons in Gulf of Suez was cited by Tromp (1951).

In 1952, a revolution ousted King Farouk and a republic was proclaimed in Egypt and in 1954, Nasser became president of Egypt. In 1953, a new mining law was issued to encourage new companies to conduct exploration. Sahara Petroleum Company was awarded a large concession covering the Western Desert north of Lat. 28° and large scale exploration was carried out which included areal photography, surface mapping, and refraction seismic and gravimetric surveys. Nakkady (1952) published key papers on the micropaleontology of Egypt. Leroy (1953) studied the stratigraphy and paleontology of the Maqfi section in the Farafra Oasis. The Geological Survey started an aggressive program of exploration. However, exploration was hampered by land mines left from WWII.

In 1955, the first offshore seismic survey was conducted by COPE in the Gulf of Suez. The Belayim Land Field was discovered by IEOC (Eni) in Miocene sandstones, limestones, and conglomerates. The field proved to contain 11 reservoir intervals (with > 1Bbbls of oil reserves), including reservoirs within the South Gharib Formation evaporites (Rohrback, 1983, El Ayouti, 1961, 1990). Sahara Oil Company started its drilling operations in the Western Desert (1955–1958), which led to the drilling of the Mersa Matruh-1, Burg El Arab-1, and Mamura-1 wells (in 1958); all proved dry, after which Sahara relinquished its concessions.

In 1956 war erupted between Egypt and Israel, which led the Egyptian president at the time, Gamal Abdel Nasser, to nationalize the Suez Canal and the majority of foreign assets. This war was followed by the defeat in Yemen in the 1960s and another defeat in the 1967 (Six Days War), during which Sinai was lost and occupied by Israel until 1985. In order to achieve his objectives, which included the building of the Aswan High Dam, Abdel Nasser switched his alliance to the Communist Block. As part of the Russian-Egyptian cooperation, Russian scientists and Engineers were brought into Egypt to replace the American and Western Europeans. However, the Russians' contributions, as far as geology is concerned, was minimal. The only visible contributions are the Tectonic Map of Egypt by Sigaev (1959) and in addition to a few palynological studies. In July 1972, Sadat expelled the Russian experts along with the Russian military from Egypt.

Following the 1956 War, the Arab countries imposed an oil embargo on the West. In 1957, the Egyptian General Petroleum Corporation (EGPC) was established to control all aspects of oil activities, including exploration, production, transportation, and refining. It was followed by the establishment of the General Petroleum Company (GPC). The Abu Zeneima SE Field in the offshore of the Gulf of Suez was discovered in Miocene rocks by Petrobel and the Abu Rudeis-Sidri Field in the basal Miocene Nukhul conglomerates (abandoned in 1998). In 1958, the Bakr Field which straddles the onshore/offshore of the Gulf of Suez was discovered in Eocene and Miocene sediments by GPC. The Kareem Field was discovered by the Egyptian General Petroleum Corporation (EGPC) in the Gharandal Group sandstones. The Rahmi Field was discovered in 1960 in Lower Eocene sediments in the onshore of the Gulf of Suez. Production of the Field started in 1975, but was abandoned in 1988 after it produced only 3 mmbbls of oil. The Belayim Marine, the first offshore field in Egypt, was discovered by Petrobel in Miocene and Upper Cretaceous (on stream since 1962); with ultimate reserves of about 5 billion barrels of oil similar to the July and Ramadan oil fields. The Morgan Field was discovered by Pan America (later Amoco, Gupco) in the offshore of the GOS in 1965 based on aeromagnetic and reflection seismic surveys (Brown, 1980), and production started in 1967; reserves were estimated at 2.5 billion barrels of oil in place, and yearly production reached about 14 million barrels in the year 2000.

Ain Shams (Ibrahim Pasha) University, the third in Egypt, was established in 1957. Nakkady (1957) discussed the biostratigraphic characteristics of the Cretaceous-Danian succession in Egypt, recognized the Maastrichtian and Danian, and correlated the succession in nine sections in Egypt.

In 1959, Sigaev compiled the first tectonic map of Egypt at the scale 1:2,000,000. Synelnikov & Kellerov (1959) carried out the earliest palynological work on Carboniferous coal samples at Um Bogma, Egypt, and assigned them a Visean age. Kummel (1960) described Middle Triassic nautiloids from Sinai. Commercial coal deposits were discovered in Middle Jurassic beds (Safa Formation, equivalent of the Khatatba Formation in the Western Desert) at Gebel Maghara in Northern Sinai by the Geological Survey of Egypt (current production 58,000 tons/year). In 1965, Al Far et al. (1965) studied the coal and stratigraphy of Jurassic deposits in Sinai, and as a consequence, Al Far (1966) established Jurassic stratigraphic nomenclature in Sinai, and divided the succession into six formations: Mashabbah, Rajabiya, and Shusha (Early Jurassic), Bir Maghara and Safa (Middle Jurassic), and Masajid (Late Jurassic).

The threat of the drowning of many of the Ancient Egyptian monuments in Upper Egypt by the Aswan High Dam led many international organizations to spend huge sums of money and efforts to salvage some of those monuments, including the cutting and re-assembling of the colossal Abu Simbel Temple. In an effort to salvage prehistoric data, Butzer (1960) published a paper under the title "Archeology and geology in Ancient Egypt" in collaboration with the renowned archeologist Kaiser, thus leading the way to modern geoarcheology in Egypt. Butzer & Hansen (1968) published the book "Desert and River in Libya". The Combined Prehistoric Expedition (1968–1976), led by Wendorf, started its systematic work in Egypt. In 1972, The Combined Prehistoric Expedition made its first excavation.

Modern Egyptian geology profited greatly from the contributions of Rushdi Said (Fig. 1.2), a Harvard graduate geologist, geoarcheologist, professor, and politician, who started his carrier as early as the late forties, which culminated with the heading of the Geological Survey. He authored and co-authored numerous papers and books since 1957.

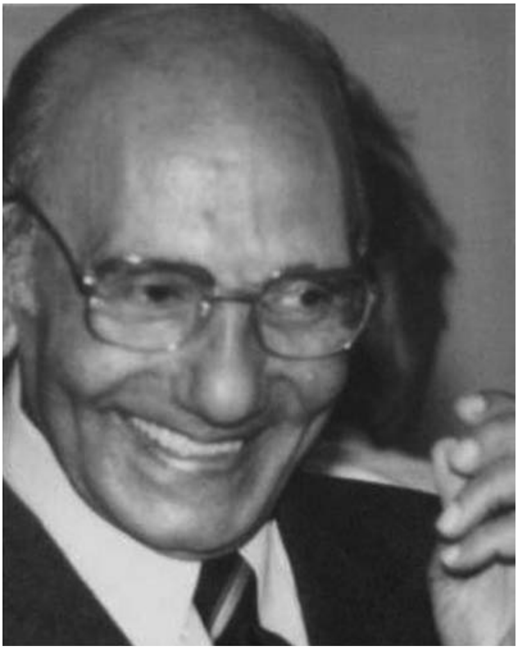

Figure 1.2 Rushdi Said (reproduced with permission of Prof. Said).

In 1961, Said examined the tectonic framework of Egypt and its influence on the distribution of foraminifera. In 1962, Said published his "The Geology of Egypt", the first detailed book on the subject since Hume's work in the 1930s. Said (1990a) edited the second edition of "The Geology of Egypt", a collection of papers by various authors.

In 1963, aeromagnetic surveying was introduced into Egypt and the entire Western Desert was covered over the next 10 years. BP also started exploring the Gulf of Suez in that year (1963). In 1966, hydrocarbon exploration in Egypt took a major leap with the discovery of the Alamein Field, the first field in the Western Desert by Phillips Petroleum in fractured Aptian dolomites. Later, oil, gas, and condensate were found in the Alamein Field in the Upper Cenomanian Baharia sands, Aptian Kharita sands, Abu Roash sands, and the Jurassic Safa sands.

Heybroek (1965) published his classical study on the evaporites in the Gulf of Suez.

In 1967, the Suez (Six-Day) War with Israel led to the loss of Sinai and the Eastern Gulf of Suez, and the closing of the Suez Canal. Another oil embargo was imposed by the Arab oil producing countries. The July Field was discovered in the Miocene of the offshore of the Gulf of Suez by Gupco, with estimated reserves of 730 mmbbls OOIP. Production of the July Field started in 1973. The discovery of the Abu Madi Gas Field in 1967, the first discovery in the Nile Delta, by IEOC in the Abu Madi Formation sands established a new hydrocarbon province in Egypt. Subsequent discoveries led to the delineation of the Messinian Abu Madi Channel in the Central Nile Delta. In 1969, the Abu Qir Gas Field was discovered northeast of Alexandria in the Abu Madi and Sidi Salem formations. During the occupation of Sinai, Israeli geologists carried out systematic geological studies. An extensive drilling program onshore and offshore Sinai led to the discovery of a number of small oil and gas fields, such as the offshore Sadot and Raad fields in 1975 in Cenomanian sands, Wakar Field (later named North Port Said) in Middle Miocene turbidite sands in 1983, the Kersh Field in 1983, and the Abu Zakn Field in 1986 in Tortonian-Serravallian sands (EGPC, 1994). IEOC discovered the Tineh Field in 1981 in Oligocene sands and the Bougaz Field in 2006. The Mango Field was discovered by Total in 1986 in lower Cretaceous sands.

In the Western Desert, Amoco discovered gas at Abu Gharadig in 1969 in the Cretaceous Kharita and Baharia Formations, and oil was discovered in other Cretaceous intervals (Abu Roash Formation) by GUPCO in the early 1970s. Philips discovered the Umbaraka Field in seven Cretaceous sand intervals (Debeis et al., 1988).

In 1968, the Organization of Arab Petroleum Exporting Countries (OAPEC) was established. The same year (1968), Rushdi Said became head of the Egyptian Geological Survey. Rushdi Said (1971) wrote "Explanatory Notes to Accompany the Geological Map of Egypt", scales 1:1,000,000 and 1:2,000,000, which included definitions of many lithostratigraphic units.

The Amal Field in offshore Gulf of Suez was discovered in 1968 in Miocene sandstones, which was put on production in 1989 by Amapetco (now operated by Pico Petroleum)(EGPC, 1996). In 1970, the offshore Badri Field was discovered in the Gulf of Suez in Miocene sands by the Gulf of Suez Oil Company (GUPCO). In 1971, the Shoab Ali Field was discovered by Tor Sinai Oil (EGPC, Amoco & IEOC) in Miocene reservoirs (mainly in the Rudeis Group).

In the Western Desert, oil was discovered in the Khalda area in 1971 by WEPCO in Cretaceous sandstones, but was considered uneconomical and abandoned (EGPC, 1992). A small discovery was made in 1971 in the Yadma Field (abandoned in 1971) by WEPCO in the Aptian dolomites based on geology. Amoco discovered the Razzak Field in Cretaceous sands and dolomites in three structural culminations. Additional discoveries were made in the Upper Cenomanian Baharia Formation in the Wadi, Meleiha (on production at 17,000 bopd in April 2006), Meleiha NE, and Meleiha SE fields.

In October 1973, the Yum Kippur War erupted. Oil embargo was imposed briefly by the Arab countries (ended the following year), but the following years and after the signing of the peace treaty with Israel, hydrocarbon exploration in Egypt entered a new phase. Egypt became member of OAPEC in 1973. The same year (1973), the July Field was discovered in Miocene sands by GUPCO, with estimated reserves of 625 mmbbls. Amoco made a small heavy oil discovery in the Ahram Field (shut- in 1974) in the Albian Kharita Formation in the Western Desert. In 1974, another giant, the Ramadan Field was discovered in Cretaceous sands by GUPCO in the Gulf of Suez (reserves of 668 mmbbls). Shell returned to Egypt in 1974 through a partnership with Deminex and BP. In 1976, the Zeit East Field was discovered by GUPCO in Miocene and Nubian sandstones. The Zeit East Field had cumulative production of 88.6 mmbbls in 2002. The horizontal well East Zeit A-19 reached a record length of horizontal section of 2700 ft (Blanchard et al., 2002). Oil was discovered in 1976 in the Qantara Formation (Qantara-1) in the Eastern Nile Delta. In 1977, the October Field (Abdine et al., 1992), the third largest oil field in Egypt after Belayim and Morgan fields, was discovered by GUPCO.

In 1978, Petrobel Petroleum Company was founded as a joint venture between Eni and EGPC for the exploitation of the oilfields in the Gulf of Suez. The Bakr W G1 and Bakr W H fields were discovered onshore the Gulf of Suez in Eocene reservoirs by the General Petroleum Company (GPC). The Ras Fanar Field was discovered with the KK84-1 well in the Gulf of Suez in Middle Miocene coralline buildups of the Nullipore Carbonates by Deminex GmbH (SUCO). The trap in the Ras Fanar Field is a tilted horst-block. The field started production in 1984 and produced 96 mmbbls of oil by 2005. The Ras Budran Field was discovered by Deminex (SUCO) in Paleozoic and Lower Cretaceous Nubian "A" sandstones in the Gulf of Suez, with estimated reserves of 150 million barrels of oil. In the Western Desert, the East Razzak Field was discovered in the Upper Cenomanian Abu Roash "G" and Baharia formations. In 1979, the Bakr W K Field was discovered in Miocene sands by the GPC onshore the Gulf of Suez. Exploration by Shell on its two concessions; Badr El Din and Sitra, in the Western Desert acquired in 1979, led to the discovery of the two fields in the early eighties.

In 1980, 3D seismic surveys were run for the first time in Egypt in the Mediterranean Sea and the Gulf of Suez. The El Khaligue Field onshore Gulf of Suez was discovered in Miocene sands by the GPC (EGPC, 1996). The Zeit Bay Field was discovered in Cretaceous by SUCO in the Gulf of Suez.

In 1981, the Amer North Field offshore the Gulf of Suez was discovered in the Belayim Formation by the GPC and the Esh El Mellaha Field was discovered onshore in Miocene sands by the Canadian Superior Group in a stratigraphic trap. Scimitar discovered the Issaran heavy oil field onshore the Gulf of Suez in the same year. The Zeit Bay Field was discovered by Deminex and partners Shell and BP. The appraisal well QQ89-1 encountered gas in basement rocks, while the appraisal well QQ89-2 encountered 253 m (830 ft) column of oil in basal Miocene Nukhul Formation (heavy oil), Middle Miocene sands, Nubian sandstones, and fractured and weathered Precambrian granites (EGPC, 1996). The Zeit Bay Field started production in 1984. The Tineh-1 oil discovery in Oligocene sands and the Temsah Field by Mobil Oil in Miocene sediments offshore Sinai by IOEC added to the prospectivity of that area. Agiba Petroleum was formed following the discovery of Meleiha Field in the Western Desert as an operating company for EGPC, IEOC, IFC, and Lukagip. Agiba also operates the Ashrafi offshore field in the Gulf of Suez.

In 1982, the offshore Hilal Field (on the B-Trend) (Helmy, 1990) was discovered in Senonian by Torsina Oil (a joint venture between BP and Amoco). The Badr el Din (BED-2) oil and gas field was discovered by Shell in Cretaceous sands and the Aghar Field by Agiba in the Western Desert. Originally, the dry well Aghar-1 was drilled by Wepco in 1970, but re-examination of well logs by Agiba led to the discovery of Aghar Field in Upper Cenomanian Baharia Formation, with estimated reserves of more than 27 mmbbls of recoverable oil (EGPC, 1992).

Egypt's daily production in 1980 was estimated at 584,148 million barrels of oil/day, 210,972 million cubic feet of gas/day (mmcfgd), and 6,952 barrels of condensate/day. In 1983, Egypt's daily production increased for oil, gas and condensate, with estimated 652,921 bopd, 257,990 mcfgd, and 7,501 bcd.[4]

4 AAPG Bull., 1983, v. 67/10, p. 1796–1797.

Minor discoveries made in 1983 included the North Shadwan (GH452 1A) Field by Amoco in Miocene sands and GS327 by GUPCO in the Gulf of Suez.

In 1984, the NE Abu Gharadig (NEAG) Field was discovered in the Abu Roash (Turonian) and Kharita (Albian) sands in an anticline bounded by faults to the north. The recoverable gas reserves were estimated at 44 bcf and recoverable oil at 1.4 mmbbls. In 1985, the Salam Field was the first discovery in Jurassic sediments of the Western Desert. The discovery well flowed >6000 bopd from the Cretaceous reservoirs and >5000 bopd from the Jurassic. Conoco Inc. bought into the Khalda Concession and the Khalda Petroleum Company was formed as a joint venture between Conoco, Texas International, and EGPC. These discoveries were followed by the Yasser-1 which flowed 8941 bopd and 13.6 mmcfgd from two separate Cretaceous intervals. The Amoun-2 well tested 4160 bopd and 12.5 mmcfgd from Jurassic sands (EGPC, 1992). The Hayat Field and Kenz Field encountered hydrocarbons in the Upper Baharia. Other discoveries were made by Agiba included Meleiha SE, Aman, Emry, and Lotus fields in the Western Desert. In 1986, the Ashrafi Field was discovered offshore the Gulf of Suez by IEOC (with partner Marathon who sold interest to Eni in 1999) in fractured granites, Nubian sandstones and Miocene sandstones. The Field has been on production since 1992, with a rate of 8100 bopd in April 2006).[5] Other Jurassic and Cretaceous discoveries by Agiba in the Western Desert followed, which included the Falak (Jurassic & Neocomian sands), Dorra (Jurassic), Zahra-1X (Aptian and Upper Cenomanian sands), Karnak, and Bardy (Baharia sands) fields.

In 1987, the Gazwarina Field was discovered in the Gulf of Suez by Marathon and partners in Middle Miocene sands, and the Badri Field was discovered by GUPCO in Miocene reservoirs.

In 1988, oil prices crashed to about $10 a barrel in July, down from $30 the year before, which had a global effect on oil exploration activities and professionals in the field. In the meantime, Shell signed the first gas clause (amended in 1993) in Egypt with EGPC for Bed-3 in the Western Desert (EGPC, 1992). The purpose of the "gas clause" was to tie gas prices to crude prices and encourage companies to invest in gas. The Abu Rudeis Marine 3 Field was discovered in 1988 in the Gulf of Suez in Turonian sandstones by Petrobel and the Esh El Mellaha East Marine Field offshore the Gulf of Suez in Miocene sands by Magapetco. In 1989, the Gemsa SE Field was discovered by Shell in the Miocene dolomitic reefal "Nullipore limestones" (Belayim Formation) in the Gulf of Suez. The Ashrafi Island Petroleum Company (Asheptco) was founded in 1989 as a joint venture between EGPC, Agip, Agiba, and partners.

In the 1990s, hydrocarbon exploration continued along with the appearance of new technologies. In 1990, the first horizontal wells in Egypt were drilled by the Khalda Oil Company (Schlumberger, 1995, El-Refaie, 1993). In 1991, the Badri E Field in offshore the Gulf of Suez was discovered in Miocene sands by GUPCO. The offshore Warda (Zaafarana) Oil Field was discovered in Miocene reservoirs by British Gas in 60 m (197 ft) of water. The discovery well Hb78-2 tested oil in five separate sandstone intervals with a cumulative rate of 7000 bopd. Consequently, the Zaafarana Oil Company was formed between EGPC and BG.

In 1992, gas discoveries continued to be made in the Western Desert. The Kanayes Field was discovered in Jurassic sands by IEOC and the Obaiyed oil and gas Field by

5 Production figures for Ashrafi, Raml, El Faras, Zarif, W. Razzak, and Meleiha are from www.Agiba.com.

Shell in the Middle Jurassic Lower Safa sands; the discovery well Obaiyed 2-2 tested 13.7 mmcfgd and 1470 bcd (production started in 1999). The latter led to the formation of the Obaiyed Company. In 1993, the Ras Qattara Petroleum Company was created between EGPC, Agip, Agiba, and partners. In 1997, Repsol discovered the Shams Field in Jurassic sandstones and Apache made a discovery in the North Alamein Field in 1998 in Alamein Dolomite and Dahab sands in the Western Desert.

The year 1994 signaled the beginning of a "Gas Boom" (Hataba, 2005) in Egypt when the proven gas reserves of about 19.7 TCF in that year rose gradually to 66.8 TCF in 2005. In the meantime, oil reserves were estimated at 3.3 Billion barrels (Oil & Gas J., 2005). The same year (1994), Apache entered Egypt with the farm-in of a 25% non-operated interest in the Western Desert's Qarun Concession. In 1995, the Ras El Ush Field was discovered by Marathon in lower Senonian and Nubian sandstones. The Denise Field, the first field drilled with Pliocene objective in the Mediterranean offshore was discovered by IEOC (Eni in Egypt, 2006). Apache also drilled the wells Shaqiq 1X (dry) and Marakia 1X (oil) in Cretaceous AEB.

In 1996, Ashrafi SW Field offshore the Gulf of Suez was discovered in Middle Miocene sediments by Ashpetco. The Ashrafi SW 1X encountered 82 m (269 ft) of net pay in the Cretaceous Nubian Sandstone and 22.3 m (73 ft) of net pay in fractured granites (Oil & Gas J., Sept. 1996). The El Faras Field was discovered the same year. Raml Petroleum Company (Rampetco) founded between EGPC, Agip, Agiba, and partners. The Raml Field was put on production at 2100 bopd in 1997.[6] In 1998, the Ashrafi S. Field offshore the Gulf of Suez was discovered in Middle Miocene reservoirs by Lukoil and the July North Field by Fanar Oil. In the meantime, Tanganyika acquired the West Gharib Block in GOS, and the Hana Field was discovered in 1999 on the West Gharib Block by Dara (Dublin/EGPC) in the Miocene Karim Formation. In 1999, the Ashrafi W Field offshore the Gulf of Suez was discovered in Middle Miocene sediments by IEOC.

Large concessions were granted in the offshore of the Nile Delta. The discovery of Ha'py Field by BP Amoco/Agip in the Ras el Barr Concession in Pliocene slope channel offshore the Eastern Nile Delta (operated by GUPCO) was made based on a high-amplitude (bright spot) anomaly. The structure in the Ha'py Field is related to the NW-SE-trending growth faults of the Bardawil Line (Abdel Asal et al., 2000, Samuel et al., 2003). The Ha'py Field was put on production in 2000 at a rate of 280 mmcfgd. In 1997, BG discovered the Rosetta gas and condensate field in Pliocene channel sands, about 60 km north of Alexandria its Rosetta Concession in the Mediterranean offshore in 61 m (200 ft) of water. The First well to be drilled in deep water offshore Nile Delta was the East Delta Deep Marine-1 (EDDM-1) in water depth 750 m (2460 ft).

In 1997, Egypt was consuming all the gas it produced. The Abu Marwa Field in the Gulf of Suez was discovered in 1997 in Lower Miocene reservoirs. Yet a new hydrocarbon province was proven in Egypt in 1997 when Apache (50% with Seagull) discovered the Beni Suef Field in Upper Egypt, with 42° API oil, in seismically identified structures, on the East Beni Suef Concession (Dolson et al., 2001, Tawfik et al., 2005). The Beni Suef-1X flowed 5,200 bopd from a 12 m (40 ft) interval at 133 m (7000 ft) depth from the Albian Kharita Formation. The Beni Suef Field is located near

6 (www.bg-group, 2011).

the northern limit of the Nile Basin as defined by Tawadros (2001). In 1998, another field was discovered near the southern edge of the Nile Basin at Kom Ombo. The Komombo-1 (re-named al-Baraka by the Petroleum Minister in 2007) was drilled by Repsol on the Ganope Block 2 and recovered 39°API light oil on test in Early Cretaceous sandstones. The Komombo Basin is a rift basin. The oil is believed to have originated from Jurassic type II–III lacustrine source (Dolson et al., 2001). In 1998, Shell signed the Northeast Mediterranean Deepwater Concession (NEMED) Agreement.

Apart from the successes achieved in hydrocarbon exploration, other major contributions to our geological and exploration knowledge were made in the field of geoarcheology during the later part of the 20th Century. The Dakhla geoarcheological multidisciplinary project (DOP) started in 1978, under the leadership of Maxine R. Kleindienst, a geoarcheologist and Pleistocene prehistorian, which passed to her successor Antony J. Mills in 2005, together with archeologist Mary A. McDonald and geoarcheologist C.S. Churcher. The team recognized a number of paleolakes and tufa terraces deposits in the Dakhla Oasis. Pleistocene terraced gravels and tufas were also mapped in the Kharga Oasis by the team members of the Kharga Oasis Project (KOP), Jennifer Smith and R. Giegengack of the University of Pennsylvania.

The 21st Century opened with one of the most horrific terrorist attacks in recent history; the attack on the twin towers in New York on September 11, 2001. The attack strained the relation between the West and East. In Tunisia and Egypt, the unexpected events of January 25, 2011 and the subsequent outcome brought new hopes and fears to the countries as well as the whole Middle East. The civil war in Libya, which is still ranging at the time of writing, has and will have a negative effect. It is not known yet how these events will affect geological and hydrocarbon exploration in the area and around the world.

Extensive efforts made in the late 1970s and early 1980s were consecrated to the solution of the Nubian Sandstone controversy. Klitzsch et al. (1979) and Ward & McDonald (1979) attempted to subdivide the Nubian Sandstone in the Western and Eastern Deserts, respectively, and represented a major step toward solving the Nubian Sandstone controversy. In 1985, a German multidisciplinary team made regional studies of the Nubian Sandstone in southern of Egypt. The results of the German Special Research Project, supported by the German Research Foundation until 1987 were published in volumes 50 and 75 of the *Berliner Geowissenschaftliche Abhandlungen*.

In 2001, Tawadros published "Geology of Egypt and Libya", with the main objective to review the geology of the two countries in the context of global and local tectonics and the stratigraphic nomenclature, and to tackle some of the chronic stratigraphic problems, such as the Nubian Sandstone, the Esna Shale, and Paleozoic and Lower Cretaceous quartzites and sandstones. The latter was fully treated in Tawadros et al. (2001).

Hydrocarbon exploration and production in Egypt entered a new era in the beginning of the century, especially in the gas sector. In 1999, The Scarab-1 and Saffron-1 wells discovered gas in two separate accumulations in the West Delta Deep Marine Concession (WDDM) in water depths of 250–850 m (820–2789 ft) (Samuel et al., 2003). The well Scarab-1 tested more than 30 mmcfgd; the Saffron-1 tested 90 mmcfgd (reserves in the two fields are >4tcf of gas). The Scarab-Saffron Field is the largest gas field development in Egypt, on production in 2004. The Simian

Field was discovered in 1999 in Pliocene sediments in the Mediterranean by British Gas. The Simian/Sienna fields began production in 2005 with a capacity of 565 mmcfgd.

The 21st Century opened with the announcement of new discoveries in 2000 in Egypt (AAPG Explorer, Jan. 2001). The Akik-1 well tested 54 mmcfgd and 543 bopd. The GS 302-2 tested 4000 bopd. The Karama-1 tested 1450 bopd and 500 mcfgd. The Lagia-6 tested 170 bopd and 300 mcfgd. The Neama-1 tested 159 bopd. The Sapphire-1 tested 35 mmcfgd and 1100 bcpd. The Tawoos-1 tested 833 bopd. The Ha'py Field came on line with 280 mmcfgd. The Karama Field was discovered by Apache in the Eastern Abu Gharadig Basin in 2001. The real "Gas Boom" started in Egypt in 2000 following the discovery of the Scarab-Saffron and Sapphire gas fields and the beginning of production from the Ha'py Field in the offshore of the Mediterranean Sea, which led the government to restructure its oil and gas industry the following year. Gas production which equalled consumption in 2001, 2002 and 2003 at 2.1 bcfgd, each; surpassed it since 2004 (graphs in Global Research; Egypt, Nov. 2006).

The Egyptian Government restructured the oil industry with the formation of three separate entities. The Egyptian Natural Gas Holding Company (EGAS) was established in 2001 as a new state-owned body, separate from the EGPC, to manage the natural gas sector. The Egyptian Petrochemical Holding Company (EChem) was established in 2002 to manage the petrochemical industry. The Ganobe El Wadi Holding Co. (previously known as the South Valley Development Company "SVDC") was established in 2003 to manage exploration and production activities in Upper Egypt south of Lat. 28°, while the EGPC controls activities north of that latitude.

In 2002, Apache discovered El Max-1X, with a 152 m (500 ft) gas column, in 945 m (3100 ft) of water, the Abu Sir-1X with 95 m (311 ft) gas column, the Al Bahig-1X in the Upper Paleocene Kafr el Sheikh sands with 75 m (247 ft) gas column in water depth of 1070 m (3510 ft). The Ozoris-1X discovery tested 2504 bopd of 38.5° API oil from the Lower Cretaceous AEB Sand. The Khepri-9 well on the South Umbarka lease tested 29.5 mmcfgd and 220 barrels of condensate per day from the AEB. The Farag Field onshore the Gulf of Suez was discovered in Eocene reservoirs by Tanganyika. In 2002, Egypt and EGAS offered 34 blocks in a bid round (4 more were added in 2003). The Scarab/Saffron Fields began production in 2003 with a capacity 700 mmcfgd. The El Wastani Field of Centurion Petroleum in the El Manzala Concession in the Eastern Delta started production at 12 mmcfgd (Centurion Oil). Eni, in partnership with BP, announced the discovery of the Tennin-1 in the East Delta Deep Block in water depth of 300 m (984 ft), which tested 24.7 mmcfgd, with estimated gas reserves of 0.5–1.0 bcf (billion cubic feet).

In 2003, Apache discovered the Qasr-IX, identified by a 3D seismic survey, and tested 51.5 mmcfgd and 2,688 bcd with a net pay of 185 m (606 ft) in six Jurassic Lower Safa and Ras Qattara reservoirs (according to Apache public announcements). The Jurassic continued potential was attested by the JG discovery by Shell, and the SD-9 by HBSI. Apache's El King-1X tested gas in Miocene and Pliocene reservoirs, and constituted the first Miocene Abu Madi deepwater 720 m (2361 ft) discovery offshore the Nile Delta. The well tested 31 mmcfgd and 757 bcd. BP announced the discovery of a large new field in the Gulf of Suez, the Saqqara Field near the Morgan Field, with estimated peak production of 40–50,000 bopd. The Egyptian government began several rounds of new concession awards in 2003, and by 2005 it had signed 35 new oil and gas exploration agreements.[7]

In 2004, 16 oil and gas discoveries were made in Egypt and six in Libya (AAPG Explorer, Jan. 2005). BP discovered Taurt 1, which tested 22 mmcfgd in one of four intervals, and was expected to go on stream in 2008. In the Ras El Barr Concession in the Eastern Nile Delta, the Raven Field (BP and RWE) was discovered NW of Rosetta which tested 37.44 mmcfgd and 741 bcd in 650 m (2133 ft) water with estimated reserves of TCF of gas. RWE Dea Egypt and partner BP discovered gas in the Polaris 1X Field in the North Alexandria Block in the West Med Deep Water (WMDW) Concession. The Polaris 1X was the first Miocene gas and condensate discovery in the Concession, in water depth of 1162 m (3813 ft). The exploratory well tested a rate of 26.7 mmcfgd from a 42 m (138 ft) with about 19 m (62 ft) of net pay in a Middle Pliocene slope channel/levee play at a depth of 2178 m (7146 ft). In 2008, BP signed a deal with EGPC and EGAS to supply natural gas to the Damietta LNG Plant and to purchase LNG from EGAS. BG also signed a deal with EGPC to supply natural gas from the Scarab/Saffron fields in WMDW to the Damietta LNG Plant.

The Bakr E1 Field offshore the Gulf of Suez was discovered in Miocene sands by GPC in 2004 and tested 2000 bopd. Shell drilled four ultra-deep wells in the NEMED Concession, Kg45-1, kj49-1 & La52-1 and made two gas discoveries. Melron (later Melrose) discovered the Aga-1 in N. Egypt which tested 9.3 mmcfgd and 19 bcd (first test of condensate in El Mansoura Concession) and the Batra South 14 in the Delta which tested 9.7 mmcfgd and 150 bcd in Pliocene sands. El Amir (NW Gemsa) was discovered in the Gulf of Suez by Vega Oil & Gas in the Ras Gharib Formation. The Fadl Field in West Gharib Block was discovered by Tanganyika. The West Ashrafi Petroleum Company was created between EGPC, Agip, Agiba, and partners. The Russian Lukoil discovered oil in the NE Geisum Offshore Block. Petrobel made three additional discoveries in the Gulf of Suez in BL 113-A-24, BM 85, and BM W1. Five exploration contracts were awarded to a newly-formed, state-owned upstream company, Tharwa Oil, four of which were in the Western Desert and one offshore the Mediterranean. In 2004, TransGlobe Petroleum and Arsenal Energy acquired 50% from Quadra Resources of Calgary share and operatorship of the Nuqra Block, which covers part of Komombo Basin in Upper Egypt, east of the Nile (see above). In the meantime, RWE Dea acquired operatorship of Al Amriya Concession in shallow waters in the West Nile Delta following its bid during the EGAS 2004 Bid round. RWE Dea AG, via its wholly owned subsidiary RWE Dea Nile GmbH, signed a new concession agreement with the government of Egypt and the Egyptian Natural Gas Holding Company (EGAS) for the Disouq Area. RWE Dea's Ras Fanar B10 well tested 3000 bopd. Shell's Sheiba 18-3 well, the first commercial discovery in the eastern part of NE Abu Gharadig Concession, tested 1600 bopd and 0.9 mmcfgd. Selpetrol's discovery, Ferdaus 1 tested 3250 bopd. Khalda's Mihos 1 well tested 41.8 mmcfgd and 1419 bcd.

Other discoveries were made in 2004; oil in West Geisum offshore block by the Russian Lukoil, the Hoshia-1 and Naiem fields by Tanganyika in Rudeis Formation, and the El Diyur Field in the Western Desert with 1000 bopd. The El Tamad Field was discovered by Melrose[8] in July 2005 in the Miocene Sidi Salem Formation in the El

7 Economic Trend Report, April 2006, Embassy of the United States, Cairo, Egypt, p. 51.
8 Melrose acquired Melron in 2006.

Mansoura Concession in the Nile Delta. The discovery was followed by the Tamad-2 well which encountered a 7.3 m (24 ft) oil column. A 2 m (7 ft) interval at the top of the oil column tested at 1,041 bpd of 45.6° API oil and 780 mcfgd. Apache made a discovery with the Syrah 1X well, northwest of the Qasr Field in 2005. The well tested 46.5 mmcfgd from Cretaceous and Jurassic horizons. The Qasr and Syrah fields represented the largest gas discoveries in the onshore of Egypt. Another discovery by Apache was the Tanzanite-1X tested 5,296 bopd and 7.7 mmcfgd in multiple pay zones in the Lower Cretaceous Alam El Bueib (AEB) sands. The Tanzanite-2 tested 2846 bopd in the Alamein Dolomite.

By the end of 2004, the remaining reserves of Egypt were estimated (Hataba, 2005) at 23 MMBOE, divided as follows: Oil: GOS 43%, Western Desert 26%, Mediterranean and Delta 13%, Eastern Desert 11%, and Sinai 7%. Gas: Mediterranean 77%, Western Desert 12%, GOS 8%, and Delta 3%. Egypt's production was about 594,000 bopd and 2.6 bcfgd, exceeding gas consumption at 2.5 bcfgd, for the first time. At the end of 2005, the estimated proven reserves were 3.71 billion barrels of oil and 66.84 bcf of gas.[9]

The First liquefied natural gas (LNG) export began in January 2005 from the Damietta and Idku facilities. The Arab Gas Line to Jordan consists of three sections. The first section was completed in July 2003 and runs from Al Arish in Egypt to Aqaba in Jordan. The second section is from Aqaba to Rehab in Jordan. An Egyptian consortium will operate the pipeline for a period of 30 years with optional extension period of 10 years after this period the ownership of the project will be transferred to Jordan. The third line extends north of the Jordanian-Syrian border to the Turkish-Syrian boarders and from the west to Banias and Tripoli in Lebanon. The Arab Gas Pipeline project was designed supply the region with Egyptian gas. However, as for the year 2007, it was facing a problem because of differences between Jordan and Egypt over prices (Alarab Alyawm, April 10, 2007).

The West Khilala Field was discovered by Melrose with the West Khilala No.1 well in October 2005 in Miocene turbidite sands,[10] with proven reserves of 218 bcf, and a production rate of 63.2 mmcfgd in 2007. The West Dikirnis Field was discovered in December 2005 with the West Dikirnis No.1 well, which encountered gas and condensate in the Miocene Qawasim Formation. The West Dikirnis No. 2 well, drilled in May 2006 tested at over 5,000 bopd. Other discoveries by Melrose include the Rummay Field in the Nile Delta and the Ferdous Field and wildcat discovery Rayan 1X in the Western Desert (OGJ, Sept. 1, 2006).

The West Manzala Concession was awarded to Centurion in 2004, but 50% was farmed out to Shell in 2006, and oil was discovered in 2006 in the Luzi-1 well with a flow rate of 9 mmcfgd and 123 bcd from Abu Madi Formation. Two wells were drilled and tested gas from Sidi Salem Formation by previous holders of the concessions: Abu Naga-1 tested gas at a rate of 5.7 mmcfgd and 360 bcd; Matariya-1 encountered high pressured gas (drilled in 1976). Dana Gas PJSC of Sharja, UAE acquires Centurion Energy International in November 2007 (Centurion Energy News Press release, 2007).

9 World Oil, Sept. 2006, p. 57.
10 Source: Melrose Resources, 3 April, 2007. Preliminary results for the year ended 31 Dec. 2006.

In 2006, Ganope offered International 2006 Bid Round 8 blocks in the Red Sea and Western Desert, including the new Mesaha Block in the extreme southwest, which was awarded to a consortium led by Melrose Resources, and the Dakhla and Diyur blocks in the Western Desert. The West Esh El-Mellaha Block was awarded to the British Aminex Petroleum, and the W. Komombo Block was awarded to the Australian Pan Pacific. In July 2006, Groundstar Resources acquired 60% working interest on the West Komombo Block (Block-3, west of Centurion's block) from Pan Pacific Petroleum Egypt Pty. In the Western Desert, Sipetrol made a discovery in the East Ras Qattara Block with the Shahd-1 well in 2006. INA partnership with RWE Dea made an oil discovery with the Sidi Rahman-IX on the East Yidma Concession in the Cretaceous Kharita and Baharia sands.

In 2007, Sipetrol made a second oil discovery in the East Ras Qattara block in Western Desert with the Ghard-1 well, which encountered 40.5° API oil in the lower Baharia Formation at a rate of 2026 bopd and 2.6 mmcfgd. The Imhotep Field was discovered by Apache in 2004 in the Jurassic Upper Safa Formation. Hathor Deep 1X on the offset of Khalda Concession tested gas in Lower Cretaceous Alam El Bueib (AEB) at a rate of 12 mmcfgd and Oil from AEB 3D at 1237 bopd. Apache made the Alexandrite 1X discovery which tested 20 mmcfgd and 4045 bopd. The Jade-1X drilled by Apache in 2007 encountered 217 ft of AEB pay and 20 m (66 ft) in the Jurassic Upper Safa Formation. In September 2007, Centurion (Sharja's Dana) discovered a new oil field in Upper Egypt. The discovery well tested 37° API oil from a Cretaceous reservoir. The West Dikirnis Field came on production in November.

In 2008, Hess and partners RWE Dea and Kufpec discover the Dekhila-1X well in the West Mediterranean (Block 1) Deepwater Concession in 1183 m (3883ft) of water. Gas de France with partner Dana discovered gas in the WEB-1X in the W. Burullus Concession, offshore the Nile Delta, which tested 27 mmcfgd from Pliocene turbidites in 62 ft of water (World Oil, July 2008). Sipetrol discovered oil in the Shahd SE-1 in the East Ras Qattara Concession in 2008, which tested 39°API oil at a rate of 2500 bopd (World Oil, June 2008). Melrose discovered 13 mmcfgd and 182 bcpd from 38 ft of pay in E. Abu Khadr-1 well and the Damas-1 which tested 14.3 mmcfgd and 105 bcpd in Sidi Salem, both in the El-Mansoura Block (World Oil, June 2008). RWE Dea discovered gas and condensate with the N. Sidi Ghazi-1X well in the Desouq Concession onshore Nile Delta, which tested 37 mmcfgd from Upper Messinian sands (World Oil, June 2008). Vegas tested 3388 bopd of 41° API oil and 4.25 mmcfgd in the Al Amir-SE-1 on the NW Gemsa Concession onshore the Gulf of Suez (World Oil, Nov. 2008). BP made other discoveries in the Northern Shedwan Block in the Gulf of Suez at a rate of 10,000 bopd and the Satis-1 in the North El Burg Block offshore Nile Delta, in 61 m (200 ft) water in Oligocene reservoir (World Oil, March 2008). Apache tested 41.6 mmcfgd and 1313 bcd from a 178 ft (54 m) pay zone in the Jurassic Lower Safa and probable 14 m (45 ft) oil pay in Jurassic AEB-Unit 6 and 9 m (30 ft) oil pay in the Lower Cretaceous Alam El Bueib in the Shushan Concession (World Oil, March 2008).

In 2009, Improved Petroleum Grp (IPR) (in partnership with Sojitz Corp) found oil and gas in the Zain-1X in the Yidma-Alamein Block, which tested 5414 bopd and 16 mmcfgd from two Jurassic intervals (World Oil, Jan. 2009). Vegas Oil & Gas discovered 5785 bopd and 7.8 mmcfgd with the Amir South-2X in the NW Gemsa Concession onshore the Gulf of Suez (World Oil, April 2009) and tested 2809 bopd and 3 mmcfgd from the Kareem Shagar Sand in the Geyad-1X on the N West Gemsa Concession and

1174 bopd and 1.3 mmcfgd in Lower Kareem Rahmi sands (World Oil, July 2009). Dana Gas discovered gas with the Azhar-1 well at a rate of 15.1 mmcfgd and 444 bcpd from a 30 m (98 ft) interval in the Upper Sidi Salem Formation; the W. Manzala-2 well in the Nile Delta (World Oil, April 2009), and gas and condensate with the Salma-1 well, from an 25 m (82 ft) pay in the Abu Madi Sandstone and 4 m (13 ft) pay in the Kafr El Sheikh Sandstone on the W Qantara Concession (World Oil, Feb. 2009), and tested 11.4 mmcfgd and 381 bcpd with Tulip-1 from Abu Madi sands (World Oil, July 2009). BP discovered gas with the Ji 50-2 Ruby-3 well on the WMDW Concession in Pliocene sands in 3018 ft of water. The Ruby-1X and Ruby-2 wells were drilled by RWE/ BP in 2002 and 2003, respectively. Apache tested 8279 bopd and 0.4 mmcfgd from Cretaceous Alam El Bueib and the Jurassic Safa formations at Phiops on the S. Umbarka Concession (World Oil, July 2009). Apache mad a number of discoveries in the Western Desert in 2009, including three Jurassic discoveries which tested a total of 80 mmcfgd and 5909 bopd, the Sultan-3X which tested 5021 bopd and 11 mmcfgd from the Alam El Bueib (AEB-6) and the Safa sands on the Khalda Concession, and the Adam-1X and Maggie-1X on the Matruh Block (World Oil, Feb. 2009).

In 2010, Eni[11] discovered oil in the Arcadia Field in Alam El Bueib Formation on the Meleiha Concession in the Arcadia IX well, with additional gas potential in the Khatatba Formation. The Arcadia Filed was put on production on July 28, 2010 (World Oil, August 2010).

1.2 LIBYA

One of the earliest voyages to Libya was made in 1797–1798 by Fredrick Hornemann who travelled by Caravan from Cairo via Gialo and Murzuk to the Niger River (Hornemann, 1802) and gave the first description of Jabal Haruj. In 1817, the Italian physician-naturalist Paolo Della Cella traveled from Tripoli to Cyrene where he recognized fossiliferous limestones with *Cardium*, *Pecten* and *Nummulites*.

In 1850, the British Government sent an expedition led by James Richardson, accompanied by Overweg and Barth to discover caravan routes in the Southern Sahara and to conclude treaties with the chieftains. Overweg identified different rocks in Tripolitania, described the Gharyan volcanics, recognized the Cretaceous rocks in Jabal Nafusah, and collected the first Carboniferous fossils in West Libya (Overweg, 1851). The latter were described by Beyrich (1952). Unfortunately, Richardson and Overweg died prematurely. James Richardson died of fever in 1851 and Overweg continued the expedition, but died in 1862 of malaria on Lake Chad.

In 1865, Rohlfs travelled across Libya during his first expedition to North Africa and described Jabal Assawda in Central Libya. In 1867, G.B. Stacey described several outcrops and discussed the subsidence of the coast near Benghazi (Stacey, 1867). Gustav Horneigal was the first European to travel from Murzuq to Tibesti in 1869 (Von Bary, 1877). In 1876–1877, Von Bary travelled over North Africa to Ghat and Tuareg (account published in German in 1890 and in French in 1898) (Von Bary, 1898).

11 Eni is Egypt's leading producer with about 230, 000 boepd, including 37,000 boepd from the Western Desert (WO, August 2010).

In 1880–1895, Rolland summarized the geological history of North Africa and provided the first geological maps of western Fezzan (Rolland, 1880, 1889). Rolland also identified Devonian and Cretaceous rocks at Jabal Akakus and Hamada al Hamra area. In 1893, Elisée Reclus (1893) wrote an exhaustive account on the geography, culture, and people of North Africa, with the exclusion of Egypt.

In Libya, Krumbeck (1906) studied the geology and paleontology of Tripolitania and identified Carboniferous fossils from the Southern Ghadames Basin. In 1911, J.W. Gregory wrote the most significant paper on the geology of Cyrenaica and summarized the results of the 1908 expedition (Gregory, 1911a, 1916). Gregory introduced a number of formational names, subdivided the Eocene succession into Apollonia, Derna, and Slonta limestones, and included the Aquitainian in Oligocene. R.B. Newton, Chapman (1911), and Gregory described the fossils collected during that expedition (Gregory, 1911b). The molluscs were studied by Bullen-Newton (1911).

In 1911, the Italians invaded Libya and the Turks surrendered in 1912. The same year (1912), the first geological map of Libya was made. In 1913, extensive geological studies of Fezzan were started by Italian geologists, notably among them are Crema, Parona (1914, 1928), Zaccagna (1919a, b), Sassi, Coggo, Stefanini, Franchi, Sanfilippo, Migliorini (1914, 1920), and Checchia-Rispoli (1913) (Crema et al., 1913). Vinassa de Regny (1912) produced a geological map of Libya at a scale of 1:6,000,000. The WWI (1914–1918) hampered geological exploration in Libya and the only apparent achievement was that of Parona (1914) who wrote a summary on the geology of Libya. In 1920, Italian Touring Club organized an excursion to Cyrenaica led by Marinelli, made geological observations, morphological studies and collected fossils, and interpreted two escarpments that border the Cyrenaica Jabal (Jabal Akhdar) as raised beaches (Marinelli, 1920, 1921, 1923). Fossils collected were later studied by Raineri, Zuffardi-Comerci (1929, 1934, 1940), Cipolla, and Checchia-Rispoli. Stefanini (1918, 1921, 1923) presented a sketch map of Cyrenaica, where he grouped all the Eocene rocks in one unit and included the Aquitainian in the Miocene instead of Oligocene. Crema (1922) studied Maastrichtian sediments of Cyrenaica and in 1926; he reported traces of oil in a well, which led to the drilling of a well in Tripolitania by Agip (the Libyan subsidiary of ENI), although it was dry.

One of the most prominent geologists of that period was Ardito Desio (1897–2001). Desio wrote extensively during his career in Libya (Ettalhi et al., 1978 show a list of more than 122 of his publications). Desio (1926–1927) led an expedition to Jaghbub Oasis. He explored the then unexplored Marmarica Plateau. Pfaltz (1930) suggested that the Cyrenaica terraces were fault controlled. Silvestri (1934) examined the fossils collected from nummulitic rocks in Derna by Desio and indicated the presence of Upper Eocene in Cyrenaica for the first time. Chiarugi (1929) studied the silicified woods found south of Wadi Faregh and Maaten Risan and correlated them with those of Jaghbub.

It was in 1930 that a more active and systematic exploration of Libya was carried out. Dalloni led a scientific mission organized by the French Government in 1930–1931 to study the entire Tibesti Massif, and produced a map at a scale of 1:500,000. Dalloni divided the Precambrian complex into Archean and Algonkian Series. Dalloni introduced the name Olochi Sandstone for a conglomeratic sandstone unit separating the Precambrian complex from the overlying "Nubian Sandstone" (Dalloni, 1934, 1945).

The Italians occupied Kufra in 1931and the Turkish control of Libya ended in 1932. During that time, Desio made an expedition in 1931 on camel backs from Jaghbub to Kufra, Arkenu, and Gebel Uweinat (Desio, 1931, 1934). Desio published three volumes[12] between 1934 and 1939, which contained the results of an expedition organized by the Royal Academy of Italy to the Kufra Basin in 1931. These reports appeared in 1934 (v. 3), 1935 (v. 1), and 1939 (v. 2). The first contained the geological data and a geological map at the scale of 1:250,000; the second volume dealt with the paleontological findings, and the third summarized the geomorphological results. During the expedition to Kufra, the crystalline massifs of Arkenu and Uwaynat (Oweinat) were described and mapped in more detail. Petrographic description of igneous and metamorphic rocks was carried out by Gallitelli (1934), detrital rocks were described by De Angelis (1934), and fossil plants were identified and illustrated by Negri (1934) and Chiarugi (1934).

The first bone fragments of large mammals were collected by Desio during his 1931 trip and were studied by Airaghi (1934). Chiarugi (1934) described silicified wood from the Kufra. D'Erasmo (1934) described Tertiary vertebrates from Sirtica during the Kufra Mission.

Desio (1931) predicted the potential of the Sirte Basin as a hydrocarbon province (today the Sirte Basin is known to contain about 80% of Libya's oil reserves and accounts for 90% of its oil production). In 1932, Desio explored the area south of Cyrenaica and collected many Oligocene and Miocene samples (Desio, 1935). The 45th Congress of the Italian Geological Society and the first to be held in one of Italy's colonies convened in Tripoli under the leadership of Paolo Emilio Vinassa de Regny (1871–1957) who wrote a brief guide for the geological excursion in Libya and constructed a new map of Libya in 1912 at a scale of 1:6,000,000. This congress was attended by some of the most prominent Italian geologists at the time, including Vinassa de Regny and Federico Sacco (1864–1948) in which Vinassa de Regny(1932) wrote a field guide. In 1933, Serra (1933–1937) described Maastrichtian mollusks from Tripolitania. Machete led a geological expedition to Cyrenaica (1934–1938). Floridian (1933, 1934) dated nummulitic limestone samples collected by Desio near Brace, Cyrenaica, as Upper Eocene; thus confirming the presence of Upper Eocene sediments in the area. Trellis (1933) was the first European to visit the north-eastern spur of the Tibesti Massif in 1930, and noticed that the area was composed of quartzite sandstones of various colors. Desio (1933) produced another map of Libya at a scale of 1:4,000,000, the first since that of Vinassa de Regny in 1912.

In 1934, Chiesa who worked on the geology of West Libya and Sirtica in Central Libya from (1934–1954) provided a geological sketch map at the scale of 1:5000,000. The 48th Annual Meeting of the Italian Geological Society was held again in 1935 in Cyrenaica, and a guidebook was compiled by Breccia et al. (1935).

Machete (1934, 1935a, b) reported the discovery of additional Cretaceous outcrops and a possible Maastrichtian limestone near the coast between Apollonia and Derna, and Senonian and Maastrichtian beds near Jardas al Abid and Majahir. He also reported the presence of vast Oligocene rocks in the area southeast of Al Makili. Machete interpreted the Cyrenaica Plateau as a double plunging anticline toward the

12 Reviewed by Sandford (1939).

east and west. Monterin (1935) described the distribution of the Nubian Sandstone in north-eastern Tibesti and divided it into two units separated by a horizon of limonitic sandstone.

During the WWI (1938–1945), geological activities resumed in Libya with the publication of the "Annals of the Libyan Museum of Natural History" in 1939. The first volume contained a paper by Desio (1939b) and a map of Libya at the scale of 1:3,000,000, as well as a report by Lapparini on the Oligocene foraminifera of the Derna area. Desio confirmed the observations of Gregory (1911a) and Pfalz (1938) on Cyrenaica and suggested that the Cyrenaica terraces represented step faults. Tavani (1938,1939, 1946) described pelecypods from the Miocene of Cyrenaica and identified new species. Coggi, L. (1940) described Triassic fossils from Jifarah. In 1940, Desio (1942) made another journey to north-eastern Tibesti sponsored by the Italian Royal Geographic Society. During that mission, he discovered Eocene rocks in the Black Jabal in the middle of Serir Tibesti. Interestingly, Desio used cars and an aircraft during the last expedition instead of camels. Desio, like Dalloni, divided the Precambrian complex into Archean and Algonkian series. In 1943, Desio published a detailed account of the mineral deposits in Libya. The following year, in 1944, led a scientific mission to Fezzan in West Libya (1944–1945) (Dalloni, 1945).

In the early 1950s major political changes took place in Libya, Egypt and neighboring countries which led to the restructuring of most of the geological and petroleum exploration organizations and laws. Libya gained independence from Italy on Christmas Eve of 1951 and a federal constitutional monarchy was formed under King Idrisi.

Active exploration for oil started in Libya in 1954 after the discovery of oil in neighboring Algeria and a Minerals Law for allocating permits to foreign oil companies was introduced. Initially, drilling was not permitted. Esso, Shell, BP and CFP were among nine international companies that obtained permits during that time. The first Libyan Petroleum Law was introduced in June 1955. According to that law, the government was to receive 12.5% royalty on the realized price of oil produced, and profits were to be divided 50-50 (Clarke, 1963). Concession 1 was awarded to Esso in West Libya and Concession 2 was awarded to Nelson Bunker Hunt in Northern Cyrenaica. Exploration for oil in Libya in 1953 led to the discovery of fossil (non-renewable) ground fresh water, about 4000 years old, in the Nubian Sandstone in Libya. The first Libyan university, the University of Libya (now El-Fateh) was established in 1955. In January 1956, 45 concessions were awarded. The first wildcat well was drilled under the new Petroleum Law, A1-18; by Libya-American Oil Company to test a surface mapped anticlinal structure in northern Cyrenaica. All subsequent wells drilled onshore Cyrenaica proved dry. Esso drilled two wells, the second well discovered gas in Concession 1 in West Libya. In 1957, the Libyan Government granted Concession 65 in the Sirte Basin to Nelson Bunker Hunt, before the discovery of oil in the Basin. The same year, BP acquired 51% in the concession and became operator.

Mobil drilled A1-57 (dry); the first well in the Sirte Basin on the Dahra Platform in 1958. The same year, the Oasis A1-32 well discovered the first commercial oil in Paleocene carbonates in the Bahi Field, followed by the B1-32 well in the Dahra Field. Mobil drilled the A1-11 discovery well in the Hofra Field, also in Paleocene carbonates. Gulf drilled three holes in the Murzuq Basin, of which A1-68 tested oil. CFP discovered oil in Devonian sandstones at Tahara. Shell made the first discovery in the northern Ghadames Basin at Tlaksin in the Late Silurian Akakus Sandstone. The Atshan Field (on trend with the Adjeleh structure in Eastern Algeria) was discovered in Lower Devonian Tadrart sands in the western Ghadames Basin by Esso, with a potential of 500 bopd. In 1958, William Berry of the University of Houston described Silurian graptolites and Lower Silurian spores from the Atshan-1 well, which was probably the first palynological study in Libya. The German company Wintershall entered Libya in that year.

In 1959, Esso discovered the giant Zelten (Nasser) Field by the C1-6 well, on the Zelten Platform in Late Paleocene reefal carbonates (Fraser, 1967, Bebout & Pendexter, 1975), with reserves of 2 billion barrels of oil. The field has been on production since 1961 and produced 2426 mmbbls of oil and 1.5 TCF of associated gas by the end of 2005 (SOC website). The Zelten reef was the subject of the classical paper by Bebout & Pendexter (1975). Also in 1959 Oasis drilled the Waha Field discovery well A1-59 in the Upper Cretaceous Waha carbonates, the Defa Field discovery well B1-59 in Early Paleocene carbonates, and the F1-32 Dahra East Field in Paleocene shelf-edge carbonates. Esso discovered the Mabruk Field in Concession 17 in heavily faulted and structurally complicated Paleocene reservoirs. Eni signed its first exploration and production agreement for Concession 82 in NE Libya in 1959, where the Ar Raml Field was discovered in Nubian Sand in 1965. Mobil discovered the Amal Field with multiple reservoirs in fractured Precambrian basement rocks, Cambro-Ordovician quartzites, Upper Cretaceous, Paleocene, Middle Eocene, and Oligocene carbonates and sandstones.

In 1960, OPEC was established. Libya joined the organization in 1962, but Egypt was not a member since it was not an oil exporting country. An active exploration phase started in Libya which led to a string of significant discoveries. By June 1960, 70% of Libya had been awarded in licence agreements. Amosea discovered the Al Kotlah Field in Concession 47 in the Sirte Basin in Upper Cretaceous reservoirs. Esso discovered the Assumood Gas Field by the H1-6 well, which produced 75 mmcfgd and 103 bcf of gas by the end of 2005 (SOC website). Esso also discovered the Raguba Field in Upper Cretaceous carbonates in Concession 20, on production since 1963 with a total of 787 mmbbls of oil and 859 bcf of associated gas by the end of 2005 (SOC website). Shell discovered the Antalat Field near Benghazi in Eocene carbonates.

The first lexicon of stratigraphic nomenclature in Libya was compiled by Burollet (1960), followed by another by the geologists of oil companies (Compagnies Pétrolieres, 1964). In 1966, a field conference on South-Central Libya and Northern Chad was held (Williams, 1966). In 1968, a field conference on Jabal Nafusah and another on Cyrenaica were held. The General Petroleum Corporation (Lipetco) (the predecessor of NOC) was established by a royal decree to participate in all phases of petroleum operations in Libya. In 1968, Libya became member of OAPEC, and Joint production sharing agreement begun. A field conference (Kanes, 1969) was held with an objective on the geology, archeology and prehistory of Southwestern Fezzan. Pesce (1969) compiled a volume of Gemini Space Photographs. In addition, a number of key papers on oil fields in Libya were published in the period 1967–1975. In 1962, a British Royal Military Academy expedition was led by Williams and Hall to explore Jebel Arkenu in Southeast Libya. Beuf et al. (1971) published the classical book on glacial deposits in Algeria and West Libya. BP discovered the Messla Field in Nubian Sandstones. Libya became the second country in the world, after Algeria, to export LNG from Marsa El Brega (capacity 125 bcf per year). A symposium was held at the University of Libya. The proceedings of the symposium were published in 1971 under the title "Geology of Libya", edited by C. Gray. Hea (1971) attempted to differentiate between Nubian and Gargaf quartzites based on petrography, which inspired the paper by Tawadros et al. (2001). The Gargaf Group was introduced by Burollet (1960) for Cambro-Ordovician succession in West Libya to include the Hassaouna, Haouaz, Melez Chograne, and Memouniat formations. The Gargaf Group was extended by Barr & Weegar (1972) into the Sirte Basin and was designated as Cambro-Ordovician. Recent studies proved the presence of Devonian, Carboniferous, Permian, Triassic, Jurassic, and Cretaceous sands (mostly based on palynology) (Tawadros et al., 2001).

The Gargaf Group was also extended to the subsurface of the Jifarah Plains and the northern Ghadames Basin in Northwest Libya by Deunff & Massa (1975) who divided it into Sidi Toui, Sanrhar, Kasbah-Liguine, Bir Ben Tartar, and Djeffara formations. Massa (1988) made a detailed study on these areas. Palynology of Cambro-Ordovician was carried out by Vecoli et al. (2000, 2009). Bryozoans were studied in detail by Butler & Massa (1996) and Butler et al. (2007). One of the key geological publications on the geology of Libya, a lexicon of stratigraphic terminology in the Sirte Basin, was compiled by Barr & Weegar (1972) under the auspices of the Petroleum Exploration Society of Libya. The lexicon included the definition of 40 new formations used by oil companies and reviewed many of the existing names. This lexicon established the stratigraphic framework of the Sirte Basin and is widely accepted among workers in Libya. A second edition of Conant & Goudarzi's 1964 Geological Map of Libya was published (1972). In 1973, A French Study Group examined the Ash Shati iron ores in West Libya.

The discovery of anhydrite in the Mediterranean Sea during the Deep Sea Drilling Program (DSDP) led to the recognition of the Messinian Salinity Crisis (Hsü, 1972, Ryan et al., 1973, Cita, 1982), a subject that is still heavily debated until today (Clauzon et al., 1995, Rouchy et al., 2006, Roveri & Manzi, 2006). Barr & Walker (1973) authored a pioneering paper on the buried Messinian Sahabi Channel[13] in Northeast Libya. In 1982, An international symposium entitled "The Sahabi Research Project, 1982" on the geology, flora and fauna of the Pliocene Sahabi Formation in the Sahabi area was held at the Naturhistorisches Museum in Main, Germany in 1981. The results appeared in Special Issue No. 4 of the University of Garyounis, Benghazi.

In 1961, BP discovered the giant Sarir 'C' Field in Concession 65 in the Eastern Sirte Basin in Lower Cretaceous "Nubian" sands based on reflection and refraction seismic. The discovery well C1-65 tested 3900 bopd. In the meantime, Amoseas discovered the Beda Field in Concession 47 and the Italian company CORI discovered oil in the deep well R1-82 in Lower Cretaceous sandstones. Oasis discovered the Giant Jalu Field in Eocene and Oligocene reservoirs, as well as the Samah, Masrab, Harash, Zaqqut, and Kalifa fields. Consequently, Oasis established a facility at Ras el Sidra and Mobil constructed another facility at Ras Lanuf to export oil from the Bahi and Dahra fields. A pipeline with a capacity of 300,000 b/d was constructed the following

13 See also Abu Madi Channel, Bahr bela ma'a, ancient desert channels, SIRX-Radar channels in Egypt. In 1979, Satellite and radar (SIR-C) images were used to interpret buried channels.

year to connect the Bahi and Dahra Fields to Ras el Sidra. Esso discovered the Meghil Field, which was put on production in 1969 and produced 392 bcf by the end of 2005 (SOC website). In 1961, Esso constructed a facility to deliver liquefied natural gas (LNG) and a 36-inch pipeline from Zaltan to Al Burayqah (Brega). The first Libyan oil was shipped in September 1961. Amendments to the 1955 Petroleum Law were introduced following these discoveries and passed in 1965.

In 1962, the National Oil Company of Libya (NOLCOL) was formed, of which 51% of the total shares were to be held by Libyan nationals (Clarke, 1963). Esso made a series of significant discoveries in 1962. The Jebel Field was found in Concession 6 in the Maastrichtian Waha carbonates, which was put on stream in 1965 with a total production of 201 mmbbls of oil and 352 bcf of associated gas by end 2005 (SOC website), the Sahel Gas Field in Concession 6 in the Upper Cretaceous carbonates, with estimated 1.54 TCF OGIP, and produced 103 bcf of gas by the end 2005 (Sirte Website), and the Hateiba Field in Upper Cretaceous carbonates, which was put on production in 1978. Oasis discovered the Belhidan Field with the well V1-59 with estimated OOIP >315 million barrels in Cambro-Ordovician "Gargaf" sandstones. The main reservoir in the Belhidan Field was recently defined as the Belhidan Formation and assigned a Devonian-Carboniferous age by Tawadros et al. (2001). Oasis also discovered the Kalanshiyu Field in the same year. Philips and Pan American (later Amoco) made a small discovery at Umm al Furud in Paleocene carbonates. Mobil had a number of discoveries in 1962, such as the Abu Maras in Paleocene carbonates and the Al Facha in Lower Eocene carbonates in Concession 11, the Ora (Tibesti) Field in Gargaf quartzites in 1962 and in Upper Cretaceous carbonates in 1964 on the Bayda Platform, and the Rakb Field in Upper Cretaceous carbonates in 1962, with additional Upper Eocene and Cambro-Ordovician quartzite reservoirs were confirmed in 1970.

In 1963, Philips and Pan American made a discovery in the E-92 in Paleocene carbonates. Oasis found oil in well YY1-59 in Middle Eocene and Oligocene reservoirs. Gulf, CFP and Oasis made other discoveries in the Ghadames Basin.

In 1964, Esso discovered the giant Attahaddy Field (developed by Sirte Oil Company and became fully on production in 2005 at 270 mmcfgd and 36,000 bcd) in fractured Cambrian quartzites in a horst fault block within the Wadyat Trough in the Sirte Basin. Tawadros et al. (2001) showed that there are two Upper Cambrian fractured quartzite reservoir intervals in the Attahaddy Field, separated by a varicolored, argillaceous, arkosic sandstone interval, commonly known as 'Red Shale'. The lower interval contains volcanic intervals that have been interpreted as shale on logs. A symposium on the Hon Graben and the Western Sirte Basin was organized in 1964. Conant & Goudarzi (1964) constructed a geological map of Libya at scale 1:2,000,000, which formed the bases of all the subsequent maps. Philips and Pan American made a discovery at Al Khuf (1964, Upper Cretaceous). Mobil made other discoveries at Ad Dib (Lower Eocene, 1964) and Farrud (Paleocene, 1964) on the Dahra-Hufra Platform. Amoseas discovered the Al Kotlah Field in Upper Cretaceous reservoirs and the Haram Field in Upper Cretaceous and Cambro-Ordovician sediments. Esso discovered the Ralah Field in Upper Cretaceous in 1964.

In 1965, the Libyan government issued new concessions. Occidental, Phillips, Aquitaine, Wintershall, and Agip, Shell, and Union Reinische were the major winners. Esso discovered the Lahib Field in Waha carbonates, which was put on production in 1967 and produced 20 mmbbls of oil and 292 bcf of associated gas by the end of 2005 (SOC website). Amoseas discovered the Nafurah Field in the Eastern Sirte Basin with the G1-51. Eni discovered the Ar Raml Field in Concession 82 in tilted fault blocks in Nubian Sand. Esso found the Lahib Field in Upper Cretaceous Waha Limestone in 1965.

In 1966, Occidental discovered the Augila Field with the D1-102 well, which tested 14,860 bopd from Precambrian, Cambrian, Middle Eocene, Paleocene, and Upper Cretaceous reservoirs. Wintershall discovered the Hamid Field in Upper Cretaceous Lidam Dolomites and Lower Cretaceous "Nubian" sandstones in Concession 97. BP discovered the Sarir L Field in Nubian Sandstone. Amoseas discovered the giant Augila-Nafurah Field in Gargaf fractured quartzites, Middle Eocene carbonates, Upper Cretaceous Bahi sandstones and Paleocene carbonates. Aquitaine made discoveries at the Mansur, Majid, D-1044, and East Masrab fields. Pan American discovered the As Sahabi Field in Concession 95 and Amoseas found the Dur Field. Mobil also made discoveries at Al Farigh, Chadar, and Marada. Esso discovered the Sorra Field in Upper Cretaceous carbonates in Concession 6, which was put on stream in 1971 with a total of 204 bcf gas by the end of 2005 (SOC website). Libyan Atlantic tested gas in B1-88 in offshore Libya.

In 1967, Occidental discovered the Intisar (Idris Field) A-D Fields in Upper Paleocene pinnacle reefs in Conc. 103 based on seismic reflection data. The Intisar A Field flowed at a rate of 43,000 bopd and the Intisar D at a rate of 74,867 bopd (the highest rate ever reported in Libya).

Desio (1968) suggested that the silicified woods west of Jaghbub originated from alluvial and gravel sediments transported at the end of the Miocene and during Pliocene by northward flowing streams from the Libyan Desert to Jaghbub. Jardiné & Yapadjian (1968) and Jardiné et al. (1974) conducted palynological studies in Eastern Algeria which was applied widely in Libya. Thusu & Owens (1985) and El-Arnauti et al. (1988) edited two volumes on the palynology of NE Libya. Massa et al. (1974) and Massa et al. (1980) on the Carboniferous of West Libya, and Massa & Moreau-Benoit (1976) on the palynology of Devonian of West Libya.

In September 1969, a revolution was led by Qaddafi, and immediately production cuts were imposed on foreign companies.

In 1969, Wintershall discovered the Jakhira Field in Lower Cretaceous sandstones in Concession 96 in the Sirte Basin, the Hamid Field in the Upper Cretaceous Lidam Formation in Concession 97, the Nakhla Field, and the Tuama Field in Lower Cretaceous sandstones. The same year, concessions were awarded to the NOC's wholly owned subsidiary AGOCO.

In 1970, Libya became one of the top 10 oil-producing countries, with a record production of an average of 3.3 million bopd (Nelson, 1979). Agip discovered the giant Abu Attiffel Field in Concession 100 (awarded in 1966) in Nubian Sandstone in the Eastern Sirte Basin, with estimated 1.1 Bbbls of oil recoverable. The Abu Attiffel Field has been on production since October 1972. The giant Wadi Field (on production since 1986) was discovered by Esso in Concession 104 (later Concession NC149) in fractured "Nubian" quartzites in the Hagfa Trough, with OOIP of more than 1.0 Bbbls of oil. The Wadi Field produced 91 mmbbls oil and 52 bcf of associated gas at end of 2005 (SOC website). The stratigraphy and nature of the Nubian Sandstone in the Wadi Field has been debated since its discovery. Bonnefous (1972), postulated correctly, albeit based on erroneous data, that the upper part of the quartzite succession in the Wadi Field, previously assigned to the Cambro-Ordovician, to be of Cretaceous age. The Nubian section in the Wadi Field was thought to contain a shale interval which El-Hawat et al. (1996) correlated with the middle variegated shale in the Eastern Sirte Basin. Tawadros et al. (2001) proved that this interval in the Wadi Field to be a volcanic succession. Aquitaine discovered Al Mheirigah Field in Paleocene reefs similar to the Intisar Reefs. Amoseas discovered the Alwan and Warid fields on the Dahra and Al Bayda Platforms, respectively, in the Sirte Basin.

In 1970, Libya nationalized the oil industry, and the National Oil Corporation (NOC), a state-owned company, was created to replace the older Libyan General Petroleum Corporation (Lipetco) and to control Libya's oil and gas production. In 1971, BP's share in the Sarir Field was nationalized. In 1973, the assets of Hunt, Amoseas, Shell, and Bunker Hunt's (BP partner) share in the Sarir Field were nationalized. In the meantime, the Libyan Government acquired 51% in concessions of Esso, Mobil, Oasis, and Occidental. Libya responded to the October 1973 war between Egypt and Israel by cutting down production by 5% and an oil embargo against the United States and the Netherlands. Disputes over oil prices that followed led to a decline in exploration activities.

In 1974, the EPSA I was introduced to replace the Joint Venture Agreement. In the new formula the Government would share 85%. The first block was awarded to Occidental. Esso and Agip (Eni) were awarded offshore concessions, including NC41. Braspetro was awarded a concession in the Murzuq Basin. In the meantime, Amoco surrendered its holdings. A new concession numbering system began with the designation NC (New Concession).

In 1976, Agip drilled the well B1-NC41 in offshore Libya in New Concession NC-41which tested 4457 bopd. It was the first commercial discovery in the offshore in Lower Eocene Nummulitic buildups. The discovery was named Al Bouri Field and came on production in 1988. Also in 1976, BP discovered the giant Messla Field north of the Sarir Field stratigraphic traps in the Nubian Sandstone. In the meantime, Gulf, CFP and Oasis made discoveries in the Ghadames Basin.

Mapping of Libya at a scale of 1:250,000 started by IRC in 1974 (completed 66 sheets in 1985). The second edition of the Geological Map of Libya (1977) was updated by Maghrabi & Cheshitev of the Industrial Research Center. Fournié (1978) published the Lexicon of offshore Tunisia, which was used equally in the offshore of Libya and formed the bases for the Libyan Lexicon of Hammuda et al. (1985). In 1980, Banerjee compiled a Lexicon of stratigraphic nomenclature of Libya.

The Geological Map of Libya (IRC) project which started in 1974 completed (66 sheets at a scale of 1:250,000). Hammuda et al. (1985) compiled a lexicon of stratigraphic nomenclature for the offshore of Libya.

In 1974, Britain severed its ties with Libya over the shooting of a policewoman in London. Deterioration of Libyan-USA relation increased when the USA imposed a ban in 1978 on sales of aircrafts and electronic equipments to Libya. In 1979, Occidental sold its interest to the government. Waha and Zueitina companies were established to run the operations of Oasis and Occidental, respectively. In 1986, USA cut its relations with Libya and sanctions were imposed by the US government, and American companies withdrew from Libya. Benghazi and Tripoli were bombed by US planes.

Rampetrol discovered a third oil pool in NC115 in peri-glacial sands in the Murzuq Basin in West Libya. In 1988, the EPSA III was offered under modified terms to allow exploration cost to be recovered from output. Petrofina of Belgium, Lasmo from UK, International Petroleum Company from Canada, INA from Croatia, OMV from Austria, Shell, and Braspetro were awarded concessions. The British Lasmo signed an exploration agreement for Concession NC174 in the Murzuq Basin in 1988 and its efforts were rewarded by the discovery of the Elephant Field 1996. The Bouri Field came on production the same year.

The EPSA II was offered in 1980. Rompetrol and BOCO signed two acreages in the Murzuq Basin; NC115 and NC101. In 1981, the USA asked all US citizens to leave Libya. Esso closed down its operations, which were transferred to the NOC in 1982, and the Sirte Oil Company was established. Mobil left Libya and handed over its operation of Amal Field to its partner the German company Veba. In the meantime, the Bulgarian State company discovered oil in NC100 (awarded under ESPA II) near the Tunisian border. The Romanian company Rompetrol (in partnership with OMV and Total) encountered oil in NC115 in peri-glacial sands in the Murzuq Basin. A total of six fields designated A to H were discovered and later grouped in the Sharara Field.[14] Production started in December 1996. The field is currently operated by Spain's Repsol and partners Total and OMV, and produced approximately 200,000 bopd in 2007.

Libya's daily production in 1983 was about 1,158,000 bopd and approximately 1.1 mmcfgd (the actual figures are not released by the Libyan government and vary considerably among the various organizations).

Harding (1984) divided the Sirte Basin succession into pre-rift, syn-rift, and post-rift sequences; a scheme that proved useful in the study of the basin. The proceedings of the symposium of 1987 were published in 1990 (Geology of Libya, volumes 4–7). Proceedings of the 1993 symposium on geology of the Sirte Basin were published in 1996 in three volumes. Tawadros (2001) published "Geology of Egypt and Libya" which reviewed the stratigraphy, tectonics, and geological history of the two countries. Hallett (2002) published Petroleum Geology of Libya, with an extensive review of the petroleum systems of Libya. A symposium on the Murzuq Basin was held in 2000 (Sola & Worsely, 2000) and another symposium was held in 2003 on the geology of Northwest Libya published in three volumes. Another geological symposium was in 2005 on NE Libya.

In 1984, NOC/Agip drilled the A1-NC120 well offshore Cyrenaica which tested 5263 bopd of 36° API Oil in Lower Cretaceous and Turonian carbonates. In 1985, Waha/Agip drilled a dry hole A1-128 offshore Cyrenaica.

Work on the Great Man-made River Project (GMR) began in 1984, at an estimated cost of $25 billion, to deliver water from the Kufra Basin to the Mediterranean coast towns. Excavations of Phase I of the project started in 1991. Phase II of the project started in 1996 with the first water delivery to Tripoli. However, the origin and exploitation of the water of the Nubian aquifer system in Northeast Africa has been disputed among hydrogeologists (Puri & Aureli, 2005). The extracted

14 Sharara Field straddles Concessions NC115 and NC186.

groundwater formed mostly during several humid phases and has been depleting for several thousand years (Pallas, 1980, Heinl & Brinkmann, 1989).

In 1991, Sirte Oil discovered the Al Wafa Field in Middle Devonian sands, on the Libyan-Algerian border, near the Algerian Alrar Gas Field (discovered by Sonatrach in 1980 with estimated reserves of 4.7 TCF of gas). Production started in 2004 at 23,000 bopd, 450 mmcfgd, and 15,000 bcd. An agreement was signed between NOC and Sonatrach in September 2006 to study the link between the Al Wafa and Alrar fields. Wintershall's As Sarah Field in Concession 96 in the Eastern Sirte Basin west of the Amal Field, was discovered in Triassic sandstones and came on production in 1991.

New confrontations between Libya and the West were renewed at the end of the 1980s. The bombing of Pan Am Flight 103 over Lockerbie, Scotland, by Libyan terrorists in 1988 strained the US-Libyan relations further. In 1992, the UN imposed sanctions on Libya for refusal to extradite two Libyan nationals accused of bombing of the Pan Am flight. Sanctions, which lasted for 10 years, prohibited all flights into and out of Libya, froze Libyan assets overseas, and banned weapons sales to Libya.

In 1994, the Elephant Field was discovered in Concession 174 in the Murzuq Basin in Late Ordovician Memouniat peri-glacial sands. Production started in 2004 with an initial flow of 10,000 bopd, and ENI as operator. The field has an estimated OOIP of 1.2 Bbbls of oil and 680 mmbbls recoverable oil (OGJ, March, 6, 1995). ENI entered the NC174 joint venture by signing a farmout agreement with Lasmo. Following the takeover of Lasmo in 2000, ENI became operator of the concession. Production started from the Sharara Field in the Murzuq Basin in 1996. In 1997, Agip (Eni) made a new discovery with the F1-NC174 well in the Elephant Field which tested 7,500 bopd of 38° API oil. Agip made other discoveries with the A1-NC175 in the Ghadames Basin at 16,260 bopd, and the B1-NC125 in the Hammeimat Trough in the Sirte Basin, which tested at 5.0 mmcfgd and 3,903 bopd. OMV acquired Concessions NC186 and NC197.

Libya entered the 21st Century with new political and economic objectives. Libya handed over the two suspects in the Lockerbie bombing for trial in 1999. The UN suspended the sanctions in 2002 and the UK re-established relations with Libya. In December 2003, the Libyan government announced its decision to eliminate materials used in weapons of mass destruction. In 2004, USA lifted the sanctions on Libya, and the UN lifted the sanctions in 2003. In May 2006, the US restored relations with Libya.

Elf Equitaine made a new discovery in 2002 in the offshore Block NC137 with the B3-NC137 well, which tested 3,600 bopd of 32° API oil; the first well by Elf Aquitaine since its return to Libya in 1996.

In the year 2000, the Ministry of Energy was abolished and the NOC became in charge of the oil sector, but was reinstated in 2005. Repsol discovered the A-Field in NC186 in the Ordovician Memouniat sands, which was put on production in 2003 at a rate of 25,000 bopd. An agreement was signed between EGPC and NOC for the construction of a pipeline between Egypt and Libya (Arab Company for Oil and Gas Pipeline). Repsol YPF discovered the D-Field in NC-186, which started production at a rate of 23,000 bopd in 2004, and made a new discovery in H1-NC186 in Ordovician Memouniat in 2005, which tested 1350 bopd. In 2003, Woodside was awarded the onshore blocks 35, 36, 52 & 53. Total announced the start of production of Al Jurf Field on the offshore Block C137.

In January 2005, Round 1 of EPSA IV offered 15 blocks in different parts in Libya. Another 17 blocks were offered in Round 2. ExxonMobil Libya began exploration in Block 44 offshore Cyrenaica awarded in Round 2. Occidental resumed its operations in the Libyan contract areas abandoned in 1980s. The Japanese Nippon Oil Exploration Ltd (NOEX) was awarded Blocks 1 & 2 in the offshore Area 2, near the Libyan/Tunisian border in Round 2 and blocks 3 & 4 in Area 40 offshore Cyrenaica, northeast of A1-NC120. BG Group PLC acquires onshore Blocks 123 (1 & 2) in the Sirte Basin, and Area 171 (Blocks 1–4) in the Kufra Basin (OGJ, Dec. 9, 2005). Norway's Hydro was awarded Block 146-1 in the Murzuq Basin. Fourteen areas onshore and offshore, with 41 blocks, were offered by NOC in Round 3 of ESPA IV (OGJ, Sept. 4, 2004).

Shell signed an agreement in May 2005 with NOC to upgrade the Marsa El Brega LNG plant operated by Sirte Oil Co. Eni won four exploration permits in the Murzuk and Kufra basins. Repsol YPF (with partner Hydro) made a total of seven discoveries including I-1, J-1, and K-1 on NC-186 in the Murzuq Basin. The I-1 and J-1 discoveries gave preliminary production rates of 2060 and 4650 bopd, respectively. The K1-NC186 tested 2300 bopd in January 2007. The field extends over the NC 186 and NC 115 licences, and may contain a total of 1.26 billion barrels of oil, with 474 million barrels of recoverable oil.

Oil exports in 2006 generated $28.3 billion for the government and were forecast to be $31 billion.[15] Estimated proven reserves (2006) were 34 billion barrels of oil and 51,500 bcf of gas (World Oil, Sept. 2006, p. 57). Average annual production in 2005 was 1.63 mmbopd (World Oil, Dec. 1, 2006).

In 2005, the $5.5 billion West Libya Gas Project (WLGP) led by Eni was inaugurated. The WLGP was designed to export gas from the Al Wafa Field in West Libya and the offshore Bahr Essalam Field (in Block NC41) to Italy, in addition to the subsea 32 inch pipeline, Greenstream (75% owned by Eni), which exports gas and condensate from North Africa to Europe. Libya planned to increase oil production to 3 million barrels/d by 2010–2911 (OGJ, Jan. 23, 2006) and embarked on an extensive exploration and production program.

Total of France struck first oil in Block NC191 in the Murzuq Basin (OGJ, July 2006 & Total's website), awarded in 2001. The well tested 675 bopd. Woodside's A1-NC210 well on NC210 in West Libya encountered oil in several pay zones and tested 5.5 mmcfgd from two zones. Well B1-NC210 encountered several hydrocarbon-bearing zones in the primary Ordovician Formation objective. The deepest zone tested 11 mmcfgd through a 56/64-inch choke.

RWE discovered oil in Concession 193 in the Sirte Basin which was awarded in May 2003 under EPSA III. The A1-NC193 well tested oil in the Paleocene Dahra Formation at a flow rate of 410 bopd (OGJ, Oct. 31, 2006). RWE Dea announced a second oil discovery on Concession NC193 awarded in 2003 in the Sirte Basin with the well B1-NC193. The well tested 933 bopd from two oil intervals in the Upper Satal and Dahra formations. A second discovery was made in the Eocene Gir in C1-NC193 which tested 393 bopd. In 2010, the RWE Dea well E1-NC193 tested 704 bopd in the Dahra Formation, and the F1-NC193 tested 439 bopd in Upper Dahra Formation (World Oil, Oct. 2008). The G1-NC193 tested 426 bopd of 34^{o} API from

15 Nickle, J., 2006. African Focus, Libya. Petroleum Africa, September 2006, p. 31–40.

Upper Satal Formation (World Oil, Nov. 2008). In 2007, RWE Dea third onshore discovery, the A1-NC195, tested 1981 bopd in the Dahra and Beda (World Oil, Nov. 2007). The B1-NC195 tested 1044 bcpd and 15.4 mmcfgd from the two formations (World Oil, June 2008).

ConocoPhilips and partners Marathon and Amerada Hess re-entered the Waha Concession, which was producing 350,000 bopd at the time (OGJ, Dec. 29, 2005 & OGJ, Jan. 11, 2006). Russia's Gazprom acquired 49% in concessions N-97 and N-98 after swabbing assets with Wintershall. Repsol's new discovery in NC115 in Murzuq Basin tested 2300 bopd.

Repsol YPF and partner Woodside Petroleum reported that the C1-NC210 in the Murzuq Basin tested 5.7 mmcfgd with an Absolute Open Flow at 10.7 mmcfgd from the Devonian Awaynat Wanin (Ouinat Ouneine) Formation. Another production test of the Mrar M7 reservoir tested 5.8 mmcfgd. The F1-NC210 well tested 280 bopd and 10 mmcfgd from the Ordovician Memouniat and Devonian sands (World Oil, March 2009).

In 2009, Repsol and partner OMV discovered oil in the A1-NC202 offshore the Sirte Basin. The well was drilled to a total depth of 15815 ft and tested 1264 bopd and 0.6 mmcfgd from the Eocene Dernah Formation (World Oil, May 2009).

In the Ghadames Basin, the A1-47/02 well in Area 47 awarded to Verenex in January 2005 tested 5,172 bopd of 46.5° API oil and associated gas at 6.7 mmcfgd in the Lower Acacus Formation. A second discovery was made by B1-47, and another discovery by D1-47/02 which tested 7742 bopd of oil from two intervals in the Lower Acacus Formation (World Oil, March 2008). The F1-47 well tested 7215 bopd. In 2010, Verenex Energy tested 4.2 mmcfgd and 900 bopd from the Ordovician Memouniat Formation, and 4.5 mmcfgd and 150 bopd from the Lower Acacus Formation. The G1-47/02a well flowed 1739 bopd from the Lower Acacus (World Oil, Nov. 2008).

Amerada Hess was awarded the offshore Block 54 north of Ras Lanuf in Round 1 of ESPA IV. In 2008, the company discovered oil in several intervals in the well A1-54/1(Arous Al-Bahar), in 2807 ft of water (Hess Corp News Release, Dec. 17, 2008). Hess estimated the reserves at 1–5 TCF of gas in 2010.

However, all exploration efforts came to a halt in the beginning of 2011 with the eruption of the civil war.

1.3 ALGERIA

The history of geological ideas in Algeria during various periods has been summarized by Larnaude (1933), Legrand (2002), Bettahar (2007), and Taquet (2007).

The first crossing of the Sahara by a European traveler took place in 1825 and 1826 by the Englishman (Scottish) Major Alexander Gordon Laing (1793–1826) of the Royal African Colonial Corps, on a mission opening up commerce and endeavouring to abolish the slave trade in that region. Leaving Tripoli, he arrived in Timbuktu (in Mali) on 18 August 1826, but he was murdered on the way back. The following year, the Frenchman René Caillé (1799–1838) crossed the Sahara from south to north via Timbuktu (Taquet, 2007). Denham, Oudney and Clapperton reached Murzuq in 1822, and then left Tripoli and travelled to Lake Chad from 1822–1825. The German Heinrich Barth, accompanied by the geologist Overweg, joined the James Richardson Expedition in 1850 and travelled to Tripoli. Overweg was the first to make geological observations and to note the presence of granites and sandstones in the Central Sahara.

Algeria was occupied by the French in 1830. The earliest geological studies were carried out by military officers, such as Rozet who established the *Commission Scientifique* in 1839 which was headed by E. Renou. In 1852, the Service des Mines was formed of a group of mine engineers and university professors. The latter included Auguste Pomel and Conrad Kilian who carried out reconnaissance geological studies in North Africa, including the Sirte Basin (Pomel, 1878). Pomel also played a role in the organization of the *Service de la Carte Géologique de l'Algérie*. He also headed the University of Algiers; followed by Ficheur in that post in 1891.

The first geological congress was held in Algiers in 1881. A geological map of Algeria at the scale of 1:800,000 was prepared for that congress (Bettahar, 2007). However, Péron established the stratigraphy of Algeria in 1883 by classifying rocks in a chronological order. His paper also included a geological map.

Rolland (1890) examined all the by then available geologic and geographic data from the Atlantic Ocean to the Red Sea and compiled what is probably the first geological map of Northwest Africa (Wendt et al., 2009). He recognized that the plateau of the Tassilis is composed of Devonian sandstones into which he included the older sedimentary cover of the Precambrian granites and metamorphic rocks of the Hoggar Massif (Tuareg Shield) in Southern Algeria.

The Foureau-Lamy expedition of 1898–1900 recognized the presence of a crystalline basement under sandstone formations (Foureau, 1898, cited by Legrand, 2002). His collection was studied by Gentil (1909). From about 1900 until the First World War, the geological explorations followed the axes of the French military progression (Ouzegane et al., 2003).

Three exploration missions to Morocco were organized by Brives (1905) from 1902 to 1904. After the First World War, the pace of geological studies in Hoggar quickened. Bütler's memoir (1922, 1924) is the first really precise description of Hoggar geology (Ouzegane et al., 2003).

Flamand (1911) made the first detailed study of the geology of the south of Algeria under the protection of 140 men of the Camel Corps (Taquet, 2007). Conrad Kilian (1898–1950), who was abandoned by his military companions, completed his exploration of the Tassilis des Ajjers and of the Central Hoggar. Among his achievements; he examined the main features of the geology of the Hoggar Massif, discovered the graptolitic shales (1928), and divided the Tassilis into two units; the Internal Tassilis which he regarded as being 'pre-Gothlandian' (pre-Silurian) comprised Lower Ordovician sandstones and the External Tassilis which consisted of upper Devonian sandstones. Kilian also indicated that the basement was Precambrian in age and divided the Precambrian sequence into two series; the Suggarian and Pharusian, separated by conglomerates. The results were submitted to the Acadamy of Sciences in a short note entitled "Aperçu general de la structure des Tassilis des Ajers" and again to the International Geological Congress in Brussels in 1925. Kilian also explored the borders of the Italian Fezzan and Algeria and discovered the Monts Doumergue. Kilian (1931) also recognized the *Continental intercalaire* with reptile and fish fossils between the marine Upper Carboniferous and the marine Middle Cretaceous, and the *Continental terminal* of Upper Cretaceous and Cenozoic age; a concept that is still in use today (Lefranc & Guiraud, 1990).

D. Dussert (1924) published on the Algerian phosphates. In the period of 1924–1929, work on the Atlas of Algeria and Tunisia, was published by Augustin Bernard & R. de Flotte de Roquevaire in 8 volumes; the first section deals with geology (published 1925) (Lespès, 1931). Jacques Levainville (1925) showed that the two horizons were of Lower Eocene" *Phosphate algerien*". J. Savornin (1931) published "*La géologie algerienne et nord-africaine depuis 1830*".

Théodore Monod (1902–2000) was another pioneer Saharan geologist and paleontologist who discovered an intermediate series between the Precambrian and the Paleozoic of the NW Hoggar (Monod & Bourcart, 1931, 1932), which he named Purple Series, the first known example of Pan-African molasse (Taquet, 2007). In 1934, he also discovered Silurian graptolitic rocks in the Tassilian borders of Ahnet.

Albert Félix de Lapparent (1905–1975) studied the stratigraphy of the Mesozoic Saharan basins, starting in 1946. De Lapparent gave a detailed account of the stratigraphy of the Gourara, of Touat and Tidikelt. During his trips, he studied the dinosaurs of the Sahara (de Lapparent, 1960) and gave the first interpretation of the geology of the Edjeleh region. He discovered the bones of a giant crocodile in an underground irrigation canal, which was later named *Sarcosuchus imperator*. His discoveries were the starting point of the study of vertebrate fauna of the Sahara.

The first oil discovery in Algeria occurred at the end of last century in the Chelif Basin (Ain Zeft). However, due to the great geological complexity of Northern Algeria, it remained mostly unexplored (Askri et al., 1995). In 1948, oil was discovered in the Oued Gueterini Field in Eocene reservoirs in Tellian nappes,[16] and gas was discovered at Berga-1 in 1954. Subsequently, the Edjeleh Oil Field was discovered in Lower Devonian sands; the Hassi Messaoud Oil Field in the Cambrian sandstones, and the Hassi R'Mel Gas Field in the Triassic in 1956.

The 19th International Geological Congress of Algiers (1952) marks the starting point of the geological exploration of the Algerian Sahara (Legrand, 2002), followed by the publication of the Lexique International (1956).

Following the discovery of oil in 1954, an enormous amount of stratigraphic and sedimentologic data were accumulated by oil companies, but unfortunately remained inaccessible. Some results were published by Legrand (1967). Askri et al. (1995), Zeroug et al. (2007) provided valuable overviews especially of the hydrocarbon systems. In the years 1974–1975 a series of geological maps of 26 sheets at the scale of 1:200,000 was published by Sonatrach-Beicip, unfortunately they were not accompanied by individual explanations. Outcrop studies of the Lower Paleozoic were made by Dubois et al. (1968), Beuf et al. (1971), and Eschard et al. (2005), while the Middle Devonian to Carboniferous rocks were examined by Remack-Petitot (1960) and, Chaumeau et al. (1961).

The Alrar Field was discovered in 1961 with the well Alrar East-1 in Middle Devonian sandstones (F3). Oil was discovered three years later with the wells Nord Alrar 103 and Nord Alrar 106 (Askri et al., 1995). The Zarzaitine Field was discovered in 1957 and production started in 1960. The gas-cap of Tin Fouye Tabankort

16 Messaaoudi, M., undated. Northern Algeria, A general overview of hydrocarbon prospectivity. Africa Session, Forum 21 Poster. WPC-cd250.

Field was discovered in 1961 in the well TFE-, but oil was found only in 1965 in the well TFEZ (Askri et al., 1995). The Rhourde El Baguel Field was discovered in 1961. It was put into production in August 1963 with well RB-1 and produces from a large accumulation set within Cambrian quartzite sandstones.

Recent oil and gas discoveries in Algeria include the Anadarko Petroleum oil discovery of oil in the Berkine Basin Block 403c/e, where the well tested 870 bopd (WO Nov. 2007). In 2008–2009, Repsol discovered gas in the KLS-1 in the Reggane Basin, which tested 22.2 mmcfgd; the OTLH-2 in the Ahnet Basin, which tested 8.8 mmcfgd on the M'Sari Akabli Block, and the A1-2 in the Berkine Basin with 5.58 mmcfgd on the Gassi Chergui Block (WO March 2009), and discovered gas in the TGFO-1 with 12.8 mmcfgd in the Emsian in the M'Sari Block (WO May 2009). Petrovietnam (PVEP) discovered oil in the BRS-6 on Block 433a in the Oued Maya Basin (WO April 2009). In the Illizi Basin, Sonatrach's Issaouane NO-1 well tested 6.22 mmcfgd from the Ordovician in the Amenas Block 240b and the Tin Dadda Sud-1 which tested 6.33 mmcfgd from Silurian and Devonian sands. In the Oued Maya Basin, the Nechou Nord-3 tested 2189 bopd and some gas, and the well Madjbeb-1 which tested 332 bopd and some gas from Triassic sands. StatoilHydro tested 7.76 mmcfgd in Devonian-Carboniferous reservoirs on the Hassi Mouina Block in Timimoun Basin (WO Sept. 2008), and in the TNK-2 which tested gas in the Lower Carboniferous (WO Oct. 2008). Sonatrach discovered gas in the Tirehoumine-2 on the Ahnet Block in the In Salah region which tested 1.75 mmcfgd from the Gedinnian (WO July 2008). Sonatrach Araret-2 (OTS-2) tested 8.3 mmcfgd in the Ahnet Basin. Sonatrach also tested 5.9 mmcfgd from a 66 ft (20 m) pay of Carboniferous reservoirs in the Tinerkouk-1 (TNK-1) (WO Jan. 2008). PetroVietnam International (PIDC) made an oil discovery on Blocks 416b and 433a with the well BRS9 with a potential flow rate of 5000 bopd (WO May 2008).

1.4 TUNISIA

In Tunisia, the first exploration expedition was the voyage of Peyssonel & Desfontaines in 1725 across Algeria and Tunisia (Burollet, 1995). Peyssonel (1738, cited by Burollet, 1995) described quarries and economic minerals, as well as the historic variations in the shorelines of Tunisia. At the same time, M.D. Shaw (1738, 1743) published an illustrated description of many fossils and minerals collected during his voyage to the Berbers region. He pointed out the Cenomanian coral *Aspidiscus cristatus*, which was later described by Lamarck.

In 1830, S.E. Hebenstreit published the results of his voyage to Alger, Tunis and Tripoli, sponsored by King Frédéric Auguste of Polonia. In 1877, Pomel carried out the first systematic geological work in Tunisia. Overweg (see Demoulin, 1931, for an account of the trip) during his travel from Philippeville to Murzuk via Tunis and Tripoli mentioned for the first time the Strombus beds of the Tunisian Sahel. Edmond Fuchs explored Tunisia from 1873–1877. He mentioned the Middle Triassic of Zaghouan and the associated faults. G. Stache also crossed Tunisia about that time and confirmed the presence of the Turonian near Gabès. The Italian G. Perpetua published the *Compendio della Geografia della Tunisia* (1880, 1883) and *Geografia della Tunisia* (1883), where he gave a detailed description of the shorelines, the relief, the islands, the Chottes, and the Sebkhas. He considered the Bou Kornine as a dormant volcano. M. Blanckenhorn (1888, cited by Burollet, 1995) presented a study on the Atlas Chain, especially the Algerian part, in "*Die geognostischen Verhältnisse von Afrika. I. Teil: Der Atlas, das nord-afrikanische Faltengebirge*".

The Scientific Exploration Mission of Tunisia "*Mission Scientifique de Tunisie*" (1885–1887) was led by the botanist Ernest Cosson (d. 1889). During that mission, Georges Rolland explored Central Tunisia, Phillippe Thomas (d. 1910) travelled in Southern Tunisia, and Georges Le Mesle (d. 1895) studied Northern Tunisia in 1889–1890. They provided a good description of the Jurassic of Zaghouan and the Eocene of Maktar and Kairouan. Philippe Thomas discovered the phosphate deposits of Jebel Tselja. The report of Valéry Mayet in 1887, although botanical and zoological in nature, contains geological information on the gypsum deposits of Oued Leben, south of Jebel Meheri, the Cretaceous of Bou Hedma, the Cenomanian *Exogyras* to the west of Orbata, and the Miocene fossils west of Chemsi. Ph. Thomas published the paleontological works made by Victor A. Gauthier (Echinoids), Arnould Locard (Molluscs), Auguste Péron (Brachiopods, Bryozoans, and Pentacrines), and H.E. Sauvage (fishs). Francis Aubert, a mining engineer, who commenced his geological research in 1884, compiled the works made by members of the Mission and constructed a map at the scale of 1:800,000 in 1892. Georges Rolland (1891) published the "*Aperçu sur l'histoire du Sahara depuis les temps primaires jusqu'à l'époque actuelle*", which included a map.[17] In 1896, Capitaine E. de Larminat studied the geography of Southern Tunisia and published the results in the "*Etude sur les formes du terrain dans le sud de la Tunisie*".

The phosphates were treated by M. G. Bleicher (1890), David Levat (1894–1895), and E. Vassel (1887, 1899), as well as E. Trodos (1898) on the phosphates of Kalaa Djerda, Edmond Nivoit (1897) on the Metlaoui and on Moulares (1903). A. Pomel defined *Dyrosaurus thevestensis* that was erroneously identified as *Crocodilus phosphaticus* by Ph. Thomas. F. Priem (1903) studied the vertebrates and the fishs in particular of the phosphates. G. Di Stefano (1903) identified new reptiles in the phosphates. Priem (1909) described an Upper Senonian fish from the Abiod Formation west of Metlaoui. V.A. Gauthier (1892) described the Cretaceous echinoids collected by M.F. Aubert and the Jurassic echinoids collected by G. Le Mesle (1896).

From 1896, the geology of Tunisia was studied extensively by Léon Pervinquière (1873–1913) (Burollet, 1995). His work was published in 1903 and included a map of Central Tunisia at the scale of 1:200,000. He continued with a number of paleontological studies in Tunisia that included the Mesozoic cephalopods in 1907 and the Cretaceous gastropods and pelecypods in 1912, as well as Quaternary studies of shorelines of Tunisia. In 1909, Pervinquière led a scientific mission in Algeria and in 1911 accompanied another mission to determine the boundary between the French Tunisia and the Italian Tripolitania. During the latter, he described the geography and geology of Ghadames (1911) and Tripolitania (1912).

Ch. Monchicourt studied the Maktar Massif in Central Tunisia. In 1902, Ph. Thomas compiled the geological description of Tunisia with the collaboration of A. Gaudry, A. Péron, and Paul Bursaux. The results were published between 1907 and 1910. The work was continued by Pervinquière and later by Emile Haug.

17 Bull. Soc. Géol. France, v. 3, no. 19, p. 237–246.

In 1912–1913, L.F. Spath described the ammonites of Jurassic Zaghouan. His observations were later confirmed by Biely & Rakus (1969–1970). In 1896, the archeologist R. Cagnat described ancient quarries and mines, in particular the lead and zinc at Jebel Ressas, and the marble at Chemtou. M. Gerest (1889) attributed an Upper Cretaceous age to Jebel Tebaga. The presence of the Triassic at Jebel Rehach was confirmed for the first time by A. Joly (1906–07) who assigned a Permian age to the lower sands. The Tunisian Atlas was studied at Bou Kornine by Janko in 1890, the area around El Kef by P. Mares in 1884, the discovery in 1893–95 of Liassic fossils by A. Baitzer in the Zaghouan Limestones which were determined by Ch. Mayer-Eymar, and the Gafsa area by E. Koken in 1909. C. de Stefani described Jurassic fossils at Jebel Aziz in 1907. Several alpine geologists also visited Northern Tunisia; among them were Léonce Joleaud (1880–1938) who identified the Lower Cretaceous at Jebel Bou Kornine (1901) who also wrote on the tectonics of Northwestern Tunisia from 1913 until the 1930s, and Pierre Termier who described many ore occurrences. Ch. Monchicourt (1913) published his thesis on the geography of the "*Haut Tell Tunisien*" using the geology of Pervinquière. Solignac (1927, cited by Boughdiri et al., 2005) carried out work in Northern Tunisia, and published his work in 1929, in which he included a map at a scale of 1:200,000. In 1934, F. Bonniard published his report on the geography of the Northern Tell based on the geology by Solignac (1929).

In the 1950s, Mattieu (1950) carried out work in Tunisia using local stratigraphic names. C. Castany (1951–1955) studied Central Tunisia. 1956 signaled the beginning of oil exploration in Tunisia. Burollet (1956) was the first to establish a systematic stratigraphic nomenclature in Tunisia. Castany (1962) included a part on Tunisia in the International Stratigraphic Nomenclature and mentioned the stratigraphic terms in use at that time.

In 1964, Glaçon & Rovier (1964) indicated the presence of limestone microbreccia at Kroumirie, and Jauzein & Rovier (1965) defined the Adissa and Ed Diss formations at Kroumirie. Busson (1967a, b) studied Southern Tunisia. Rakus & Biely (1971) defined the "*Formation calcaire de l'Ouest*" in the Lower Liassic of the Tunisian Dorsal. Bajanik et al. (1972) revived the names of the Miocene Beglia and Saouf formations and introduced the Mahmoud Formation, Cap Bon Group, Sehib Formation, and the Bou Sefra Facies. In a jubilee volume dedicated to Solignac in 1973, many new formations were introduced by various authors, such as the Tithonian Ressas Formation, Djebel Siouf Limestone, Cherahil Formation, Haffouz Facies, Korbous Limestone (Comte & Dufaure, 1973), and Oued Hamman Formation (Hooyberghs, 1973). Biely et al. (1974) revised the Neogene stratigraphy in Northern Tunisia and introduced the names Bejaoua Group, Medjerda Group, and Oued Mellegue Group with its two formations, Tessa and Oued Djouana. Turki (1975) introduced Gridja Formation for the Aptian at Djebel Bargou, and Khessibi (1975) defined the continental Kebar Formation for the Middle Cretaceous at Djebel Kebar. Dominique Massa carried out many studies on the Paleozoic of Libya and Southern Tunisia since the 1960s.

In May 1964, Tunisia's first oil field, El Borma, was discovered in Triassic reservoirs near the Algerian border. Other fields in Tunisia include the 7 November, Ashtart, Bouri, El Biban, Ezzaouia, Sidi El Kilani, El Menzah, Cercina, Miskar, and Tazarka. The *Entreprise Tunisienne d'Activités Petrolières* (ETAP) was established in March of 1972 to manage exploration and production activities in the country.

The Isis Field in the offshore of Tunisia was discovered in 1974, but remained undeveloped until December 2001.

Bishop (1975) published his classical paper on the geology of Tunisia and adjacent parts of Algeria and Libya, followed by a second paper (Bishop, 1988) on the hydrocarbon geology of East-Central Tunisia. Robinson & Wiman (1976) reviewed the stratigraphic subdivisions of the Miocene rocks in the sub-Dorsale in Tunisia and placed the top of Saouf Formation in the late Tortonian based on planktonic foraminifera. The Petroleum and Exploration Society of Libya publishes "Guidebook to the Geology and history of Tunisia for its 9th Annual Field Conference (1976), where Burollet (1976) reviews the Tertiary geology of Tunisia. Fournié (1978) compiled the "Lithostratigraphic Nomenclature of the Upper Cretaceous and Tertiary Series of Tunisia" sponsored by Serept and Elf-Aquitaine where he revised the stratigraphic nomenclature of Tunisia and introduced 10 new formations. Ferjani, Burollet & Mejri (1990) review the petroleum geology of Tunisia under the auspices of the *Entreprise Tunisienne d'Activités Petrolières*.

In 2007, Eni's Karma-1 well on Adam Concession tested more than 4000 bopd. Nakhil-1 well on Bordj el Karma Permit produces 1200 bopd (Eni's Website, Jan. 2007). PA Resources AB began producing 20,000 bopd from Didon Field offshore Tunisia (World Oil, May 2007). Pioneer Natural Res made a discovery in Shaheen-1 on Jenein Block, with daily gross production of 8000 boe from multiple zones (World Oil, July 2007). In 2008–2008, PA Resources made an oil discovery with Didon North-1 on the offshore Zarat Block, which tested 46 ft of pay in the El Guaria Formation (World Oil, Jan. 2009). BG discovered a 200 ft gas column in the RM-1 well on the Hassi Ba Hmaou Permit; the well tested 8.7 mmcfgd at depths 2917-2943' (World Oil, Aug. 2008).

Like Egypt, Tunisia was shaken by unexpected events in January 2011, which led to a change in government.

1.5 MOROCCO

One of the earliest scientific reports on Morocco was that of Hodgkin in 1864 who wrote an account on Sir Moses Monteflore's Mission to Morocco. In 1868, Rohlfs visited Morocco before he embarked on his famous voyages in North Africa. In 1870, Mourlon published in the Bulletin De l'Academie Royale de Belgique a description of fossils collected by Desquin and stored at the Museum of Brussels.

In 1871, a botanical expedition into Morocco was led by Joseph D. Hooker (1817–1911) and John Ball (1818–1889), accompanied by the tile-maker, botanist and geologist George Maw (1832–1912). The results of the expedition were published in 1878 in "Journal of a Tour in Marocco and the Great Atlas". The book included an appendix by G. Maw entitled "Notes on the Geology of the Plains of Marocco (*sic.*) and the Great Atlas" and included the first geological cross-section of the High Atlas.

Lieut. Washington wrote some notes on the geological features of the district between Tangier and Morocco and published in the first volume of the Journal of the Royal Geographical Society an article entitled "Geographical Notice of the Empire of Marocco" (Hooker et al., 1878). A geological memoir by Henri Coquand

(1811–1881) was published on the environs of Tangier and the northern part of Morocco (Coquand, 1847). A paper was read by G. Maw before the Geological Society of London in 1872 on the northern promontory of Morocco, facing the strait of Gibraltar. South of Tangier, M. Desquin (Hooker et al., 1878, p.448) collected the Upper Cretaceous fossils *Inoceramus*, *Ostrea nicaisei*, *O. syphanx*, *Globiconcha ponderosa*, *Trigonia castas*, and undet. *Echiondermata*. James Smith (J. Geol. Soc., v. 2, p. 41, also in Hooker et al., 1878, p. 448) mentioned *Terebratula fimbriata* and *T. concinna* from the "Lower Oolite" in the Gibraltar Limestone, which Coquand compared with the Jurassic Tetuan Limestone near Tetuan (Tetouan) and divided it into four units of marls, dolomites, calcareous sandstones with odor of petroleum, and lithographic limestones with siliceous concretions. Maw suggested that the Tetuan Limestone is separated from the Cretaceous Series to the northwest by a major N-S fault that runs in the middle of the Tangier promontory. Maw also described a 200 m (656 ft) cliff near Cape Cantin which consists of alternating beds of grey and reddish fine-grained sandstones and beds of ferruginous carbonates. Maw collected specimens of *Exogyra conica*, *Ostrea leymerii*, and *O. Boussingaulti* near Staffi, which were dated as Neocomian. Maw also identified Miocene and Pliocene beds near Staffi and Eocene beds of clays and red ferruginous marls with oyster beds containing *Teredina personata* in an escarpment at Sidi Ammar, overlain by a bed with *Balanus sulcatus*, *Pecten beudanti*, *Arca*, *Buccinum prismaticum*, and *Conus*, which were assigned to the Miocene. In addition, Maw identified metamorphic rocks north of the City of Marrakech, and micaschists intruded by porphyritic dikes at Djebel Tezah.

In 1883, Charles-Eugène de Foucauld wrote "*Reconnaissance au Maroc*" (1883) where he described Jebel Sirous. In 1889, Joseph Thomson published "Geological Map of Southwestern Morocco 1:500,000". The Expedition of Emin Pacha left in April 1890 for Bagamoyo, the results of which were reported in "*Resultat de la dernière expedition de Emin Pasha*" by B. Auerbach (1894). The results of another expedition were published in 1891 "*Expedition du Comte Telek* (1887–1888)". In 1892, P. Schnell wrote an account titled "*Marrokisches Atlas*". In 1897, M.R. de Flotte de Roquevaire published topographic maps at the scale of 1:1,000,000 (1897 & 1904). In 1899, Joseph Thomson wrote the paper "The Geology of Southern Morocco and the Atlas Mountains".

In 1900, the first collection of Carboniferous material from the Zousafana Valley was made by officers of Colonel Bertrand's detachments. The paleontological results were published by Ficheur (1900).[18] In 1901, the Carboniferous was recognized in outcrops at Tidikelt, NW of Hoggar by Commandant Cauvet, at Tademait by Lieutenant Besset, at Touat by Commandant Deleuze, and at Ahnet by Lieutenant Mussel. In 1904, R. De Flotte (1904) made a map of Morocco at a scale of 1:1000,000. Louis Gentil began his expeditions in 1904, and in 1905, he published the "*Mission de Segonzac: Dans le Bled es Siba*" in the Western Atlas. Paul Lemoine introduced the "*Carte géologique schmatique* 1:2,000,000". Gentil (1906) gave an account of the geological contributions in Morocco and discussed the results of A. Brives' 1905 work in the Atlas Mountains. In 1907, Gentil wrote a note entitled "*Esquisse géologique du Haut Atlas occidental*" to accompany a map at the scale of 1:750,000, where

18 Weynat (1985, p. 300).

he discussed again the stratigraphic and geographic subdivisions of the High Atlas proposed by Brives. We see also the first mention of Carboniferous at Djerada in Morocco by Gentil (1908). In 1912, Gentil published *Le Maroc Physique* (1912), where he presented the first geological map of Morocco. In 1911, G.B.M. Flamand carried out surveys in the area NW of Hoggar.

In 1912, Morocco was occupied and became a French protectorate.

The Carboniferous was recognized at In Tedreft, south of Hoggar by Chudeau (1913), and in Central Morocco by Gentil (1914). Carboniferous plants collected by Commandant Carrier were studied by Fritel (1925), and the Carboniferous was identified at Iullemedden by Boureau (1953). In 1918, the first geological map of the Western High Atlas made by Louis Gentil was published by E. Suess in *La Face de la Terre* and the French edition *Das Antlitz der Erde*. In 1924, exploitation of phosphate started at Khourbiga (Charles & Charles, 1924). In 1927, Bourcart discovered *Archaeocyathus* in the Moroccan Anti-Atlas. In 1936, H. Termier (1936) published "*Etudes géologiques sur le Maroc central et le Moyen Atlas septentrional*" in four volumes in *Notes Mémoires de la Service Géologique Maroc*. In 1950, E. Roch (1950) published *Histoire stratigraphique du Maroc* to accompany the geological maps at scale of 1:500,000 published by the Geological Survey of Morocco.

In March 1956, Morocco gained its independence from France to become the Kingdom of Morocco, with Mohammed V as the king of the new monarchy.

In 1960, a book entitled *Livre à la mémoire du Professeur Paul Fallot* was published in 1960–62, and offers a summary of the geology of the Atlas and Rif Domains (Missenard et al., 2008). A. Michard (1976) summarized the geological knowledge of Morocco in his *"Eléments de Géologie Marocaine"*. In 1980, Gabriel Suter (1980) constructed new geological and structural maps of the Rif at a scale of 1:500,000.

In the 1990s and the beginning of the 21st Century, a tremendous amount of research papers and post-graduate thesis have been produced. Worthy of mentioning are two major compilations: Jacobshagen (1988) edited a book on the Atlas System of Morocco, and most recently, Michard et al. (2008) compiled in one volume a variety of papers written by many experts in the geology of Morocco.

From 1900 to 1928, petroleum exploration was carried out in the vicinity of oil seeps, which led to the discovery of the Ain Hamra oil pool in the Rharb Basin in 1923. The *Bureau de Recherches et d'Exploitations Minières* (BRPM) was created in 1928 and the *Société Chérifienne de Pétrole* (SCP) was established in 1929 and carried out most of petroleum exploration activities. Hydrocarbon exploration continued in 1937 in the Rifian and Prerifian zones of Morocco by the *Societé Chérifiane des Pétroles* with a drilling campaign of 160 shallow wells; only 12 wells were >1000 m (3281 ft), to solve tectonic problems (Célérier, 1937). Four occurrences of hydrocarbons were located as a result of that campaign; two at Djebel Tselfat, one at Djebel Bou Draa, and one at Djebel Outita. All occurrences were considered uneconomical, but the potential of the Lower Jurassic (Domerian) limestones was shown. Exploration efforts since that time led to the discovery of a number of oil and gas fields. The most important fields are situated in the Essaouira and Gharb (Rharb) Basins in Western Morocco. Morocco also has oil shale deposits (Kolonic et al., 2002) at Tangier, Timahdit and Tarfaya in the Atlas Mountains which were studied in the 1930s. Seismic reflection techniques were first introduced in the Rharb and Prerif basins in 1935 and in the

Essaouira, Souss and Guercif basins in 1955 (Onhym, 2000, www.onhym.com). Oil and gas discoveries were made in the Prerif Ridges and in the Sidi Fili Trend. A new Hydrocarbon Law was passed in 1958. Wells drilled between 1958 and 1981 led to further discoveries in the Essaouira and Rharb Basins. In 1981, the *Office National de Recherches et d'Exploitations Pétrolières* (ONAREP) was created by the Moroccan government. A total of 85 wells have been drilled in the period 1981–2003, and led to the discovery of Meskala Field in the Essaouira Basin, in addition to several biogenic gas accumulations in the Rharb Basin. The Hydrocarbon Law was amended in 1992, and in 2003 ONAREP and BRPM were merged into a newly formed entity, ONHYM.

In 2008–2009, Circle Oil made a gas discovery with CGD-0, which tested 3.9 mmcfgd from the Lower Guebbas Formation (World Oil, Jan. 2009). Repsol-YPF discovered gas in the offshore Anchois-1 well in the Tanger-Larache area; about 40 km offshore Morocco from two gas pays totaling 427 ft, with estimated recoverable reserves of 100 bcfg (World Oil, May 2009). In January, 2011, Circle Oil announced that the ADD-1 exploration well on the Sebou Permit, Rharb Basin, has tested 3.57 mmcfgd on a 24/64' choke from the Hoot and Guebbas formations.

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PART 2

Tectonic framework of North Africa

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Chapter 2

Northeast Africa's Basins

The tectonic setting of North Africa is an integral part of global tectonics. It is related to the formation and break-up of the super-continents Rodinia, Gondwana and Pangaea, the rotation of the different continents relative to each others and the opening and closing of major present-day and paleo-oceans, such as the Iapatus, Atlantic, Pacific, and Tethys. These events led to rifting, shear movements, uplifts, volcanic activities and thermal subsidence throughout the geologic history of the area. The tectonic history of the area becomes less clear as we move down the geologic column due to the lack of data on one hand, and the overprinting of the older tectonics by younger ones.

North Africa can be divided into six major domains; each is subdivided into various tectonic elements (Fig. 2.1): 1) The Precambrian basement, which includes the African-Nubian Shield and the West African Craton. 2) The Sahara Platform that includes cratonic basins, tectonic highs, arches, and platforms. 3) Rifted marginal basins. 4) Rift basins, 5) The Atlas/Alpine folded belts. 6) Passive continental margins.

The cratonic basins include the Nile Basin in Egypt, and the Kufrah, Murzuq, and Ghadames basins in Libya. Algeria encloses the Ghadames/Illizi/Berkine, Oued Mya, Mouydir, Ahnet, Timimoun, Bechar, and Tindouf basins. Tunisia includes the northern part of the Ghadames Basin, the Pelagian Shelf, and Western Tunisia (Atlas Basin). Morocco contains numerous basins, although much smaller than those of Egypt, Libya, and Algeria; such as the Anti-Atlas, Prerif, Boudenib, Tafilalt, Maider, Ouarzazate, Zag, Tindouf, Draa, Missour, High Plateaux, Saïs, Tadla, Haouz, Bahira, Tagalft, Guercif, Beni Znassen-Beni Bou Yahi, Souss, Argana, and Taoudenni basins; the latter is located mostly in Mauritania. The rifted marginal basins include the Northern Egypt Basin, the offshore Nile Delta Basin, the Cyrenaica Basin, and the Jifarah Basin. Rifted basins include the Red Sea and Gulf of Suez in Egypt and the Sirte Basin in Libya, and the Mediterranean Basin. The passive margins include the Mediterranean and Atlantic margins and their offshore basins, such as the Agadir, Rharb (Gharb), Doukkala, Essaouira, Tarfaya, Safi, and the Atlantic Deepwater Frontier. The Alpine/ Atlas folded belts are located mostly in Morocco and northern Algeria and Tunisia.

2.1 MEDITERRANEAN BASIN

The Mediterranean Sea is an east-west elongated trough extending for 3500 km (2175 miles) separating the continents of Africa, Europe, and Asia (Fig. 2.1).

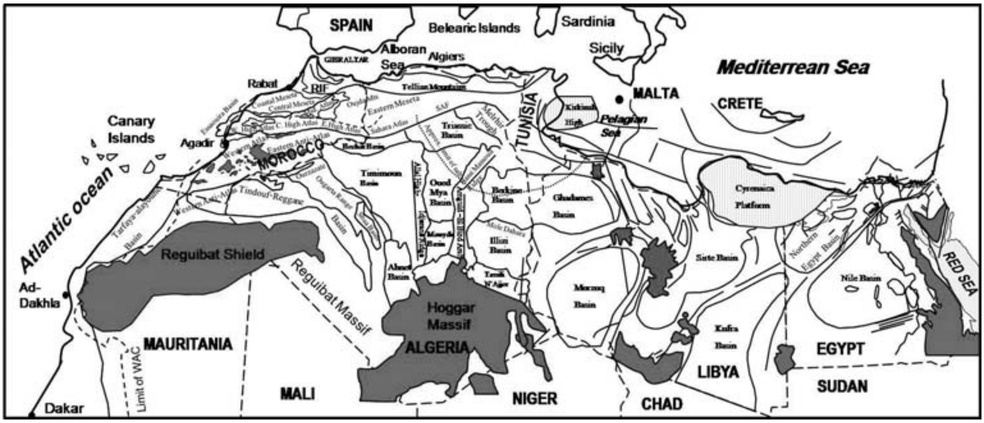

Figure 2.1 Tectonic map of North Africa (compiled from Tawadros, 2001, Cochran & Peterson, 2001, Piqué, 2003, Michard et al., 2008). International boundaries are approximate (See color plate section).

The Mediterranean is bordered on the north by the Alpine Chain and to the south by the African Platform and the Atlas Chain. It is connected to the Atlantic Ocean via the Strait of Gibraltar and with the Black Sea in the northeast via the Straits of Dardanelles and Bosporus. The man-made Suez Canal connects it to the Red Sea.

The Mediterranean Sea is divided into several subbasins separated by ridges, escarpments, and deep channels. The Peninsula of Italy, Sicily, Malta, Pantelleria, and Cap Bon Peninsula in Tunisia, mark the limit between the Eastern Mediterranean and the Western Mediterranean (Alboran) basins. The southeastern part of the Eastern Mediterranean is known as the Levant Sea. The Ionian Abyssal Plain, the Pelagian Sea, the Messina Cone, the Hellenic Trough, and the Mediterranean Ridge are often referred to as the Central Mediterranean.

The continental shelf, delimited by the 200 m (656 ft) contour, is narrow offshore Egypt and Eastern Libya and wide off West Libya and Tunisia. The eastern margin of the Mediterranean is steep and marked by recent faulting and submarine canyons (Derin & Garfunkel, 1988) and by the Oligocene Dead Sea fault system and the Syrian Arc fold system of Northern Sinai. The latter extends offshore the continental slope, resulting in deep, broad NE-SW-trending anticlinal features (Chanliau & Bruneton, 1988, Yousef et al., 2010). In Tunisia, the Pelagian Platform extends offshore to about 120 km. The Algerian margin is about 5 to 10 km in average and is 20–30 km wide off Morocco.

The Pelagian Sea is occupied by the mostly submerged Pelagian Platform (Burollet, 1979), also known as the Sicilio-Tunisian Platform (Biju-Duval et al., 1974). The Pelagian Platform is limited to the north by the Sicily Channel and the Pelagian Islands and to the south by the Tripolitania Trough (Sabratah Basin). The Jarrafa Graben, which is located to the north of the Tripolitania Basin, is an asymmetric, NW-SE-trending trough, parallel to the other Pelagian channels. Its northern flank is a monocline formed by Miocene sediments dipping to the south which are overlain by a thick Pliocene-Quaternary sedimentary succession; its southern flank is made up of faulted Miocene and thin post-Miocene rocks (Bellaiche & Blanpied, 1979). The Malta Escarpment, an abrupt N-S-oriented submarine cliff with elevations of more than 1000 m (3281 ft), marks the limit between the Ionian Sea and the Pelagian Sea. The water depth in the Pelagian Sea varies from 0–400 m (0–1312 ft), although the NW-SE oriented grabens, such as the Pantellaria and Linosa channels which occur within the Sicily Channel may reach depths of more than 1300 m (4265 ft) and 1600 m (5250 ft), respectively (Winnock, 1979, 1981). These channels have been interpreted as rift basins delimited by dip-slip bounding faults, representing a short rifting episode during the Maghrebian folding and thrusting episode (Argnani & Torelli, 2001). The continental shelf area is delimited by the 200 m (656 ft) contour and it includes the Gulf of Hammamat, the Gulf of Gabes, and the Adventure, Malta, and Medina banks. The Pelagian Platform extends inland northwards into the Ragusa region in Southern Sicily and westwards into Tunisia and Northwest Libya. The Pelagian Platform represents the extension of the African Platform and it is probably underlain by a continental crust (Biju-Duval et al., 1974, Burollet, 1979, Bishop & Debono, 1996). It formed part of a subsiding passive margin since about the Late Early Triassic (Liassic) (Jongsma et al., 1985) and it was dominated by shallow-water Mesozoic and Cenozoic carbonate sediments. The northern part of the Pelagian Platform was affected by NE-SW-oriented horizontal Alpine movements and the southern part by vertical displacements associated with N-S, E-W and NW-SE-oriented old basement faults (Bellaiche & Blanpied, 1979). The Azizia-Tebaga Fault in NW Libya and Tunisia separates the African Shield from the Pelagian Block (Conant & Goudarzi, 1964). This fault was active as a large right-lateral shear during the Atlas compression phase, and probably represents a basement feature (Burollet, 1991).

2.2 ALBORAN SEA

The Alboran Sea (Fig. 2.2) is the westernmost portion of the Mediterranean Sea, lying between Spain on the north and Morocco and Algeria on the south. The Strait of Gibraltar, which lies at the west end of the Alboran Sea, connects the Mediterranean with the Atlantic Ocean. Its average depth is 445 m (1461 ft) and maximum depth is 1500 m (4920 ft). The Alboran Sea is limited on the west by the Strait of Gibraltar and on the East by a line passing through Capo de Gata in Spain. Mud diapirism and mud volcanism occur in the West Alboran Basin major sedimentary depocenters (Sautkin et al., 2003). The sedimentology and sequence stratigraphy of the West Alboran Basin have been the subject of various studies (Comas et al., 1992, 1999, Watts et al., 1993, Soto et al., 1996, Chalouan et al., 1997, Perez-Belzuz et al., 1997).

The Alboran Sea (Fig. 2.2) falls at the boundary of two lithospheric plates (Europe and Africa) and marks the limit between an oceanic domain on the west and a continental domain to the east (Hatzfeld & Frogneux, 1980).

A variety of models have been proposed to explain the synchronous extension and compression that occurred in the Alboran region and its surroundings during the Early Miocene despite the continued convergence of Africa and Iberia (Hatzfeld & Frogneux, 1980, Calvert et al., 2000). The Alboran Sea appears to be a complex of pull-apart

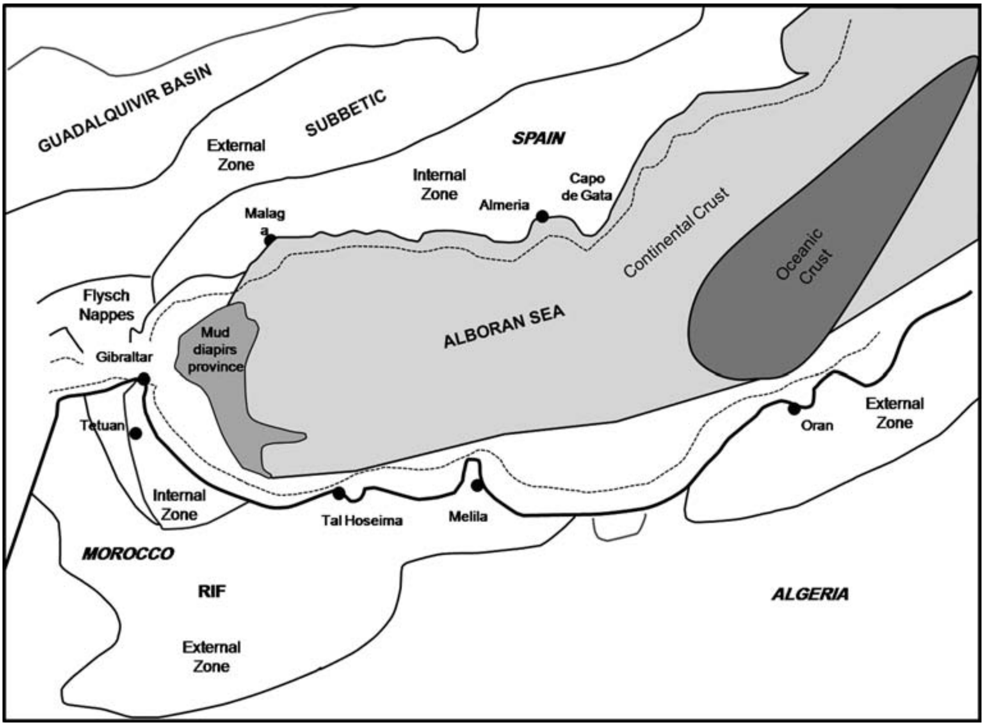

Figure 2.2 Alboran Sea (after Sautkin et al., 2003, Crusts are after Calvert et al., 2000).

basins that forms a zigzag relay between the Gulf of Cadiz and Algeria (Ammar et al., 2007). The present compressional deformation of the Northwestern African Mediterranean margin is dominated by strike-slip movements on the Algerian margin (Mauffret, 2007). North of Boumerdes-Zemmouri, the oceanic crust is deformed by south-dipping blind thrusts. Off Eastern Algeria and Tunisia, the deformation is more intense but limited to the north by the continental slope. After the attachment of the Kabylies to the Africa Plate around 18 Ma, the crust has been thinned and the Algerian Basin opened during the middle-late Miocene. From the late Miocene to the Present the margin has been thickened through transpression and uplifted (Mauffret, 2007).

The nature of the crust in the Mediterranean Basin is still debated. The crust is believed to be variously continental (Hirsch, 1984, Hirsch et al., 1995, Ricou et al., 1984), oceanic surrounded by a thinned granitic continental crust (Biju-Duval et al., 1974, Schuster, 1977, Le Pichon, 1988), or transitional (oceanized) between a typically continental (sialic) and a typically oceanic (simatic) crust (Menard, 1967, Smith & Woodcock, 1982). Bijou-Duval et al. (1974) suggested an oceanic crust underneath all of the Mediterranean. Smith & Woodcock (1982), based on seismic data, favored an oceanic or a transitional (i.e. oceanized) crust for the deeper parts of the Levant Basin. However, they speculated that the Levant Sea is either a remnant of the Neo-Tethys Ocean or a subsiding portion of a continental crust. Hirsch (1984) and Ricou et al. (1984) interpreted the Levant Sea as part of the Gondwana platform. Biju-Duval et al. (1974), Burollet (1979), and Bishop & Debono (1996) believe that the Pelagian block is underlain by a continental crust. Therefore, generalizations about the nature of the crust in the Mediterranean can not be made. It appears, however, that the crust is oceanic (or oceanized) in the center of the basin and continental around the periphery and in the Pelagian Sea. A Neogene oceanic crust occur beneath the majority of the Western Mediterranean, although most of the Alboran Sea is underlain by both Neogene oceanic and continental crusts (Calvert et al., 2000, Fig. 1.1).

The evolution of the Mediterranean Basin and the problems associated with the different interpretations have been reviewed by Biju-Duval et al. (1974), Smith & Woodcock (1982), and Robertson & Dixon (1984). There are disagreements on the times, number, and models of rifting in the Mediterranean. At least nine rifting episodes which took place during the period from the Late Permian to Maastrichtian have been suggested in the literature. During that time, the African and European plates were moving relative to each other, due to lateral shear stresses combined with the rotation of Africa. These processes were attributed to the opening of the Atlantic Ocean (Biju-Duval et al., 1974), which resulted in an equal number of rifting episodes in Atlantic and the Atlas Domain in NW Africa. The Southern, Central, and Northern Atlantic opened at different times. These movements and rifting phases interfered with one another to give a very complex history (Sengör et al., 1984). The history of the Northern Alpine tectonics (Mesozoic-Cenozoic) is even more complex.

Virtually nothing is known about the pre-Permian history of the Mediterranean Sea. However, the Mediterranean was a part of Gondwana during that time, and probably the Paleozoic epeiric seas which covered most of Gondwana also covered the Mediterranean. The Taconian, Caledonian, and Hercynian events must have had their effects on the area.

Gondwana was dominated during the Middle Carboniferous Hercynian (Variscan) Orogeny by a compressional regime caused by the collision between Africa and Eurasia on one hand and the subduction of the oceanic plate along the Paleo-Pacific on the other (Visser & Praekelt, 1996). This phase resulted in the formation of a number of uplifts on the northern edge of Gondwana, such as the Gargaf Arch, the Tibesti Arch (Goudarzi, 1980), the Sirte Arch, the Gharyan Dome (Burollet et al., 1971, Koehler, 1982) in Libya, strike-slip faulting and uplifting in the Meseta, Anti-Atlas, and Atlas Domains in Morocco (Michard et al., 1982, Saber et al., 2007), and the Helez Geanticline in Northern Sinai (Gvirtzman & Weissbrod, 1984, Weissbrod & Horowitz, 1989). Compressional regimes resulted also in the formation of mega-shear systems, such as the Falkland-East Africa-Tethys Shear (Visser & Praekelt, 1996). Renewed movements occurred along the Trans-Africa Lineament (Nagy et al., 1976) and the Pelusium Shear (Neev, 1977). Thick Carboniferous-Permian shallow-marine detrital and minor carbonate sediments were deposited in the Jifarah Basin in NW Libya north of the Azizia Fault (Koehler, 1982), the Permian Basin in Tunisia (Burollet et al., 1971, Bishop, 1975), Cyrenaica (El-Arnauti & Shelmani, 1988), and the Northern Western Desert (Keeley, 1989, 1994).

Late Permian-Middle Triassic dextral (clockwise) motion of Africa relative to Eurasia created a wedge-shaped westward-narrowing arm of the paleo-Tethys (Robertson & Dixon, 1984). This phase of rifting led to the collapse of paleohighs, subsidence, and widespread basin formation in North Africa, especially around the margins of the Tethys. The Pelagian block, Jifarah Plains, Cyrenaica Basin, Northern Egypt Basin and Northern Sinai probably subsided at that time and received thick sediments. The Pelagian Shelf was dominated by carbonates (Van Houten & Brown, 1977). Late Permian shallow-water carbonates were deposited in the southeastern part of the Eastern Mediterranean (Levant Sea) and in northern Sinai (Derin & Garfunkel, 1988, Druckman, 1974a & b, Bartov et al., 1980). Permian clastic deposition dominated in the southwestern Atlas Chain, Tebaga in Tunisia (Kilani-Mazrzoui et al., 1990, Toomey, 1991), the Tripolitania Basin, Jifarah Plains (Del Ben & Finetti, 1991), Northern Cyrenaica, Central Sinai, and the Gulf of Suez region. Carbonates with local reef development (Toomey, 1991, Rigo 1995, Rigby et al. 1979, Boote et al., 1998) and evaporites were deposited in the Gulf of Gabes and Tunisia, where halite forms domes and diapirs (Gill, 1965, Burollet, 1979, 1991, Bishop, 1988), and Algeria (Galeazzi et al., 2010, Bourquin et al., 2010). Middle Triassic sandstones were deposited in the Eastern Sirte Basin (Shelmani et al., 1992, Thusu, 1996, Thusu & Mansouri, 1998) contemporaneous with the collapse of the Kalanshiyo Arch. Polymictic conglomerates were formed along the coastal plains of the Levant Sea as a result of foundering of the Helez Geanticline (Druckman, 1984, Gvirtzman & Weissbrod, 1984, Weissbrod & Horowitz, 1989). In the northern Ghadames Basin, polymictic conglomerates were associated with the collapse of the Gharyan Dome and movements along the Azizia Fault (Mokaddem, 1995).

The fate of the Paleo-Tethys Ocean[1] and the exact timing of the opening of the Neo-Tethys are not known. It has been suggested that the Paleo-Tethys was destroyed before the opening of the Neo-Tethys in the Late Triassic. Its demise was the result of the convergence of the African and European plates toward each other and the northward subduction of the oceanic plate (Dewey et al., 1973, Smith & Woodcock, 1982). Sengör et al. (1984) and Robertson & Dixon (1984) argued that the disappearance of the Paleo-Tethys was coeval with the propagation of the Neo-Tethys. According to their model, the Neo-Tethys started to form in the Middle Triassic, but the closure of the Paleo-Tethys was not complete until the Late Triassic. The present Mediterranean basins are believed, in either case, to be relics of the Mesozoic and Cenozoic Neo-Tethys basins.

The northern margin of the Tethys Ocean, now located in Turkey, is demarcated by a series of ophiolitic belts. Arguments exist about their origin, time of emplacement, and whether they belong to one oceanic basin or to a number of basins (Spray et al., 1984, Knipper et al., 1986, Robertson, 1994). These ophiolites have a complex history and most of them probably resulted from multi-step development (Knipper et al., 1986). Ophiolites in the northern Mediterranean probably represent ancient oceanic crust of the paleo-Tethys and neo-Tethys oceans formed during Triassic-Cretaceous rifting phases (Biju-Duval et al., 1974). All these ophiolitic massifs were thrust over the continental margin at the end of Cretaceous (Whitechurch et al., 1984). Spray et al. (1984) and Knipper et al. (1986) suggested that the ophiolites were generated at a spreading centre in the Middle Jurassic, and were thrust onto the Arabo-African continental margin during the Upper Jurassic-Early Cretaceous. Robertson (1994) suggested that the Eastern Mediterranean ophiolites were formed in

1 Ruban (2007) argued that since the "Tethys" was made up of several oceans, there was no unique ocean which might have been called "Tethys Ocean".

a supra-subduction zone setting during the Maastrichtian, because of the continuing narrowing of the Neo-Tethys.

A renewed rifting phase took place during the Late Triassic-Early Jurassic. Opening of the Central Atlantic Ocean by Middle Triassic time led to a left-lateral (sinistral) motion of Eurasia relative to Africa (Robertson & Dixon, 1984, Zülke et al., 2004). Rifting led to the formation of the Essaouira, Tarfaya, Agadir, Haha, Doukkala, Souss, and Aaiun basins in Morocco (Medina, 1995, Le Roy et al., 1998, Le Roy & Piqué, 2001, Hafid et al., 2008, Zühlke et al., 2004, Davison & Daily, 2010). A shallow-water carbonate platform was formed in the Pelagian Sea (Bosellini & Hsü, 1973). This platform was dominated by dolomites and oolitic limestones (Bishop, 1988, Bishop & Debono, 1996). The platform was separated from the North African continental facies belt by the Tripolitania and Jarrafa basins. These two basins subsided thermally (Benniran et al, 1988) and received thick carbonate, marl, and shale deposits. Volcanics were encountered in boreholes in the offshore of Libya, such as in the A1-NC35a well (Winnock, 1981, Jongsma et al., 1985, Bishop & Debono, 1996) and point to extensional tectonics. Extensional features consist mainly of tilted basement blocks, covered by Jurassic and Cretaceous sediments (Burollet, 1991). Salt swells and diapirs are common in the Guercif Basin in Morocco (Bernini et al., 1999), the Atlantic margin of Morocco (Lancelot & Winterer, 1980, Hinz et al., 1982, Holik & Rabinowitz, 1992), the Tripolitania Basin offshore Libya (Bishop & Debono, 1996) and Tunisia (Bishop, 1988) due to sediment loading. Diapirs pierce the Mesozoic and Cenozoic successions, often forming long subsurface salt walls (Burollet, 1991). These salts are the extension of the evaporite deposits of inland NW Libya and Tunisia. The development of horsts and grabens, the formation of sea channels, crustal thinning, and magmatism dominated in the Ionian Sea and the Sirte Rise (Del Ben & Finetti, 1991). Another shallow-water carbonate shelf composed of high-energy sediments and fringing reefs was formed in the Levant Sea; they grade inland into low-energy carbonate muds and dolomites (Derin & Garfunkel, 1988) and then into continental deposits.

The Middle-Upper Jurassic time appears to have been a quiet period in North Africa. Pelagic nodular limestones, fossiliferous limestones and dolomites with salt diapirs are common in these sediments on the eastern platform of Tunisia and Algeria (Bishop & Debono, 1996). Shallow-marine carbonates and clastics were deposited in the northern Western Desert, and Northern and Central Sinai.

During the Late Jurassic-Early Cretaceous time, activity of intra-plate hotspots caused extensive magmatism, uplift, and erosion in the offshore of the Mediterranean Sea, the Sirte Basin, and NW Africa (Westphal et al., 1979, Van Houten, 1983, Garfunkel & Derin, 1984, Derin & Garfunkel, 1988, Garfunkel, 1991, Wilson & Guiraud, 1998, Guiraud et al., 2005). The South Atlantic opened during the Early Cretaceous (Neocomian-early Aptian), accompanied by anti-clockwise rotation of Africa (Maurin & Guiraud, 1990, Guiraud & Maurin, 1991, 1992, 1993). These events led to the formation of thick continental clastics of the so-called Nubian Sandstone. Basalts and breccias are commonly associated with these deposits in the Pelagian Platform (Jongsma et al., 1985, Bishop & Debono, 1996), the Sirte Basin (Massa & Delort, 1984, Tawadros et al., 2001), and the Northern Egypt Basin (Keeley, 1994). The Atlas Mountains in Morocco and Algeria were dominated by the deposition of continental redbeds with dinosaur bones and tracks (Mekahli et al, 2004, Charrière et al., 2005).

This phase was followed by a period of faulting and magmatic activities associated with extension and rifting (Del Ben & Finetti, 1991, Mattoussi Kort et al., 2009) during the Late Cretaceous. Eastern Tunisia onshore and offshore display crustal thinning induced from the Tethyan rifting, which affected the subsequent evolution of the North African passive margin during the Late Cretaceous and the creation of the fold-thrust belt and associated foreland deformations. The thinned crust led to the rise of basalt magma and hydrothermal fluids (Mattoussi Kort et al., 2009). A combination of subsidence and sea-level rise led to a new phase of carbonate deposition (Le Pichon, 1988). In Malta (Pedley et al., 1976) and in the offshore of Libya (for example in the Tama-1 well) (Bishop & Debono, 1996), these carbonates are made up of shallow-water high-energy limestones and dolomites. The shallow-water carbonates around the flanks of the Tripolitania Basin change facies into deep-water limestones and shales in the centre of the basin (Bishop, 1988, Bishop & Debono, 1996, Benniran et al., 1988). Early Aptian to Maastrichtian shallow-water carbonates containing zones of rudistid reefs were deposited in SE Tunisia and extended offshore onto the Pelagian Platform, such as in the A1-NC35a well (Jongsma et al., 1985). These rudistid build-ups form hydrocarbon reservoirs in the Isis Field (34°37′N, 12°41′E) (Bishop & Debono, 1996). Late Cretaceous carbonates on the Cyrenaica Platform, the Northern Western Desert, and Northern Sinai, change facies seaward into deep-water shales Bauer et al., 2001, 2002, 2003, 2004).

Communication between the Mediterranean and the South Atlantic took place intermittently during Late Cretaceous time (Reyment, 1966, 1971, 1981, Reyment & Reyment, 1980, Collignon & Lefranc, 1974, Kogbe, 1980). The Cenomanian-Turonian interval reflects poorly oxygenated condition in the Tethys (Oceanic Anoxic Event "OAE") (Schlanger & Jenkyns, 1976, Kuhnt et al., 2004, Kolonic et al., 2005, Keller et al., 2009, Sepúlveda et al., 2009), which resulted in the deposition of dark-colored marly limestones proven to be a source rock for hydrocarbons (Bishop, 1988, Kolonic et al., 2002, Lüning et al., 2004a, b). This phase was terminated by Senonian and later deformation related to plate collision and the Alpine Orogeny (Derin & Garfunkel, 1988, Le Pichon, 1988). Basin inversion during the Santonian compression phase resulted in the formation of a number of anticlinal structures, such as the Atlas Chain (Beauchamp et al., 1996, 1997), the Al Jabal Al Akhdar in Northern Cyrenaica and Esh el Mellaha in the Gulf of Suez Region (Bosworth et al., 1999). These anticlinal structures with faulted northern flanks (Conant & Goudarzi, 1967, Röhlich, 1974, 1980) continue into the Mediterranean offshore area, where a deep trough with more than 5000 m (16,405 ft) of sediments is present (Biju-Duval et al., 1974).

The uppermost Cretaceous-Early Tertiary compressional tectonics were associated with the middle Alpine (Laramide) Orogeny. This compressional regime led to dextral movements in the Mediterranean and the northward subduction of the Tethys oceanic crust, and eventually to the closing of the Mediterranean (Biju-Duval et al., 1974). The Cyprus Arc and the Mediterranean Ridge mark the convergence between the Eurasian and African plates. They divide the Eastern Mediterranean into a thrust-belt with Cenozoic sedimentary basins to the north, and a passive and subsiding African continental margin with Mesozoic sediments to the south (Le Pichon, 1988). Important tectonic movements took place in the Sirte Rise and the Pelagian Platform during that time (Schuster, 1977). These stresses caused uplifting accompanied by northward tilting of North Africa. The sea transgressed southward and

Maastrichtian chalks covered most of North Africa. Maastrichtian sediments were deposited unconformably on older rocks in platform areas in the Sirte Rise, the Sirte Basin, and Egypt, which remained high areas during most of the Late Cretaceous (Del Ben & Finetti, 1991). In the Ragusa Platform in southern Sicily, Maastrichtian limestones overlie a volcanic formation dated at around 71 Ma (van den Berg & Zijderveld, 1982). Maastrichtian volcanics are also present in the B1-NC35a well offshore Libya (Jongsma et al., 1985).

Uplift during the Uppermost Maastrichtian-Early Tertiary resulted in the development of a regional unconformity at the Cretaceous-Tertiary boundary (Keller, 1988, Keller et al., 1995, Adatte et al., 2002, Bensalem, 2002, Gardin, 2002, Karoui-Yaakob et al., 2002). In the offshore well B1-NC35a, Early Maastrichtian shallow-water algal limestones with *Orbitoides* are overlain by pelagic Danian sediments with karst fill (Jongsma et al., 1985). Karstification on top of similar Maastrichtian carbonates was also reported from the subsurface of the Sirte Basin (Jones, 1996), and attests to an unconformity at the K/T boundary. In Northern Sinai, Maastrichtian chalks are separated from the Paleocene shales by paleosoil horizons (Hirsch, 1984).

The Tertiary and Quaternary tectonics in the Pelagian Sea acted along WNW-ESE and ENE-WSW axes (Blanpied & Bellaiche, 1983). Subduction (and/or thrusting) of the Tethys oceanic crust in the Northern Mediterranean continued during the Tertiary. In the meantime, reactivation of ancient faults and subsidence in the southern Mediterranean and North Africa took place due to extensional stresses. Subsidence led to the deposition of Tertiary carbonates on the platform areas and thick shale sections in the troughs (Fournié, 1978, Bishop, 1988, Bishop & Debono, 1996, Schuster, 1977). Nummulitic banks developed in the Pelagian Platform during the Early Eocene, especially in Egypt, Libya and Tunisia, and form reservoirs in the Ashtart Field in the Gulf of Gabes, at the Sidi El Itayem Field in the Sfax area, Eastern Tunisia, and the Bouri Field offshore Libya (Bishop, 1988, Ben Ferjani et al., 1990, Bernasconi et al., 1991, Loucks et al., 1998a & b). Deep-marine sediments persisted in the Tripolitania Basin (Jongsma et al., 1985, Benniran et al., 1988).

The Late Oligocene was also dominated by the deposition of carbonates on the Pelagian Platform. Coralline carbonates crop out in Malta (Pedley et al., 1976) and locally in NW Libya (Hladil et al., 1991). However, over most of Libya and Egypt Oligocene deposits are dominated by continental and fluvio-marine clastics. Tectonic movements accompanied by a global relative drop in sea level (Vail et al., 1977, Haq et al., 1987) led to a hiatus during the Oligocene. This hiatus was detected in the A1-NC35a well offshore Libya (Jongsma et al., 1985) and Egypt (Dolson et al., 2005, Kuss & Boukhary, 2008, Boukhary et al., 2008). The Dead Sea faults which delimit the southeastern Mediterranean (Druckman, 1974) were formed. In the Atlas System, the widely recognized angular unconformity between the Oligocene and older sediments coincides with the Atlas Orogeny. This unconformity pre-dates the emplacement of the Tell units. This unconformity is observed in the Tell below the M'sila Basin (Bracène & Frizon de Lamotte, 2002), but is absent in the Tell nappes where the passage from Upper Eocene to Oligocene is transitional (Benaouali-Mebarek et al., 2006). Late Tertiary clastics were shed from the Tellian Atlas in Northern Tunisia (Benniran et al., 1988, Bédir et al., 1991).

The Pelagian Shelf was a subsiding stable area during most of the Miocene with less than 200 m (656 ft) of Miocene sediments (Winnock, 1981). Miocene shallow-water carbonates crop out on the surface in the islands of Malta and Gozo (Pedley et al., 1976), the Ragusa region in Southern Sicily, as well as the Island of Lampedusa (west of Malta) (Burollet, 1979). Early Miocene carbonates consist of deep-water *Globigerina* limestones, which contain shallow-water fauna and phosphatic material. This mixing of deep and shallow-water faunas was a result of slumping (Pedley et al., 1976), probably caused by movements on the Malta Escarpment. Movements along the Malta Escarpment also caused gravity sliding and the displacement of allochthonous masses during the Miocene (Schuster, 1977). This sliding led to the formation of submarine topographic features, such as the Mediterranean Ridge and the Messina Cone in the northern Ionian Sea. These gravity flow deposits are also known on land in Italy and Sicily (Biju-Duval et al., 1974), where they overlie a thick Mesozoic-Cenozoic sedimentary succession. The Cenozoic sediments extend southward toward the Gulf of Sirte, but no allochthonous masses are present.

Locally on the southern edge of the Jarrafa Trough reefs were developed during the Late Miocene (Blanpied & Bellaiche, 1983). The formation of the deep-sea channels in the Pelagian Sea is related to extensional tectonics during the Miocene and post-Miocene times (Burollet, 1979, 1991). Rifting was due to basement extension associated with shear faults, which border these channels (Burollet, 1991).

During the Messinian, the isolation of the Mediterranean and the fall of sea level led to desiccation of the Mediterranean Sea (Ryan et al., 1973, Ryan, 1978, Hsü, 1972a & b, Hsü, 1977, Hsü et al., 1973). This drying-up period resulted in the deposition of evaporites, which include salts of more than 2,000 m (6562 ft) in thickness in some areas (Le Pichon, 1988). Discovery of these anhydrites during the DSDP (Ryan et al., 1973) triggered controversies around what is known as "the Messinian Salinity Crisis". Many attempts have been made to explain the origin of these enigmatic evaporites encountered in such a deep basin like the Mediterranean Sea (e.g. Ryan et al., 1973, Cita, 1982, Sonnenfeld, 1975, Fabricius, 1984, Roveri & Manzi, 2006, Roveri et al., 2006). The origin of evaporites in the Gulf of Suez and the Red Sea Basin is also controversial, but the connection between the processes which led to the formation of these evaporites in the two areas is rarely made. A comparative study of the two evaporitic basins may prove to be helpful in solving some of the problems.

The Messinian sediments encountered in all the wells in the Pelagian Sea contain more than 10 m (33 ft) of anhydrite (Jongsma et al., 1985), and they are overlain unconformably by open-marine Pliocene sediments. On seismic sections, the Pliocene-Quaternary sediments have low velocities and the Miocene evaporites have high velocities (Winnock & Bea, 1979). For this reason, the top of the Messinian represents a good seismic marker, known as the "M" reflector (Ryan et al., 1973). Over large areas on the Pelagian Platform, the "M" reflector is absent and the Pliocene-Quaternary sediments are reduced in thickness (Jongsma et al., 1985). Erosional channels are observed in the "M" reflector on the southern flank of the Pelagian Platform. Erosional effects of a river system at the same level in the Tripolitania and Jarrafa troughs are also believed to have taken place at the end of the Messinian. The "M" reflector in many places in the Levant Sea marks the top of the evaporites, but where the evaporites are absent; it denotes an erosional unconformity (Ben Avraham & Mart, 1981).

Major post-Miocene tectonics are reflected in the topography of the "M" reflector in the Central Mediterranean. An extensional phase at the end of the Miocene was followed by a compressive phase at the end of the Pliocene, followed by another extensional phase in the Quaternary (Bellaiche & Blanpied, 1979). E-W dextral wrenching took place in the Ionian Sea (Jongsma et al., 1985). Dense block faulting affected the Pelagian Platform (Burollet, 1979, 1991, Winnock, 1981). This faulting was accompanied by basic volcanism, which resulted in the formation of the Pantellaria and Linosa islands. More than 1000 m (3281 ft) of Pliocene-Quaternary sediments accumulated in the Tripolitania Basin. These sediments are probably the result of continental or shallow-marine deposition (Winnock & Bea, 1979).

The Western Mediterranean (Alboran Sea) was a land area in early Tertiary times and was subject to strong volcanic and seismic activities. The area was dominated by convergence and compression during the Alpine/Atlas Orogeny, which lead to the formation of the Atlas Mountains and Rif domains. The Western Mediterranean basins, such as the Alboran, Balearic and Tyrrhenian basins were formed during the Neogene. Their origin was attributed to vertical foundering (Laubscher & Bernoulli, 1977) associated with rifting (Hsü, 1972). The Maghrebian Cenozoic Orogenic Domain consists of two different systems (Benaouali-Mebarek et al., 2006): The Tell-Rif or Maghrebides and the Atlas, extending from Morocco to Algeria and Tunisia as a result of the closure of an oceanic domain (Fig. 2.1).

Communication between the Mediterranean and Red Seas took place during the Lower and Middle Miocene (Hughes et al., 1992), and ceased in the Pliocene as a result of the uplifting of Sinai.

The ancestral Nile Delta has been active since the Oligocene and migrated eastward during the Miocene, but deltaic sediments of the present-day delta were deposited only from the latest Miocene time onward (Said, 1981, Harms & Wray, 1990). The Middle Oligocene and earliest Miocene were times of low sea level and erosion in the Nile Delta region. This phase led to the development of an extensive erosional unconformity (6 Ma hiatus) in the south of the delta. Marine transgression took place southward only in Burdigalian. The platform margin trends E-W and is located in the Central Nile Delta (Harms & Wray, 1990). Another hiatus occurred during the early Middle Miocene (Serravallian-Tortonian), followed by subsidence during the late Tortonian and early Messinian, especially in the Eastern delta.

The present-day Nile Delta extends for a long distance offshore Egypt in the form of an asymmetric cone, known as the Nile Cone (Biju-Duval et al., 1974) (Fig. 2.1). Recent sediments are relatively thin in the east (Damietta Fan) and pinch out in the north on the Erathostheus Plateau. A thick Pliocene-Pleistocene deltaic wedge was deposited when sea level was restored to near-present level (Harms & Wray, 1988). These sediments thicken to more than 2000 m (6560 ft) to the west in the Rosetta Fan and gradually thin northward on the Mediterranean Ridge (Biju-Duval et al., 1974). Large folds, developed between the Rosetta Fan and the Mediterranean Ridge, are probably due to Messinian salts. On the Mediterranean Ridge, Messinian evaporites are overlain by Pliocene-Quaternary pelagic marls, clays, silts, and sandstones interbedded with volcanic ash (Ryan et al., 1973, Biju-Duval et al., 1974). Major gas discoveries have been made in the Nile Delta (Abu El -Ella, 1990, Abdel Aal et al., 2000, Samuel et al., 2003, Sharp & Samuel, 2004), the offshore deep marine slope channels of the Nile Delta, such as the Abu Qir, Sequia, King, Max, Scarab, Saffron, Sapphire, Serpent, and Simian in the Western Delta (Sharaf, 2003, Samuel et al., 2003, Sharp & Samuel, 2004, Whaley, 2008) and the Ha'py, Denise, Temsah, Karous, and Darfeel fields offshore the Eastern Nile Delta (Heppard & Albertin, 1998, Barsoum et al., 1998, Abdel Aal et al., 2000, Sharaf, 2003).

The Pliocene-Quaternary succession, between 1000–2000 m (3281–6562 ft) in thickness in the SE Mediterranean is predominantly detrital and is composed of marls, shales, and sandstones. Its major source is the sediments of the Nile (Mart & Ben Gai, 1982). This succession forms a sedimentary prism along the continental margin of the SE Mediterranean. It overlies a thick Miocene succession between 1000–1500 m (3281–4922 ft) in thickness (Biju-Duval et al., 1974). Diapirs are common (Ben Avraham & Mart, 1981) as a result of loading of the evaporitic sequence.

2.3 NILE BASIN

The Nile Basin (Fig. 2.3) corresponds to the "Stable Shelf" of Said (1962a) and partly to the Nile Basin of Kostandi (1963) and the Assiut Basin of Klitzsch et al. (1979), Hendriks et al. (1990), and Hermina (1990). It covers the southeastern part of Egypt and Southern Sinai. It is bordered in the east and south by the Precambrian basement complex. In the west and north, it is bounded by the Northern Egypt Basin. The Nile Valley runs in a N-S direction in the middle of the basin. The basin-fill is dominated by Cambrian to Eocene continental and shallow marine sediments up to 4000 m (13,124 ft) in thickness, and is composed of sandstones, shales, marls, and limestones. Tectonic elements consist mainly of folds and mild flexures bounded by faults. The boundary between the Nile Basin and the Northern Egypt Basin is marked by NE-SW-trending domal structures, such as the Abu Roash, Bahariya, and Kharga uplifts, and multi-directional faulting. This boundary corresponds to the Trans-Africa Lineament (Nagy et al., 1976) and the Pelusium Shear (Neev, 1977). This major NE-SW lineament is associated with the conjugate NW-SE Tibesti Lineament (Guiraud et al., 2000), which extends from Southwestern Algeria to Kenya with a possible Proterozoic origin. The Nile Basin is divided into a number of sub-basins separated by arches. A number of small basins have been also identified in the present work. These basins are designated informally as the Esna Basin with thick Cretaceous sediments, the Mut Basin with a thick Danian shale section, and the Farafra Basin with a thick Landenian shale section. However, the limits and extent of these elements are not clear. Oil and gas discoveries were made in the Beni Suef and Kom Ombo basins (Dolson et al., 2002), located at the northern and southern edges of the basin as delineated by Tawadros (2001).

2.4 NORTHERN EGYPT BASIN

This is a marginal basin, which represents a transitional zone between the North African and the Mediterranean Basin. It corresponds to the "Unstable Shelf" of Said (1962a), which covers most of the northwestern part of Egypt, the Nile Delta, and Northern Sinai (Fig. 2.3). It includes major basins and uplifts, such as the Ghazalat, Tenehue, Qattara, Abu Gharadig, Alamein, Rissu, Shushan, and Fayium (Gindi) basins. Northern Sinai consists of several basins and highs trending NE-SW. It represents the second largest hydrocarbon province in Egypt. Active exploration since the late 1960s lead to the discovery of numerous oil, gas, and condensate fields in the area.

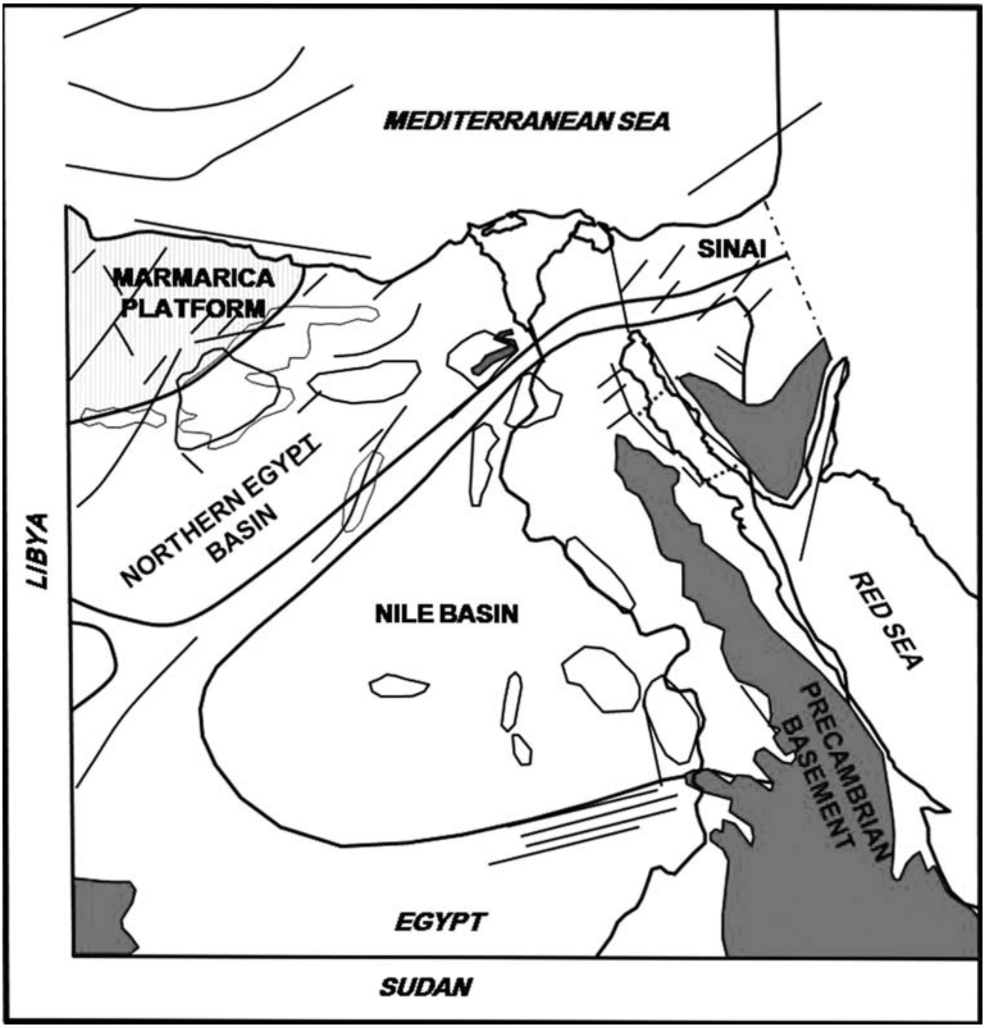

Figure 2.3 Tectonic map of Egypt.

The onshore of central Sinai, includes the South Yelleg, North Fallig, East Maghara, North Maghara, and NE Sinai basins. The offshore Sinai includes the Walker-Port Fouad, Sadot, Tineh, and Mango basins. Oil and gas were discovered in the Tineh, Port Fouad, Abu Zakin, Walker, South Rafah, and Mango fields (Alsharhan & Salah, 1996). The Northern Egypt Basin is floored by Pan-African basement rocks. The sedimentary section is approximately 183 m (600 ft) in the south and increases to more than 7620 m (25,000 ft) in the coastal areas in the north. The succession is made up of sandstones, shales, and carbonates ranging in age from Cambrian to Tertiary. The northern margin of the Paleozoic Ghazalat Basin is formed by the Umbaraka ridge striking E-NE. The eastern and western boundaries are determined by N-S syn-depositional faults associated with basic intrusives. It is bordered on the west by a regional basement ridge and on the south by the NE-striking Siwa High.

The Northern Egypt Basin and the Sirte Basin in Libya form a triangular area bordered on the southeast by the Tibesti-Kalanshiyo-Bahariya Arch, on the southwest by the Ben Ghanimah-Brak and Gharyan uplifts, and on the northern side by the Jifarah-Cyrenaica-Matruh strike-slip faults (Fig. 2.1). The Egyptian part of the triangle is dominated by NE-SW trending folds and E-W and NE-trending faults, while in Libya it is dominated by NW-SE faults. The Tibesti-Kalanshiyo-Bahariya Arch coincides with the western boundary of the "Trans-Africa Lineament" of Nagy et al. (1976) and its northern extension, the Pelusium Shear of Neev (1977). These lineaments represent a Pan-African zone of crustal weakness within the African-Nubian Shield. This lineament probably acted as a path for the migration of a hotspot (the Darfur hotspot) between the Late Jurassic-Aptian in the Levant and the Late Oligocene-Early Miocene in northwestern Sudan (Garfunkel, 1991). This lineament includes the Bahariya Fault, which may extend southwestwards into the Farafra Oasis, and an inferred fault east of the El Guss Abu Said section. According to Said (1962a) folding in the Bahariya Oasis took place in post-Cenomanian time. Both the southeastern and southwestern borders of the triangle are characterized by Tertiary volcanic activities. The Levant is underlain by a NNE-SSW-trending extensional margin of Late Triassic-Early Jurassic age. The Eastern Mediterranean Basin initially developed as a left-lateral ocean-continent transform boundary separating oceanic crust of the Southern Tethys from the mildly-extended continental crust of Northern Egypt (Longacre et al., 2007).

The Northern Egypt Basin was active throughout the Phanerozoic and connected to the sea in the north. Deposition ended in the Ghazalat Basin during the Strunian (Keeley, 1989) and started at that time in the Tenehue Basin and continued until the Early Permian. The Mesozoic passive margin in the Western Desert region is developed above a broad NW-trending basement arch of Late Carboniferous age (Aadland & Schamel, 1988).

The Abu Gharadig and Fayium (Gindi) basins are separated structurally by the Kattaniya Ridge (Abdallah & Moustafa, 1988). Both basins are bounded on the north by another major ridge associated with Cretaceous and Tertiary faulting. A major platform with a thin sedimentary cover forms the southern margin (Awad, 1984). The Abu Gharadig Basin is an E-W trending structurally-controlled basin developed as a result of deep crustal extensional tectonics that affected northern Egypt during the Mesozoic (Bayoumi & Lotfy, 1989). The stratigraphic sequence includes Early Paleozoic sediments overlain by Mesozoic and Tertiary deposits with more than 2000 m (6562 ft) of fluvio-marine, shallow marine, and deep marine Upper Cretaceous sediments. The basin was initiated in response to the left-lateral motion of Africa relative to Europe during the Late Jurassic, which reached its acme in the Upper Cretaceous, and led to the opening of the Tethys. This phase resulted in the formation of the two E-W listric faults that bound the basin on the northern and southern sides. The development of the basin halted as a result of the dextral shear movement of Africa that led to the closing of the Tethys and basin inversion during the Santonian (Keeley, 1994, Guiraud, 1998, Guiraud & Bosworth, 1997, Bosworth et al., 1999, Guiraud et al., 2005). The basin was uplifted and tilted northward as a result of the NW-SE compressive stresses during the Uppermost Cretaceous-Early Tertiary Laramide Orogeny. Oil has been discovered recently by Apache Oil in the North Qarun Field in the Gindi Basin from the Lower Cretaceous Kharita and Cenomanian Baharia sandstones. The oil pools in the field are associated with two sets of faults, trending NW-SE and NE-SW (Oil & Gas Journal, 1996a). The four Mesozoic subbasins, Shushan, Alamein, Abu Gharadig, and Gindi, contain up to 300 mmbbls of proven reserves.

2.5 GULF OF SUEZ & RED SEA

The Red Sea region (Fig. 2.4) was a stable craton from Early Paleozoic to Late Eocene (Plaziat et al., 1990). Compressive strike-slip faulting was initiated during the Oligocene.

The Gulf of Suez is an elongated NW-SE-trending trough, extending over 320 km in length, and bounded by the Pan-African basement on both sides. The Gulf of Suez is divided into three provinces (Moustafa, 1976): A Northern Province, a Central Province, and a Southern Province. These zones are separated by transform faults or "hinge zones" (accommodation zones of Bosworth & McClay, 2001 and Younes & McClay, 2002) and are characterized by a change in the general structural dip. They can be studied in outcrops in the Gebel Gharamul area (Coffield & Schamel, 1989). The Northern and Southern provinces dip to the southwest, whereas the Central province dips to the northeast. The Northern and Central Provinces are separated by the Zaafarana Hinge Zone. The Morgan Hinge/Accommodation Zone (Younes & McClay, 2002) separates the Central Province from the Southern Province. The three provinces are termed the Ataqa, Gharib, and Zeit Zones, respectively. A third zone in the Northern Red Sea, the Duwi Accommodation Zone, has been described by Younes & McClay, 2002). The surface expression of the accommodation zones, as in the Gebel Gharamul region, is dominated by a basement promontory, where a southwest-dipping half-graben and a northeast half-graben intersect (Coffield & Schamel, 1989). The draping over of the pre-rift and synrift successions over these fault blocks results in an inhomogeneous stratigraphic succession within the accommodation zones. The structure of the Gulf of Suez area is governed by normal faults and tilted blocks whose crests constitute the main target for hydrocarbon exploration. The fault pattern consists of two major sets of trends (Colleta et al., 1988); longitudinal faults parallel to the rift axis, created in an extensional regime during Neogene time, and transverse faults with N-S to NE-SW dominant trend, which are inherited passive discontinuities in the Precambrian basement. The Precambrian basement displays a system of regional deep-seated, left-lateral, NW-oriented faults and shear zones (Younes & McClay, 2002). One of these is the Najd Shear Zone, which extends for a distance of 1200 km in a NW-SE direction from Saudi Arabia to the Central Eastern Desert of Egypt (Sultan et al., 1988). The Zaafarana Accommodation Zone separates the SW-dipping Darag half-graben in the north from the NE-dipping October graben to the south. When the rift faults transect the pre-existing Precambrian shear zone, the polarity (or dip direction of fault blocks) changes (Younes & McClay, 2002). The Suez vertical rift movements were explained by two hypotheses: a) the advection of a hot mantle away from the center of the rift combined with regional stretching of the lithosphere (Chenet et al., 1987). This advection was responsible for the uplift of the rift shoulders. At present, the Lower Miocene coarse clastics near the border faults of the rift are 300 m (984 ft) above sea level. b) Large doming with erosion before

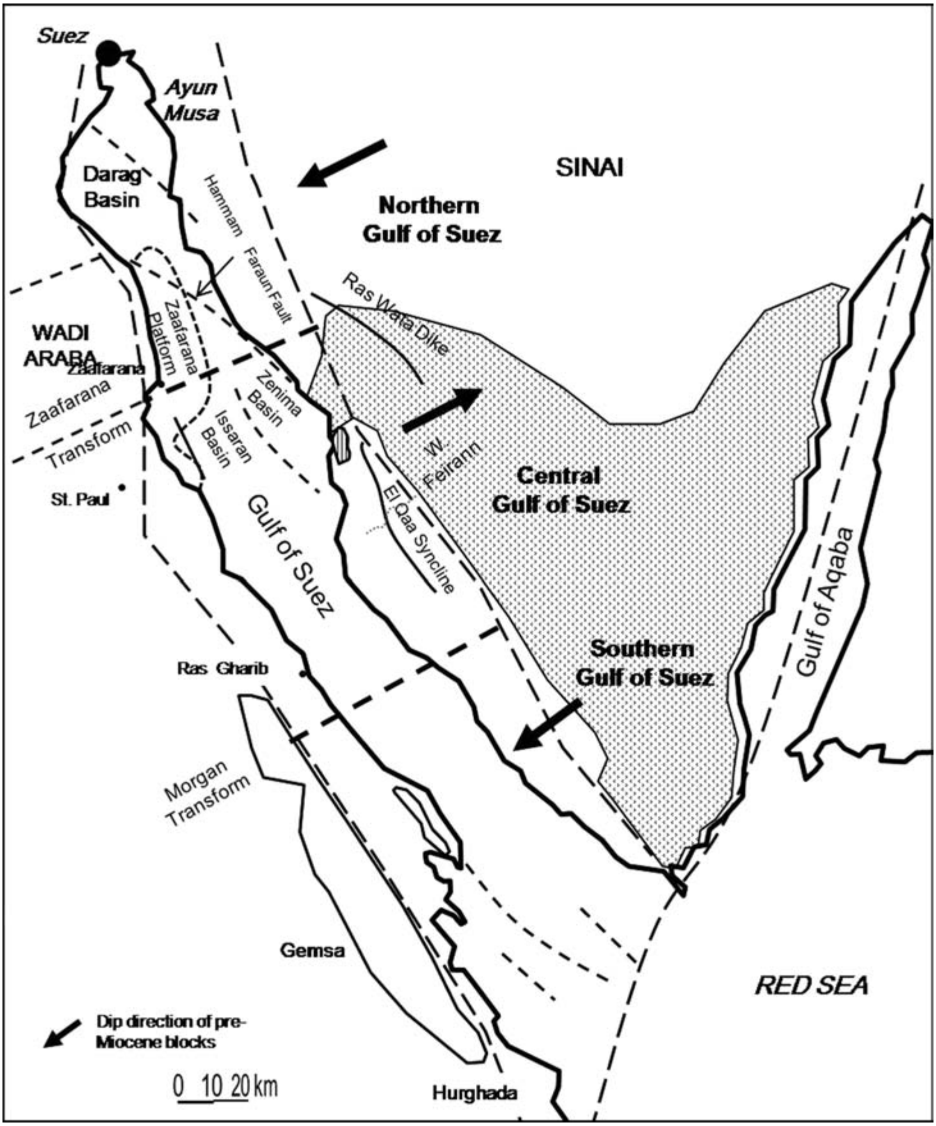

Figure 2.4 Gulf of Suez structure.

the rift. However, the presence of the Eocene deposits in the center of the Gulf rules out this hypothesis (Chenet et al., 1987).

The stratigraphic section of the southern part of the Gulf of Suez (Fig. 2.5) consists of pre-rift, proto-rift, syn-rift, and post-rift sequences bounded by unconformities (Garfunkel & Bartov, 1977, Orszag-Sperber et al., 1990, Schütz, 1994). The pre-rift sequence unconformably overlies the Precambrian basement. It is approximately

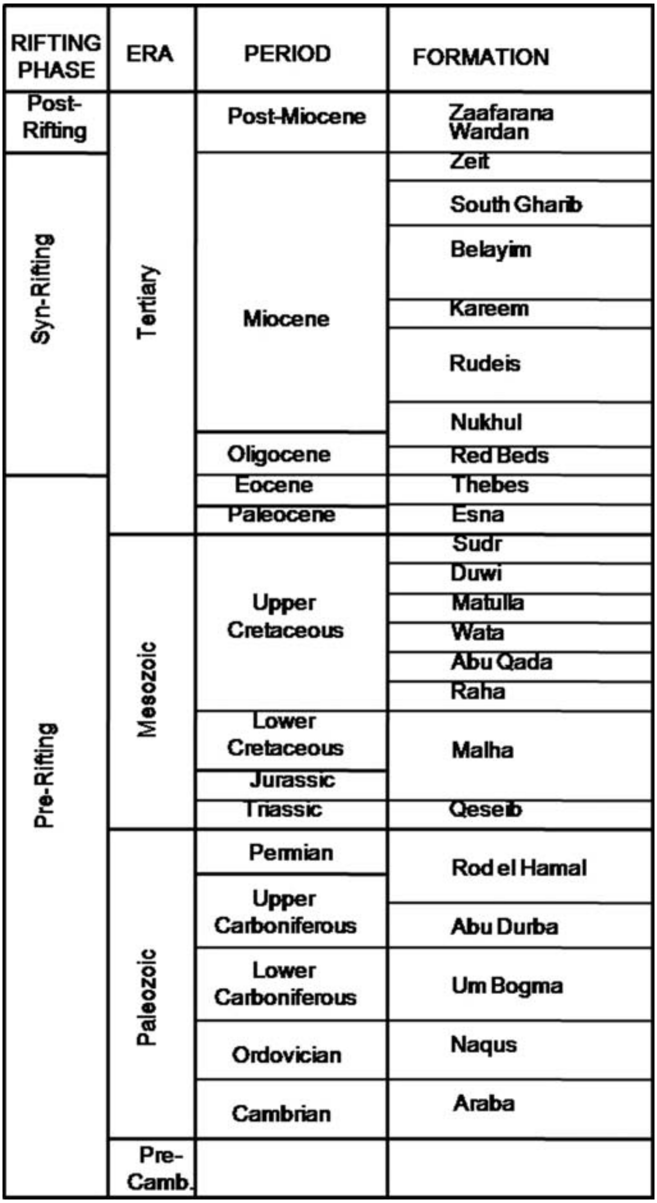

Figure 2.5 Stratigraphic column of the Gulf of Suez.

914 m (3000 ft) in thickness. The sequence consists of Early Cretaceous non-marine, well sorted, arkosic and kaolinitic sandstones, 152–488 m (1500–1600 ft) thick, Turonian-Late Senonian marine deposits, approximately 229 m (750 ft) thick made up of limestones, shales, and sandstones, and Maastrichtian chalks. These rocks

are overlain unconformably by Paleocene calcareous marine shales and Ypresian cherty limestones. The facies constitute a platform opening northwards to the Tethys (Orszag-Sperber et al., 1990). The pre-rift sequence is separated from the Proto-rift sediments by an angular unconformity. The proto-rift sediments are of Late Oligocene-Early Miocene age, and they are localized within the earliest grabens. The syn-rift sequence is variable in thickness and reaches up to 3657 m (12,000 ft) in low areas. It is composed of Lower-Middle Miocene open-marine clastics and Middle to Upper Miocene evaporites. The sedimentary sequence is cyclic, reflecting episodic uplift, erosion, and gradual in-filling of the basin. Fine-grained clastics are dominant in the deeper troughs, shallow marine reefal carbonates on the crests and submarine highs, and sands in the marginal seas (Hughes et al., 1992). The Lower Miocene Gharandal Group, which includes the Abu Zneima, Nukhul, and Rudeis formations represent the syn-rift sequence (Winn et al., 2001, Malpas et al., 2005). It overlies the early syn-rift Oligocene redbeds and conglomerates of the Tayiba Formation exposed at Wadi Tayiba on the eastern side of the Gulf of Suez (Jackson, 2008). The Gharandal Group starts with redbeds and basic volcanics of the Abu Zneima Formation, followed upward by conglomerates, sandstones, and carbonates of the Nukhul Formation and the *Globigerina* marls, sandstones, and conglomerates of the Rudeis Formation (Jackson et al., 2005, Malpas et al., 2005). The post-rift sequence is composed of post-Miocene sands and limestones, separated from the syn-rift sequence by an unconformity (Orszag-Sperber et al., 1998). During the Pliocene, the rift opened to the Indian Ocean and connection with the Mediterranean ceased.

2.5.1 Evolution of the Red Sea and the Gulf of Suez

The evolution of the Red Sea, the Gulf of Suez, and the Gulf of Aqaba rifts has been discussed by scores of workers and is still in much debate. Some of the main points of controversy are: 1) Whether structure is the product of strike-slip faulting (Makris & Rihm, 1991, Girdler, 1991a & b, Rihm et al., 1991, Makris et al., 1991) or normal faulting (Heybroek, 1965). 2) The amount of offset along the rifts (Makris & Rihm, 1991, Girdler, 1991a & b, Rihm et al., 1991, Makris et al., 1991, Mart, 1991). 3) Whether displacement was continuous (Bartov et al., 1980) or occurred in more than one discontinuous phase (Quenell, 1958, Makris & Rihm, 1991, Girdler, 1991a & b). 4) The nature of the crust underlying the rifts and whether it is oceanic (Makris & Rihm, 1991, Girdler, 1991, Rihm et al., 1991, Makris et al., 1991) or continental with limited oceanic crust (Morgan, 1983). 5) Inherited from these problems are the tectonic models of the evolution of the Red Sea. For example, one model suggests a pull-apart basin with the formation of a new oceanic crust (Makris & Rihm, 1991, Girdler, 1991, Rihm et al., 1991, Makris et al., 1991). Another model proposes continental stretching accompanied by intrusion of volcanics (Coutelle et al., 1991).

The tectonic history of these rifts can be summarized as follows:

1 The Red Sea region in Egypt was a stable craton from Early Paleozoic to Late Eocene (Plaziat et al., 1990), probably forming the eastern extension of the Nile Basin. The Sinai was a part of Arabia and the Red Sea Rift was already a zone of structural weakness or a suture zone during the Pan-African Orogeny approximately 600 Ma (Harris & Gass, 1981, Makris & Rihm, 1991).

2 Rifting and magmatism started in the southern Red Sea around 30 Ma ago (lower Oligocene) and propagated in the central Red Sea around 25 Ma ago (upper Oligocene) (Perry & Schamel, 1990, Bohannon & Eittreim, 1991, Makris & Rihm, 1991, Girdler, 1991a & b). As rifting began, very thick Miocene salt and evaporite sections accumulated in the trough.
3 The geometry of the initial rift line was controlled by the combination of extensional stress fields due to the anticlockwise rotation of Arabia with the pre-existing structures. Lineament analysis of the bathymetry in the northern Red Sea axial valley and reflection seismic show good correlation with the bordering eastern and western continental plates (Coutelle et al., 1991).
4 In the Red Sea the directions of the master faults and plate motion are oblique to one another which led to the development of pull-apart basins (Makris & Rihm, 1991). Pull-apart basins form where the direction of motion of continental plates differs from those of the master fault (Mann et al., 1983). The amount and rate of creation of oceanic sea floor decrease from south to north consistent with the anticlockwise rotation of Arabia (Girdler, 1991). The two sides of the Red Sea display two different tectonic processes. The formation of pull-apart basins and oceanization took place on the western flank. Stretching occurred on the eastern flank. Therefore, the eastern and western flanks are asymmetrical (Makris & Rihm, 1991). The thickness of the eastern cratonic continental crust thins eastwards from more than 35 km to less than 20 km over a distance of 50 km. The western continental crust on the other hand changes abruptly eastward into an oceanic crust less than 10 km thick (Rihm et al., 1991, Makris et al., 1991).

   There is a very strong support for the presence of an oceanic floor in the Red Sea. In the northern Red Sea, marine magnetic anomalies suggest the occurrence of sea floor spreading (Girdler, 1991a & b). The Bouguer gravity anomalies (Girdler, 1991a & b, Makris et al., 1991) are zero to +20 mGal near the coast and increase to a maximum of 60 to 100 mGal over the deep water suggesting an oceanic crust. The seismic refraction data (Makris et al., 1991) indicate that the continental crust thins rapidly toward the coast and high velocities are present beneath the main axial trough (Girdler, 1991a & b). Heat flow systems show values 10 times higher than average in the center of the rift and 2 times higher on the flanks (Makris et al., 1991).
5 Intensified rifting and magmatism started in the northern Red Sea/Gulf of Suez around 20 Ma (Burdigalian), followed by extensional shoulder uplift and basin subsidence (block faulting) in the Gulf of Suez (Garfunkel & Bartov, 1977). A series of NW-SE-trending diabase dikes occur in southeastern Sinai (Bartov et al., 1980, Eyal et al., 1991, Baldridge et al., 1991, Stern et al., 1988). The dikes are tens to hundreds of kilometers long and commonly occur as swarms. The dikes are intersected and laterally offset by a series of N-S trending faults. The age of these dikes is approximately 20 Ma (Baldridge et al., 1991). Magmatism was followed by a phase of subsidence and extension in the Gulf of Suez between 19 and 16 Ma (Burdigalian) (Chenet et al., 1987, Moretti & Chenet, 1987, Moretti & Colleta, 1987, 1988). Large doubly-plunging folds formed in pre-rift strata during the Late Oligocene-Miocene extension of the Red Sea rift, such as the asymmetric syncline of the Duwi and Hamadat areas near Safaga (Khalil & McClay, 2002).

6 Approximately 14 Ma ago (Serravallian) the strike-slip movements switched from the Gulf of Suez to the direction of the Gulf of Aqaba-Dead Sea Rift (Ten Brink & Ben Avraham, 1989). Quennell (1958) suggested that the two series of faults on both sides of the Dead Sea Rift were offset 107 km sinisterly by the rift boundary fault, and argued that horizontal displacement took place in two steps. During the first (latest Oligocene/early Miocene) the movement was 62 km, and the second (Pliocene-Pleistocene) was 45 km. However, the 107 km of sinistral offset along the Gulf of Aqaba-Dead Sea Rift was challenged by Mart (1991) who argued that when the depositional facies and isopach contours are interpolated across the Rift, they appear to be continuous and indicate that lateral displacement was only 10 km. Bartov et al. (1980) and Eyal et al. (1981) suggested that left-lateral displacement of 105–110 km between Sinai and Arabia occurred in one continuous tectonic phase starting in the Middle Miocene.

7 At the end of the Miocene, the Strait of Bab al Mandab opened and waters from the Indian Ocean flooded the Rift ending the evaporite basin (Girdler, 1991a & b).

8 The last phase of evolution of the Red Sea is the seafloor spreading which commenced 5 Ma ago (Pliocene) in parts of the central and southern Red Sea and is still propagating northward. The exposed part of the rift was extensively intruded by gabbroic to dioritic plutons and dyke swarms 5-2 Ma ago (Bohannon & Eittreim, 1991). Pliocene-Pleistocene oozes were deposited on top of the Miocene evaporites.

2.6 CYRENAICA/MARMARICA PLATFORM

The Mediterranean margin of Libya consists of three physiographic provinces, the Pelagian Shelf, the Sirte Embayment, and Offshore Cyrenaica. Cenozoic strata along much of the Libyan margin have a progradational character punctuated by surfaces of erosion and margin failure, seismically coincident with the top of Messinian unconformity (Fiduk, 2009).

The Cyrenaica platform in Northeast Libya (Fig. 2.6) is separated from the Sirte Basin to the west by an arcuate fault (Antelat Fault) of Tertiary age (Burollet et al., 1971, Goudarzi, 1980) and from the Mediterranean Basin by the Jabal Akhdar uplift. The boundary between the Jabal Akhdar and the Cyrenaica platform is marked by a deep-seated fault which rises up to 882 m (3894 ft) above sea level (Röhlich, 1974). It extends eastward into Egypt under the name of Marmarica Plateau. The geology of the Jabal Akhdar and Cyrenaica was studied by Gregory (1911), Klitzsch (1970), Röhlich (1974, 1980), Klen (1974), Zert (1974), and El-Hawat & Shelmani (1993). The subsurface geology has been reviewed by El-Arnauti & Shelmani (1988), Thusu et al. (1988), Grignani et al. (1991), and Hallett (2002).

The Cyrenaica platform was the site of a marginal basin (the Al Jabal Al Akhdar Trough) with accumulations of thick sediments ranging from Paleozoic to Tertiary and probably formed a part of the Northern Egypt Basin. Up to 3000 m (9843 ft) of Mesozoic marine sediments have accumulated in the Jabal Akhdar Trough (Klitzsch, 1970). These rocks are mostly limestones, with some sandstones and shales. They include turbidites, debris flows and slumps. Deep-marine shales accumulated

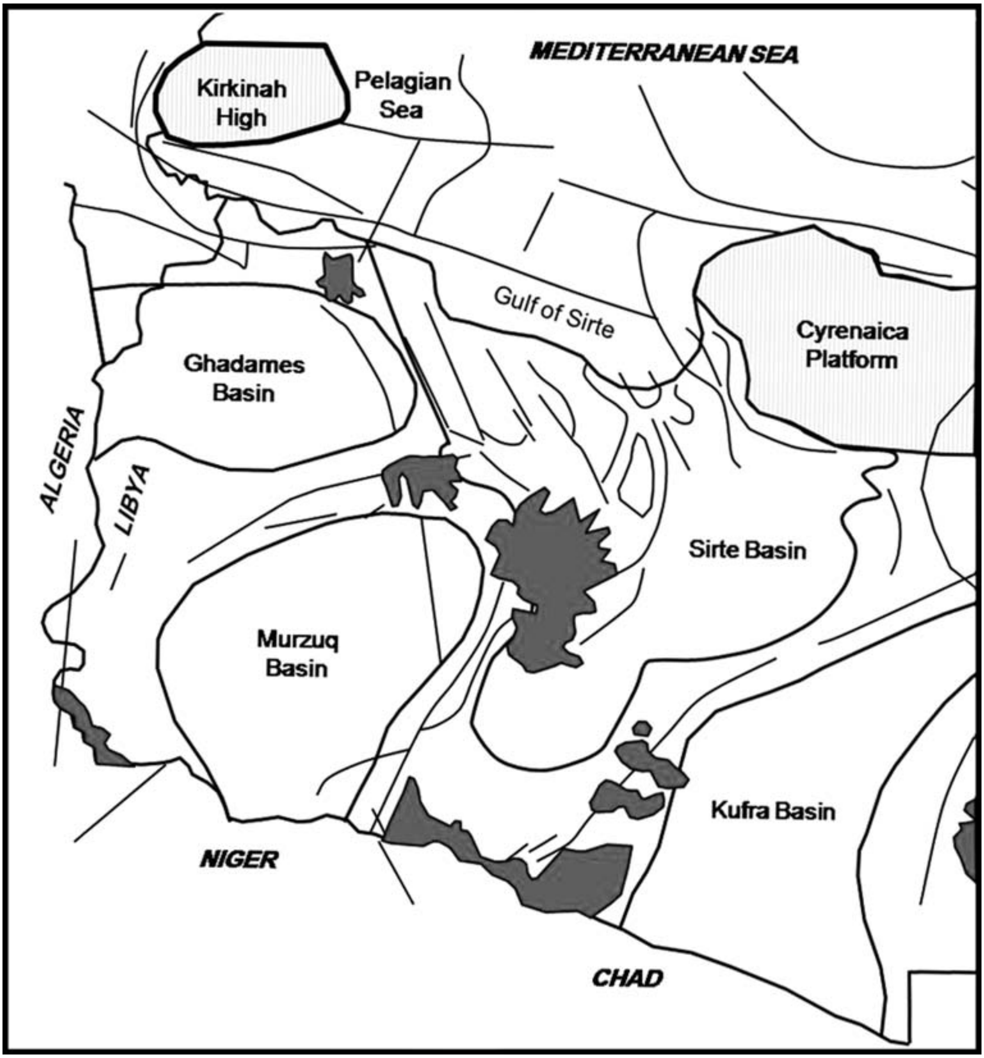

Figure 2.6 Tectonic map of Libya.

mostly in the basin to the north. The exposed section in the Jabal Akhdar ranges in age from Cenomanian to Eocene. Röhlich (1974, 1980) divided this geologic section into two depositional cycles: The first cycle includes Cenomanian to Coniacian sedimentation which was ended by an orogenic phase during the Santonian, leading to basin inversion. Stresses produced high-angle faults striking NE-SW, E-W and NW-SE, and an ENE-WSW-striking arch. The latter emerged as an island during the Santonian and it was deeply eroded. North of the arch, deposition continued uninterrupted. The second cycle includes Campanian to Landenian sediments. Deposition was dominated by neritic sediments during Late Senonian time and by chalky limestones containing planktonic foraminifera during the Paleocene. This cycle ended following an Early Eocene uplift of the area and subsequent erosion which produced a regional unconformity separating the Cretaceous from the Tertiary (Röhlich, 1980, Barr & Berggren, 1980), and it was followed by the deposition of Ypresian to Middle Miocene sediments. The latter form the plateau.

2.7 SIRTE BASIN

The Sirte (Sirt) Basin (Fig. 2.6) is the sixth largest hydrocarbon province in the world, with oil and gas reserves of 33–45 BBOE (Macgregor & Moody, 1998). It contains most of the hydrocarbon reserves in Libya, and approximately 29% of Africa's total reserves (Chatelier & Slevin, 1988). It consists of NW, EW and NE-SW arms with attendant faults. These faults divide the basin into a large number of platforms and basins. They include the Amal Platform-Rakb High, Maragh Trough, Ajdabiya Trough, Suluq Basin, Hameimat Trough, Jahama Platform-Zelten Platform, Marada (Hagfa) Trough, AzZahra (Dahra)-Al Hufrah Platform, Al Kotlah Trough, Al Bayda Platform, Southern Shelf, Dur Al Abd-Zellah Trough, Tumayyim Trough, Waddan Uplift, Al Hulayq High, and Hun Graben. These tectonic elements are described in detail by Hallett & El-Ghoul (1996), Anketell (1996), and Abadi et al (2008). Sediments in the Sirte Basin range in thickness from 1500–7000 m (4921–22,966 ft) (Goudarzi, 1980), and range from Cambrian to Tertiary. The intersection of faults of different orientations created a complex system of horsts and grabens, which controlled hydrocarbon accumulations and source rock distribution. In the Sirte Basin, oil is dominant, gas occurs only in three fields. The oil has 32°–44° API, and a sulphur content of 0.15–0.66% (Parsons et al., 1980).

The Sirte Basin is bounded on the west side by the Hun (Hon) Graben, a NW-SE elongated graben, which appears as a huge furrow cutting the present-day relief (Cepek, 1979), and separates the Sirte Basin from the Hamada al Hamra Platform (Ghadames Basin). The Hun Graben is one of the youngest tectonic elements and the only outcropping graben in the Sirte Basin. The graben is floored with basement schists and it contains about 1500 m (4922 ft) of sediments ranging in age from Triassic to Oligocene (Anketell, 1996, Hallett & El-Ghoul, 1996). The fault zone on the west boundary of the graben consists of several sub-parallel faults accompanied by brecciated zones. The nature and origin of the Hun Graben is controversial. Klitzsch (1967, 1970) assumed that the block of the Hun Graben sunk 500 m to 800 m (1641–2625 ft) against the Hamada al Hamara block. Cepek (1979), on the other hand, estimated a throw of 100 to 120 m (328–394 ft). Klitzsch (1967, 1970) suggested that the tectonic development of the Hun Graben started prior to the Late Cretaceous. He also postulated that the western boundary of the graben is Paleocene in age. However, Cepek (1979) inferred that the graben is probably Oligocene in age.

The Zellah Trough contains over 3600 m (11,811 ft) of sediments (Hallett & El-Ghoul, 1996). It is bounded to the west by the Waddan Uplift and to the east by the AzZahrah-Al Hufrah Platform. The Zellah Trough is divided into several subbasins, such as the Facha Graben, Ar Ramlah Syncline, Ayn An Naqah subbasin and Maamir Graben (Schröter, 1996, Johnson & Nicaud, 1996). Northwards it extends into the Dur al Abd Trough and southwards it connects with the Tumayyim Basin. The southern part of the Zellah Trough is floored with basement volcanics and the northern part with quartzites. The Tumayyim Basin contains over 3000 m (9843 ft) of sediments overlying basement metamorphic rocks. The Zellah Trough did not develop before 60 MM years ago (Gumati & Nairn, 1991).

The AzZahrah-Al Hufrah Platform is separated from the Al Bayda Platform by the NNE-trending Kotlah Graben. The eastern edge of the AzZahrah-Al Hufrah Platform is marked by the Manzila Ridge. It remained as a land area until the onset of the Cenomanian transgression where sandstones were deposited (Barr & Weegar, 1972). Isolated parts of the platform remained as land areas during the Santonian-Coniacian and Maastrichtian marine transgressions. Carbonates and shales are the dominant lithologies on the platform. The Kotlah Graben contains a thick Upper Cretaceous (Cenomanian-Maastrichtian) section of clastics, evaporites, and shales. The Al Bayda Platform is connected to the Southern Shelf by a NW-SE-trending horst (Sinha & Mriheel, 1996).

The Hagfa Trough (also known as Maradah Trough or Kalash Trough) is a deep, narrow graben, located between the AzZahrah-Al Hufrah and the Jahamah platforms in the north, and between the Al Bayda and Zelten platforms in the south. It is bounded in the offshore by the As Sidrah High. Displacement on the faults in the centre of the basin reaches 1800 m (5906 ft) (Hallett & El-Ghoul, 1996). The Hagfa Trough contains a sedimentary sequence of more than 6000 m (19,685 ft). The succession is composed of Cambro-Ordovician quartzites, Upper Jurassic-Early Cretaceous sandstones, Cenomanian sandstones and shallow-water carbonates, Turonian evaporites, with more than 295 m (968 ft) of halite in the southern part of the trough, Coniacian-Santonian shales, limestones, and dolomites, deep-water Campanian-Maastrichtian organic-rich shales, and deep-water Maastrichtian-Paleocene argillaceous carbonates. The trough was active between 60 and 40 MM years ago (Gumati & Nairn, 1991).

The Ajdabiya Trough (also known as the Maragh Trough) is the largest and deepest of the Sirte Basin troughs. It contains over 6000 m (19,685 ft) of sediments, including 2000 m (6562 ft) of Miocene rocks. Upper Jurassic-Early Cretaceous sandstones were encountered in places (Anketell, 1996). The trough was relatively inactive during the Paleocene, but was reactivated again during the Eocene (Hallett & El-Ghoul, 1996). The Ajdabiya Trough is bounded to the west by the Assumood Ridge, and further south by the Zelten Platform. To the east, it is flanked by the Cyrenaica Ridge and the Amal High. Southwards it terminates against the Messlah-Sarir High. Northwards it widens into the offshore and onto the Sirte Rise (Del Ben & Finetti, 1991). The Wadayat Trough is a small asymmetric half-graben extending westwards from the Ajdabiya Trough to the south of the Assumood Ridge, from which it is separated by a major fault. The trough contains over 4500 m (14,764 ft) of sediments.

The Hameimat Trough in the eastern part of the Sirte Basin is located between the Amal and Messlah highs. Eastwards it connects with the Jaghbub-Siwa Basin through the Abu Attifel Subbasin (El-Arnauti & Shelmani, 1985) and westwards into the Ajdabiya Trough. The trough is floored by Precambrian basement rocks, which are overlain by more than 2500 m (8200 ft) of Upper Jurassic-Lower Cretaceous to Oligocene rocks, and possibly includes Permo-Triassic rocks (Thusu, 1996, Gras, 1996). The trough contains several of the largest oil fields in Libya, such as the Jalu, Sarir, and Abu Attiffel fields, as well as the An Nafurah and Awjilah fields. The Abu Attiffel Basin is an ENE-WSW depression bounded by several pre-Mesozoic basement highs, such as the Al Jaghbub, Kalanshiyu and Majid uplifts. A system of syn-sedimentary listric normal faults has affected the sedimentation at different times (Rossi et al., 1991). The Sarir Trough (equivalent to the Qattarah Graben, El-Arnauti & Shelmani, 1985) is a relatively shallow trough located between the Messlah and Sarir highs. It contains about 3800 m (12,467 ft) of sediments. The trough is floored with Precambrian basement rocks, and by a variable thickness of Nubian Sandstones. The southern margin of the granitic and metamorphic Messlah High is dissected by an *en échelon* fault pattern caused by a right-lateral sense of shear contemporaneous with basement controlled extensional faults (Gras, 1996). The Hameimat Trough may bear genetic relationships with the northern Western Desert basins, such as the Abu Gharadig Basin.

2.7.1 Evolution of the Sirte Basin

Because of the absence of deep seismic refraction data, one can only hypothesize about the origin of the Sirte Basin. Since Harding (1984) divided the sedimentary fill of the Sirte Basin into pre-graben, syn-graben, and sag basin successions, several attempts have been made to refine these subdivisions. There is no general agreement on what constitutes the pre-rift and syn-rift sequences. Disagreements are probably due to the multiple rifting stages that led to the formation of the Basin. For example, the Nubian sandstones (Late Jurassic-Early Cretaceous) were considered as pre-rift by Harding (1984), Baird et al. (1996), and van der Meer & Cloetingh (1996), and syn-rift by Gras (1996), Schröter (1996), Tawadros et al. (2001), among many others. It is possible that the Sirte Basin area went through multiple stages of rifting since the Middle Triassic and that different parts of the basin acted differently at different times. Only in the Upper Paleocene-Eocene time the whole basin acted as one unit, and showed the highest rate of thermally-driven subsidence (downwarping) (Gumati & Kanes, 1985, Gumati & Nairn, 1991, Schröter, 1996, Bender et al., 1996, Baird et al., 1996). This phase of subsidence and burial was the major process of hydrocarbon generation in the Sirte Basin (Bender et al., 1996).

The Sirte Basin, with its three arms, has been viewed by many workers as a failed triple-junction system. This model has been opposed by Baird et al. (1996) because of their belief that the southeast sector of the basin, i.e. the Hameimat-Sarir Basin, is older than the two other sectors. The three arms, directed NW-SE, SW-NE, and E-W, correspond to three pre-existing arches, the Sirte Arch, the Tibesti Arch and the Kalanshiyo Arch, respectively. The meeting point of these three arms is probably the Baydah Platform, the centre of the Al Haruj al Aswad and the Jabal asSawda volcanics. The NW-SE arm is on trend with the South Sudan rift basins (Schull, 1988).

In spite of recently published extensive works (including three volumes in 1996), the origin of the Sirte Basin is still not very well documented and very little is known about the history of the basin in pre-Cenomanian times. The Precambrian basement structure in the Sirte Basin was probably the main controlling factor on the subsequent tectonic history of the region. NW-SE-oriented pull-apart basins probably formed in the region during the Pan-African Orogeny (Schandelmeier, 1988), followed by extension and the formation of horsts and grabens during the Cambrian (Klitzsch, 1971, Schandelmeier, 1988). Subsidence was accompanied by the deposition of shallow-marine Late Cambrian sediments and the emplacement of acidic volcanic rocks (Tawadros et al., 2001). This extension phase continued into the Early Carboniferous and it was succeeded by thermal uplift and erosion during the Late Carboniferous and Permian. Thermal uplift was caused by the Hercynian Orogeny, on one hand, and the subduction of the Proto-Pacific oceanic plate underneath the Gondwana continent (Visser & Praekelt, 1996), on the other. These events must have affected the Sirte Basin area but were camouflaged by the later events. There is now ample evidence that Devonian, Carboniferous and Triassic sediments occur in several parts of the Sirte Basin (Thusu, 1996, Wennekers et al., 1996, Tawadros et al., 2001).

Central Libya remained apparently a positive area (the Sirte Arch) until the Early Cretaceous when the arch collapsed. The grabens were filled with predominantly continental sandstones of the "Nubian" type (Tawadros et al., 2001), and remained subaerially exposed until the Cenomanian.

The evolution of the Sirte Basin is marked by various rifting phases from the Early Cretaceous to early Eocene (Abadi et al., 2008). The rifting phases accompanied changes in the plate motions of Africa relative to Europe, and the rifting in other African basins. Subsidence initially occurred in narrow troughs, which gradually widened to incorporate platforms until finally the whole basin subsided at the end of each rift cycle (thermal subsidence).

The origin of the basin can be explained in terms of mantle upwelling following melting due to hotspot activities. Strike-slip faulting and extension of the region took place above a fixed mantle "hotspot" over which Africa rotated in Late Jurassic-Early Cretaceous times (Van Houten, 1983). Asthenospheric upwelling yielded voluminous basalt magmas (Tatsumi & Kimura, 1991), especially during the Jurassic (Guiraud, 1998). Rhyolites and basalts in the Sirte Basin gave K-Ar dates of 161 Ma and 151 Ma (Bathonian and Tithonian), respectively (Hallett & El Ghoul, 1996). However, these ages should be considered as minimum due to argon (Ar) evaporation. Jurassic volcanics are also common in the subsurface of the northern Western Desert of Egypt (Bayoumi & Lotfy, 1989). This upwelling resulted in thermal thinning of the lithosphere due probably to subcrustal erosion. The increased volume associated with subcrustal erosion and the heat generation from magma resulted in the doming and expansion of the crust. This process could have produced a crustal uplift of approximately 1–2 km (Arthyushkov et al., 1991) and the formation of the Sirte Arch. This uplift was accompanied by the cracking of the rigid crust in response to the rotation of Africa relative to the European block. Strike-slip movement along the Jifarah-Cyrenaica shear zone associated with the opening of the Mediterranean Sea resulted in the collapse of the Sirte Arch and the formation of the Sirte Basin. The motion was sinistral during the Early Cretaceous (Burollet, 1993, Anketell, 1996). This motion was translated eastwards into the Sirte region. The collapse of the Sirte Arch probably took place in different steps. The initial collapse started in the Triassic in the Eastern Sirte Basin and led to the initiation of the Sarir and Hameimat troughs, followed by the collapse of the main arch during the Lower Cretaceous (Tawadros et al., 2001). Only the northeastern end of the Tibesti arm collapsed at that time. Contemporaneous subsidence of half-graben and pull-apart basins in the Benue area, northern Cameroon, and southern Chad took place (Maurin & Guiraud, 1990, Guiraud, 1990, Guiraud & Maurin, 1991, 1992, 1993). The strike-slip motion of

Africa was followed by an N-E motion until Campanian times (Anketell, 1996). The evidence for this motion is supported by the change of magmatic activities from older to younger along the track of the Darfur hotspot (Garfunkel, 1991) in a southwest direction. A new phase of extension and subsidence, with faulting and graben formation, occurred from Cenomanian to Campanian time (Gumati & Kanes, 1985, Gumati & Nairn, 1991, Schröter, 1996, Baird et al., 1996) when the sea encroached on it (Barr & Weegar, 1972). The formation of horsts and grabens was induced by the first collision between Eurasia and Africa, which led to NW-SE compressional stress and associated SW-NE distension (Burollet, 1993). A quiescent period followed before convergent movement in a northerly direction was resumed in the early Eocene (Dewey et al., 1973). Thermally-driven subsidence dominated (Gumati & Kanes, 1985, Gumati & Nairn, 1991, Schröter, 1996, Baird et al., 1996), and the former structures were sealed by platform sediments (Burollet, 1993). In the Late Eocene, the motion of Africa relative to Europe changed from compressional to right lateral, then into a NW-SE compressional regime in the Early Miocene (van der Meer et al., 1993). The Alpine-related tectonic pulses in the late Eocene resulted in northward tilting of the Sirte Basin (Gruenwald, 2001). A regional unconformity separates the Eocene carbonates from the overlying Oligocene clastics.

2.8 MURZUQ BASIN

The Murzuq Basin in Southwest Libya (Fig. 2.6) is a Paleozoic cratonic basin. It is bordered on the north by the Gargaf Arch, on the east by the Tibesti Massif, and on the west by the Akakus-Tadrart Range where Early Paleozoic sediments are exposed. The Precambrian basement of the Hoggar Massif which crops out further to the southwest is separated from the Illizi Basin in Algeria by the Tihemboka Arch.

The basin is floored by Archean and Proterozoic basement rocks of the East Saharan Craton (Vail, 1991, Bauman et al., 1992). The basement is composed of Precambrian high-grade metamorphic rocks associated with plutonic rocks as well as low-grade metamorphic to unmetamorphosed rocks of the Infracambrian Mourizidie Formation (Belaid et al., 2009). Its eastern rim coincides with the boundary between a Precambrian oceanic basin to the west and a platform area to the east (Nagy et al., 1976, Ghuma & Roger, 1980).

During the Caledonian, Hercynian and younger tectonics, the Murzuq Basin was divided into various uplifts and troughs with different orientations (Fürst & Klitzsch, 1963). The basin-fill consists of marine sediments ranging in age from Cambrian to Carboniferous, followed by continental Mesozoic sediments.

The Murzuq Basin contains approximately 600 MMBOE of recoverable reserves (Boote et al., 1998). Reservoirs are provided by Cambrian, Devonian, and Carboniferous sediments, and hydrocarbons originated from Silurian and Devonian source rocks (Lüning et al., 2000c, d). However, Silurian Hot Shales are missing in few wells, such as the A1-NC190 and A1-NC186 (Belaid et al., 2009).

Pull-apart basins, oriented NW-SE probably formed during the later stages of the Pan-African Orogeny in the Early Cambrian (Schandelmeier, 1988, Klitzsch, 1971). From the Middle Cambrian, vertical movements along the old basement faults took place due to the extensional stress regime which dominated North Africa during that time. During the Middle to Late Cambrian times, the area subsided and it was covered by shallow epicontinental seas, where shallow-marine and locally fluvial clastic sediments were deposited (Korab, 1984, Radulovic, 1984).

The area was uplifted in the Lower Ordovician, followed by the formation of hills and valleys, which were later filled with peri-glacial deposits during the Late Ordovician glaciation episode. The Caledonian tectonics acted along a NW-SE axis (Klitzsch, 1963, Fürst & Klitzsch, 1963, De Lestang, 1965). The Brak-Bin Ghanimah High divided the basin into two subbasins after the Ordovician (Fürst & Klitzsch, 1963), the main Murzuq Basin and the Dur al Qussah Basin. The Tihemboka Arch is Middle Devonian in age. Movement on the Arch started during the Givetian-Frasnian (Legrand, 1967, Burollet & Manderscheid, 1967, Burollet et al., 1971) and was submerged in the middle Famennian. In eastern Algeria, the Lower Devonian sediments are reduced in thickness near the Tihemboka Arch and they are absent on top of the Arch (Legrand, 1967). Five main unconformities have been recognized in the Murzuq Basin (Belaid et al., 2009):

1 Alpine and Austrian events: these events occurred during the Cretaceous (Austrian) and during the Tertiary (Alpine) after the deposition of the Mesak Formation.
2 Base Jurassic unconformity: this event is represented by Jurassic sediments unconformable overlying Lower Carboniferous (Marar Formation) in the eastern and north-eastern parts of the Murzuq Basin.
3 Hercynian tectonics: this event greatly affected Carboniferous sediment thickness. Upper Carboniferous (Tiguentourine Formation) is missing as result of erosion.
4 Caledonian event: the Caledonian period is of major importance in the Murzuq Basin and during the uplift of the Al Gargaf Arch. The Silurian section comprises the Tanezzuft and Acacus formations in the eastern part of the basin.
5 Taconian unconformity: this event at the base of the Silurian exerts important controls on the distribution of the Hot Shale source rock. In some parts of the Murzuq Basin, the Ordovician Memouniat sandstones were partially eroded.

The Hoggar Massif to the southwest and the Tibesti range to the east were covered with ice (Beuf et al., 1971), probably during the early parts of the Ordovician. The melting of the ice cap during the Late Ordovician resulted in the deposition of glacio-marine deposits (Radulovic, 1985, Protic, 1985). Epeirogenic uplift and erosion followed.

The Silurian transgression which took place probably during a brief period of tectonic stability led to the deposition of graptolitic shales, which provide source for hydrocarbons in West Libya and Eastern Algeria (Lüning et al., 2000c, d, 2004a, b, Sikander et al., 2003). Epeirogenic uplifting of the area caused a regional regression during the upper part of the Silurian, and the whole area was transformed into dry land by the end of the Silurian. Continental, deltaic and shallow-marine conditions dominated during the Early Devonian. By the Upper Devonian time, the Gargaf Arch was developed and separated the Murzuq Basin from the Ghadames Basin (Seidl & Röhlich, 1984). The two basins were connected through a passage along the western side of the plunging arch. Along the northern shore of the Murzuq Basin, shallow marine conditions resulted in the formation of oolitic ironstones of the Wadi Ash Shati (Goudarzi, 1970, Seidl & Röhlich, 1984). Marine conditions persisted to the