The Sirte Basin Province of Libya—Sirte-Zelten Total Petroleum System

By Thomas S. Ahlbrandt

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Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. For this project, the world was divided into eight regions and 937 geologic provinces. Of these, parts of 128 geologic provinces were assessed for undiscovered petroleum resources. The primary documentation for these assessments is in U.S. Geological Survey World Energy Assessment Team (2000). The petroleum geology of these priority and boutique provinces is described in this series of reports. Seventy-six "priority" provinces (exclusive of the United States and chosen for their high ranking) and 52 "boutique" provinces (exclusive of the United States) were selected for appraisal of oil and gas resources. Boutique provinces were chosen for their anticipated petroleum richness or special regional economic or strategic importance.

The purpose of the World Energy Project is to assess the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but must be at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment. The total petroleum system includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that (1) has been generated by a pod or by closely related pods of mature source rock, and (2) exists within a limited mappable geologic space, along with the other essential mappable geologic elements (reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum. The minimum petroleum system is that part of a total petroleum system encompassing discovered shows and accumulations along with the geologic space in which the various essential elements have been proved by these discoveries.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered fields constitute a single, relatively homogeneous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system may equate to a single assessment unit, or it may be subdivided into two or more assessment units if each unit is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually.

A graphical depiction of the elements of a total petroleum system is provided in the form of an events chart that shows the times of (1) deposition of essential rock units; (2) trap formation; (3) generation, migration, and accumulation of hydrocarbons; and (4) preservation of hydrocarbons.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and will identify the same type of entity in any of the publications. The code is as follows:

Example

Region, single digit	**3**
Province, three digits to the right of region code	3**162**
Total petroleum system, two digits to the right of province code	3162**05**
Assessment unit, two digits to the right of petroleum system code	316205**04**

The codes for the regions and provinces are listed in U.S. Geological Survey World Energy Assessment Team (2000).

Oil and gas reserves quoted in this report are derived from Petroconsultants' Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

Figure(s) in this report that show boundaries of the total petroleum system(s), assessment units, and pods of active source rocks were compiled using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute's ArcWorld 1:3 million digital coverage (1992), have no political significance, and are displayed for general reference only. Oil and gas field centerpoints shown in these illustrations are reproduced, with permission, from Petroconsultants (1996).

Abstract

The Sirte (Sirt) Basin province ranks 13th among the world's petroleum provinces, having known reserves of 43.1 billion barrels of oil equivalent (36.7 billion barrels of oil, 37.7 trillion cubic feet of gas, 0.1 billion barrels of natural gas liquids). It includes an area about the size of the Williston Basin of the northern United States and southern Canada (≈490,000 square kilometers). The province contains one dominant total petroleum system, the Sirte-Zelten, based on geochemical data. The Upper Cretaceous Sirte Shale is the primary hydrocarbon source bed. Reservoirs range in rock type and age from fractured Precambrian basement, clastic reservoirs in the Cambrian-Ordovician Gargaf sandstones, and Lower Cretaceous Nubian (Sarir) Sandstone to Paleocene Zelten Formation and Eocene carbonates commonly in the form of bioherms. More than 23 large oil fields (>100 million barrels of oil equivalent) and 16 giant oil fields (>500 million barrels of oil equivalent) occur in the province.

Production from both clastic and carbonate onshore reservoirs is associated with well-defined horst blocks related to a triple junction with three arms—an eastern Sarir arm, a northern Sirte arm, and a southwestern Tibesti arm. Stratigraphic traps in combination with these horsts in the Sarir arm are shown as giant fields (for example, Messla and Sarir fields in the southeastern portion of the province). Significant potential is identified in areas marginal to the horsts, in the deeper grabens and in the offshore area.

Four assessment units are defined in the Sirte Basin province, two reflecting established clastic and carbonate reservoir areas and two defined as hypothetical units. Of the latter, one is offshore in water depths greater than 200 meters, and the other is onshore where clastic units, mainly of Mesozoic age, may be reservoirs for laterally migrating hydrocarbons that were generated in the deep-graben areas.

The Sirte Basin reflects significant rifting in the Early Cretaceous and syn-rift sedimentary filling during Cretaceous through Eocene time, and post-rift deposition in the Oligocene and Miocene. Multiple reservoirs are charged largely by vertically migrating hydrocarbons along horst block faults from Upper Cretaceous source rocks that occupy structurally low positions in the grabens. Evaporites in the middle Eocene, mostly post-rift, provide an excellent seal for the Sirte-Zelten hydrocarbon system. The offshore part of the Sirte Basin is complex, with subduction occurring to the northeast of the province boundary, which is drawn at the 2,000-meter isobath. Possible petroleum systems may be present in the deep offshore grabens on the Sirte Rise such as those involving Silurian and Eocene rocks; however, potential of these systems remains speculative and was not assessed.

Introduction

The Sirte Basin province ranks 13th among the world’s petroleum provinces, exclusive of the U.S. provinces, with 43.1 billion barrels of oil equivalent (BBOE) of known petroleum volume, and it ranks 15th if U.S. petroleum provinces are included (Klett and others, 1997). The Sirte Basin province is considered a “priority” province by the World Energy Assessment Team as described in the Foreword. Sixteen giant (>500 million barrels of oil equivalent (MMBOE)) fields occur in the province; reservoirs range in age from Precambrian to Miocene. Exploration has focused on structural highs, principally the horst blocks such as the Waddan, Az Zahrah, and Zaltan platforms (also variously known as Jebel Uddan, Beda, Dahra, Al Hufra, and Zeltan platforms) (figs. 1, 2). These platforms are dominated by carbonate and bioherm Tertiary reservoirs of Tertiary age. In the eastern Sirte Basin, significant stratigraphic clastic traps superimposed on structural highs principally occur in Mesozoic clastic reservoirs such as at Sarir and Messla fields (fig. 1).

The Sirte Basin province is characterized by one dominant petroleum system, the Sirte-Zelten, which is subdivided into four assessment units (fig. 1). The Sirte Basin (also referred to as “Sirt Basin”) is a late Mesozoic and Tertiary continental rift, triple junction, in northern Africa that borders a relatively stable Paleozoic craton and cratonic sag basins along its southern margins (fig. 2). The province extends offshore into the Mediterranean Sea, with the northern boundary drawn at the 2,000 meter (m) bathymetric contour. The thickness of sediments in the province increases from about 1 kilometer (km) near the Nubian (also known as Tibesti) Uplift on the south to as much as 7 km offshore in the northern Gulf of Sirte. The onshore area is relatively well explored for structures, which are dominated by regionally extensive horsts and grabens (fig. 2). Hydrocarbon resources are approximately equally divided between carbonate and clastic reservoirs (pre-Tertiary, dominantly clastic; Tertiary, dominantly carbonate reservoirs). The prospective area in the province covers about 230,000 km^2 (Montgomery, 1994; Hallett and El Ghoul, 1996; MacGregor and Moody, 1998). The offshore portion (figs. 3, 4) is far less explored and its petroleum potential is largely unknown.

Offshore, geologic relations in the Sirte Basin province indicate a potential for major reserves to be added by the dominant Mesozoic system, but Paleozoic and Cenozoic petroleum systems may be proven to exist as well. Speculative hydrocarbon systems are also postulated for the eastern part of the province, including Lower Cretaceous and Triassic source rocks (Mansour and Magairhy, 1996; Burwood, 1997; Ambrose, 2000), as well as Eocene and Silurian source rocks in the deeper grabens and offshore areas (Hallett and El Ghoul, 1996).

Recent petroleum geochemistry data confirm the dominance of the Upper Cretaceous Sirte Shale (equivalent to the upper part of the Rakb Group; see fig. 7) as the source of hydrocarbons in the Sirte Basin (Ghori and Mohammed, 1996; Baric and others, 1996). Recent exploration suggests additional potential in the grabens, particularly in the southern part of the Zallah Graben (Abu Tumayam), the Marada Graben (Maradah), and the Sirte Graben (Ajdabiya, Kalash, or Sirt), as discussed by Hallett and El Ghoul (1996, fig. 5). Hydrocarbons generated by Eocene source rocks, particularly in the offshore, offer speculative potential as well.

Acknowledgments

The Sirte Basin was studied utilizing both published data and proprietary databases, including the 1996 Petroconsultants file, the 1998 Geomark oil geochemical file, and other industry sources. References listed in this publication reflect the most relevant or current information in the author’s opinion, and also include items resulting from searches of the GEOREF database as well as other pertinent geologic information. Basic geologic and petroleum information was utilized from USGS Open-File Reports 97-470A (Persits and others, 1997) and 97-463 (Klett and others, 1997), Digital Data Series 60 (U.S. Geological Survey World Energy Assessment Team, 2000), and UNESCO 1:5,000,000 tectonic and geologic maps of Africa.

Province Geology

Province Boundary

The south and southeast boundaries of the Sirte Basin province (2043) are drawn at the Precambrian-Paleozoic contact along the Nubian Uplift and its northeast-trending extension, termed the Southern Shelf (figs. 1, 2) or also referred to as the Northeast

Figure 1. Sirte-Zelten Total Petroleum System showing boundaries of the total and minimum petroleum system, pods of active (thermally mature) source rock, four assessment units, and oil and gas field centerpoints (named fields exceed 100 million barrels of oil equivalent). Note the 200 m bathymetric isobath forms boundary between Offshore Sirte Hypothetical Assessment Unit (20430103) and Central Sirte Carbonates Assessment Unit (20430102). The 2,000 m bathymetric isobath forms northern boundary of province, total petroleum system, and Offshore Sirte Hypothetical Assessment Unit 20430103. Projection: Robinson. Central meridian: 0.

Figure 2. Structural elements of Sirte Basin. Troughs and grabens, platforms and horsts are synonymous terms. Individual horsts and grabens possess multiple names. For example, the Sirte (Sirt) Trough is also known as the Kalash or Ajdabiya Trough, as noted (modified from Ambrose, 2000). Barbs show direction of relative movement on faults.

Tibesti Arch/Alma Arch uplift by some authors (for example, Futyan and Jawzi, 1996). The Cyrenaica Shelf (also referred to as a platform, including both basin and uplift) forms the eastern and northeastern border. The western border, generally called the Western Shelf (fig. 2), is a combination of the Nubian Uplift and a northwest-trending extension called the Fezzan Uplift (Tripoli-As Sawda Arch); the latter feature intersects the Nafusa (Talemzane-Gefara) Arch, an east-west-trending arch along the northwest margin of the province (Persits and others, 1997; fig. 3). The northern margin is the 2,000 m bathymetric contour (isobath) in the Gulf of Sirte (figs. 1–3). Offshore the province is separated from the Pelagian Basin petroleum province (2048) by the Medina Bank (fig. 3). To the west is the Hamra Basin, to the south the Murzuk Basin, and to the east the Cyrenaica Basin (2041) (fig. 1). Alternative basin outlines have been drawn (for example, Montgomery, 1994; Futyan and Jawzi, 1996, Selley, 1997); however, the Sirte Basin boundary outline as just described was drawn based upon surface geologic and subsurface tectonic maps prepared at a scale of 1:5,000,000 by UNESCO and shown on supporting maps such as the Africa geologic map prepared for the World Energy Project (Persits and others, 1997).

Geographic Setting

The Sirte Basin is a triple-junction continental rift along the northern margin of Africa (fig. 2). It is bordered on the north by the Gulf of Sirte (Sidra) in the Mediterranean Sea. Although the Nubian Uplift rises to 3,000 m south of the Sirte Basin, much of

Figure 3. Central Mediterranean Sea, showing USGS-defined Pelagian province and offshore areas of Sirte Basin, the Sirte Rise. Structural high boundaries are based on seismic data and drawn on 1.0 and 1.8 second two-way travel time intervals (modified from Finetti, 1982; Bishop, 1988; Jongsma and others, 1985; and Klett). Section *A–A'* is shown in figure 4.

the land area in the basin is characterized by desert steppes and includes eolian deposits of the Kalanshiyu and Rabyanah Sand Seas of the Sahara Desert. In a relatively narrow, northern coastal strip, some land areas are as much as 47 m below sea level. The Sirte Basin is roughly the size of the Williston Basin in North America (≈490,000 km^2). Libya is the fourth largest country in Africa and the 15th largest country in the world.

Political and Exploration History

Libya became an independent nation in 1951; however, it has a complex early history dating back to 10,000 years before the present (B.P.) when Neolithic cultures domesticated cattle and cultivated crops in the coastal zone. Until about 4,000 B.P., nomadic cultures thrived in what is now the Libyan Desert (part

Figure 4. Northeast-southwest offshore regional cross section showing structural, tectonic, and crustal relationships in offshore Sirte Rise to Hellenic Arc (modified from Finetti, 1982).

of the Sahara) in what was until then a savanna environment. About 4,000 B.P., either migration occurred or the population was absorbed into the Berber tribe. Phoenicians, Greeks, Romans, Muslims, the Turks of the Ottoman Empire, and finally the Italians subsequently occupied this area prior to its independence. Libya was liberated from the Italians and Germans in World War II, and Britain acted as the country's administrative overseer from 1943 to 1949. Following a period of transition under the United Nations, a Libyan government was formed in 1951. Concerned about domination by foreign interests, Libya passed basic minerals laws in 1953 and 1955; multiple concessions were then granted to Esso, Mobil, Texas Gulf, and others, resulting in major oil discoveries by 1959. By 1969, production from the Sirte Basin exceeded production from Saudi Arabia (3 million barrels of oil per day (MMBOPD), which has now decreased to 1.5 MMBOPD (Yergin, 1991; Petroconsultants, 1996; EIA, 1997). Libya nationalized its oil industry in 1973, and some U.S. oil companies began withdrawing from Libya in 1982, following a 1981 U.S. trade embargo. By 1986, the remaining U.S. companies were ordered to cease activities in Libya. In 1992, the United Nations sanctioned Libya in response to the 1988 bombing of a Pan American flight over Scotland. Additional sanctions applied by the U.S. Sanctions Act of 1996 were relaxed in 1999. Today, U.S. and other companies have commenced reentry into Libya, and a number are currently active, led by AGIP (Italy), OeMV(Austria), Veba (Germany), TOTAL (France), Nimir (Saudi), WOC (NOC, Conoco, Marathon, Amerada Hess), ETAP (Tunisia), and others.

The first reported occurrence of petroleum in the Sirte Basin was observed in a coastal water well drilled by Italian colonists, Libya having become an Italian colony following a 1911–1912 Turkish-Italian war in which Italy controlled part of the country (and ultimately the entire country in 1923). The Italian government embarked on geologic investigations of the area and produced a geologic map in 1934. Shows of natural gas were observed in the late 1930's, but World War II interrupted exploration efforts. Competitive bidding for petroleum concessions was subsequently permitted by two mineral laws passed in 1953 and 1955, and exploration by Esso, Mobil, Texas Gulf, and others commenced with seismic, magnetic, and gravity data being collected. From 1956 to 1961 giant oil fields were discovered, including Amal, Sarir, and Raguba (Montgomery, 1994, fig. 1). Lewis (1990) documented the interesting discovery history of these fields including the notation that the Sarir field was nearly bypassed because oil was not anticipated in the Nubian Formation. That formation was subsequently shown to be a prolific reservoir with initial production rates of 20,000 barrels of oil per day (BOPD). By 1961, Libya was exporting oil, and by 1966 it had become the seventh largest oil-producing nation. For a period in the 1960's, Libya exceeded Saudi Arabia in petroleum exports (Yergin, 1991).

According to Hallett and El Ghoul (1996), 9,850 wells have been drilled in the Sirte Basin, and of those 1,578 were wildcats. They reported 100 billion barrels of oil (BBO), 50 trillion cubic feet (TCF) of associated gas, and 20 TCF of non-associated gas in place. Clifford (1984) reported 27.9 billion barrels of reserves (recoverable oil). Based on data from Petroconsultants (1996), the USGS reported that known petroleum reserves in the Sirte Basin province (2043) were 43.1 billion BBOE (36.7 BBO, 37.7 TCF natural gas, 0.1 billion barrels of natural gas liquids (BBNGL); Klett and others, 1997), an amount that constitutes 1.7 percent of the world's known oil reserves. Exploration has focused on structural highs (horsts) with little exploration of intervening grabens such as those shown in figure 6. Recent drilling has demonstrated potential in the grabens; for example, such shows as observed in well A1-119 on the Al Brayqah Ridge within the Ajdabiya (Sirte) Trough (Graben) (Hallett and El Ghoul, 1996) provide a strong indication that future drilling in the deep trough areas may result in the discovery of several billion barrels of additional oil reserves. Even though the Sirte Basin is the most explored province in Libya, significant potential remains particularly in the grabens and offshore areas.

The prospective area of the Sirte Basin occupies about 230,000 km^2, with a wildcat drilling density of one new field wildcat per 145 km^2 (Hallett and El Ghoul, 1996). The overall drilling density of the basin is 3.3 wells per 100 km^2 (MacGregor and Moody, 1998), with an average field depth of 2,100 m. By comparison, the northern North Sea is nearly three times more intensely explored (nine wells per 100 km^2) to average depths of 3,000 m. MacGregor and Moody (1998) believed that the petroleum discoveries in the future for the Sirte Basin lie in refocusing exploration to subtle forms of traps such as hanging wall closure, relay ramps, and stratigraphic traps; such subtle traps, they pointed out, are represented in the North Sea but have yet to be developed extensively in the Sirte Basin. Recent indications of hydrocarbons within grabens suggest that these areas have potential as well as clastic reservoirs beneath the carbonate reservoirs in the Central Sirte Basin (Hallett and El Ghoul, 1996). The offshore area beyond 200 m depths is largely unexplored, but it has both significant hydrocarbon potential and significant exploration risk.

Geologic Setting

The Sirte Basin province is considered to be a holotype of a continental rift (extensional) area and is referred to as part of the Tethyan rift system (Futyan and Jawzi, 1996; Guiraud and Bosworth, 1997). The structural weakness of the area is exemplified by alternating periods of uplift and subsidence originating in late Precambrian time, commencing with the Pan African orogeny that consolidated a number of proto-continental fragments into an early Gondwanaland (Kroner, 1993).

Early Paleozoic history of the Sirte Basin reflects a relatively undisturbed Paleozoic cratonic sag basin with intermittent periods of arching in the Paleozoic(?) (for example, formation of a regional uplift referred to as the Sirte Arch; Bellini and Massa, 1980; Van Houten, 1980; Anketell, 1996). The timing of this uplift is debatable; historically it is considered to be a mid-Paleozoic event, but it could have formed in the Mesozoic preceding an Early Cretaceous rifting event.

Rifting commenced in the Early Cretaceous, peaked in the Late Cretaceous, and terminated in early Tertiary time, resulting in the triple junction (Sirte, Tibesti, and Sarir arms; see inset, fig. 2) within the basin (Harding, 1984; Gras and Thusu, 1998; Ambrose, 2000). According to Anketell (1996), the Early Cretaceous rifting reflected east-west sinistral shear zones (strike-slip) that strongly controlled clastic deposition in the Sarir arm, but

Figure 5. East-west onshore structural cross section across Sirte Basin (modified from Roohi, 1996a). Note name changes for troughs and platforms relative to figure 1 and nearly vertical displacement on faults (heavy dashed lines).

Figure 6. Pre-Hercynian subcrop map in Sirte Basin area (modified from Hallett and El Ghoul, 1996).

Ambrose (2000) alternatively proposed that dextral shear forces dominated this period of deformation in the Sarir arm. Dextral shear forces dominated Late Cretaceous tectonism, as discussed by Gras (1996), Guiraud and Bosworth (1997), and Ambrose (2000). The Late Cretaceous rifting event is characterized by the formation of a series of northwest-trending horsts and grabens that step progressively downward to the east; the Sirte Trough (variously known as the Ajdabiya Trough, the Abu Attifel Graben, the Hameitat, Kalash, or Sirt trough or graben (Finetti, 1982; Montgomery, 1994; Hallett and El Ghoul, 1996; Roohi, 1996a, b; Mansour and Magairhy, 1996)) represents the deepest portion of the basin (figs. 2, 3, 4, 5). These horsts and grabens extend from onshore areas northward into a complex offshore terrane that includes the Ionian Abyssal Plain to the northeast (fig. 3). This plain is underlain by oceanic crust that is being subducted to the north and east beneath the Hellenic arc (Westaway, 1996, fig. 4). The Pelagian province to the west, particularly the pull-apart basins of the Sabratah Basin and extending along the South Cyrenaica Fault Zone (SCFZ) and the Cyrenaica Platform to the east, is strongly influenced by extensional dextral strike-slip faulting (Anketell, 1996; Guiraud and Bosworth, 1997; fig. 2). To the south, the Nubian Uplift is the stable continental basement for this rifted basin.

Although the timing of formation of the Sirte Arch is uncertain, sufficient uplift of the area now known as the Sirte Basin took place to cause erosion of pre-Cretaceous sediments over a wide area (fig. 6). An argument favoring the deformation to be of Mesozoic age rather than Paleozoic age may be that it was related to the west-to-east migration of a mantle plume across North Africa that was followed by Cretaceous rifting (Guiraud and Bosworth, 1997). The youngest rifting in North Africa is now east of the Sirte Basin in the Red Sea where rifting is active today.

Syn-rift clastics of the Sarir Sandstone (Nubian Sandstone equivalent) in the eastern part of the Sirte Basin province accumulated in and across a series of east-west-trending horsts and grabens in the Sarir arm during Middle and Late Jurassic and Early Cretaceous time (fig. 2). This depositional period was followed by rifting along the northeastern arm of a triple junction that resulted in the formation of a series of northwest-southeast-oriented horsts and grabens (Sirte arm) beginning in the Late Cretaceous and extending into the early Tertiary. Transpressional forces elevated platforms (horsts) in the Tibesti and Sirte arms to higher structural elevations than in the nearby Trias/Ghadames province to the west in Algeria or the Cyrenaica Platform (Shelf) to the east (figs. 1, 2, 5).

The Sirte Basin is asymmetric, deepening to the east as shown in figure 5. The relative relief on the juxtaposed horst and graben blocks increases to the east coincident with significant thinning of sediments across the province. Erosion associated with the Sirte Arch resulted in truncation of the Paleozoic sequence in the Hamra Basin and western Cyrenaica Platform, but these deposits were preserved offshore (Hallett and El Ghoul, 1996; fig. 6, this report). Cambrian-Ordovician sediments were also preserved over much of northern Libya prior to the formation of the Sirte Arch (El-Hawat and others, 1996). Progressive erosion of younger sediments and subsequent episodes of block faulting resulted in placing these mostly clastic Paleozoic and Mesozoic reservoirs in a structural high position with respect to thermally mature Cretaceous source rocks that occupied the deeper portion of the basin (fig. 5; Hallett and El Ghoul, 1996). The Sarir arm (eastern limb) of the triple junction in the Hameimat and Sarir Troughs is thought to have an Early Cretaceous origin in which clastic reservoirs are juxtaposed against basin structures (El-Alami, 1996a; Gras and Thusu, 1998; Ambrose, 2000). The syn-depositional clastics of the Sarir Formation occupy structural lows in the Sarir arm, and stratigraphic traps are important components of the petroleum system of this area. These Cretaceous clastic reservoirs are treated as a separate assessment unit within the total petroleum system. To the west, Late Cretaceous and lower Tertiary carbonate reservoirs, commonly reefs or bioherms

Figure 7. Stratigraphic section in central Sirte Basin (Sirte and Tibesti arms) (modified from Barr and Weeger, 1972; Montgomery, 1994). Primary hydrocarbon source and seal rock intervals are shown. Reservoirs are indicated by dots.

Figure 8. Stratigraphic section in eastern Sirte Basin (Sarir arm). The Sarir Sandstone is equivalent of the Nubian Sandstone of figure 7. Modified from Ambrose (2000).

on the northwest-southeast-trending horsts, are the dominant reservoirs in the remaining two arms (the Tibesti and Sirte arms) of the triple junction.

The complex tectonic history of the Sirte Basin resulted in multiple reservoirs and conditions that favored hydrocarbon generation, migration, and accumulation, principally on or adjacent to the horst blocks. Carbonate reservoirs including bioherms mostly Paleocene and Eocene age (some Oligocene), were also concentrated on the structural highs in the central Sirte Basin, principally along the southern portion of the province in the Az Zahrah, Al Bayda, and Al Janamah Platforms (also known as the Zeltan, Beda, Dahra, and Zalten Platforms, figs. 2, 5). These reservoirs were in turn charged by vertical migration along faults during the peak petroleum generation period of the early Tertiary; the conditions favoring concentration of petroleum in reservoirs of various ages along horst boundaries are demonstrated in figure 5. The so-called transfer zones of Harding (1984), Knytl and others (1996), and Van Dijk and Eabadi (1996) provide opportunities for the development of stratigraphic or a combination of stratigraphic and structural traps orthogonal to the trends of the horsts and grabens. Stratigraphic nomenclature used in this report is shown in figures 7 (Sarir arm) and 8 (Tibesti and Sirte arms).

Total Petroleum System

Petroleum Occurrence

There is one dominant total petroleum system in the Sirte Basin, here named the Sirte-Zelten Total Petroleum System. The naming of the total petroleum system follows the convention of Magoon and Dow (1994) whereby the principal source rock is the Upper Cretaceous (Senonian/Campanian) Sirte Shale (also referred to as "Sirt Shale") of the Rakb Group (figs. 7, 8, 9; El-Alami, 1996a, b). Some authors have distinguished an Upper Sirte Shale (Campanian) and a Lower Sirte Shale (Turonian), separated by a Tagrifet Limestone (Coniacian/Santonian); all are considered source rocks (Mansour and Magairhy, 1996).

The reservoirs in the total petroleum system are nearly equally divided between clastic and carbonate rocks: clastic fields have 14.5 BBOE known reserves versus 10.6 BBOE known reserves for carbonates as of 1994 (Montgomery, 1994). However, as shown by Harding (1984), the carbonates of the Paleocene Zelten Formation, containing an estimated 8.5 BBO of ultimate recoverable reserves (33 percent of total EUR), are the single largest reservoirs. The Sirte-Zelten Total Petroleum System is divided into four assessment units (fig. 1), as will be discussed later.

The Sirte Basin is an example of a dominantly vertically migrated petroleum system as shown by Harding (1984), wherein Upper Cretaceous oil charges multiple reservoirs along fault zones adjacent to horsts and grabens (Price, 1980, fig. 9). Guiraud and Bosworth (1997) demonstrated the importance of right-lateral wrench fault systems of Senonian age, and pointed out that the periodic rejuvenation of these systems in the Sirte Basin was particularly important to vertical migration of petroleum. Refinements of a dominantly vertical horst and graben

Figure 9. Schematic cross section showing general structural position, stratigraphic age, and lithology of most traps within the onshore Sirte Basin (modified from Harding, 1984). Note Upper Cretaceous source rocks charging multiple reservoirs on platforms (horsts). Barbs show direction of relative movement on faults.

Figure 10. Burial history curve for deepest portion of Sirte Trough (the Hameimat Trough), southeastern Sirte Basin (modified from Bender and others, 1996). USS, upper Sarir Sandstone; VS, variegated shale; MSS, middle Sarir Sandstone.

model were provided by Baird and others (1996), who argued for normal listric extensional and growth faults in the Sirte Basin as opposed to the more nearly vertical faulting described by Harding (1984). The structural history is also complicated by the development of transfer or relay fault zones (transtensional and transpressional areas) that produced additional migration routes to reservoirs occupying horst blocks (Knytl and others, 1996; Van Dijk and Eabadi, 1996).

A contrasting view is offered by Pratsch (1991), who believed that the Sirte Basin was an example of lateral migration and vertically stacked hydrocarbon systems isolated from each other. However, the oils in the various age reservoirs have been shown to be genetically linked (for example, El-Alami, 1996b; Gumati and Schamel, 1988; Gumati and others, 1996). Internal seals occur between the major reservoirs, so if one were considering the oils at a reservoir or play level (regardless of the source of the oil) then Pratsch's concept is understandable. At the larger petroleum system level, on the other hand, the Sirte Basin is considered to be an example of a composite petroleum system in which petroleum sourced from Upper Cretaceous shales has migrated into multiple age reservoirs, dominantly vertically along normal, transfer, relay, or wrench faults adjacent to horsts. (See Harding, 1984; Baird and others, 1996; Van Dijk and Eabadi, 1996; and Guiraud and Bosworth, 1997.)

Source Rock

Published studies support the interpretation that the Sirte Shale (Upper Cretaceous, Campanian/Turonian) is the dominant source rock in the Sirte Basin petroleum province (Parsons and others, 1980; Gumati and Schamel, 1988; Montgomery, 1994; El-Alami, 1996b; Ghori and Mohammed, 1996; Mansour and Magairhy, 1996; Macgregor and Moody, 1998; Ambrose, 2000). The thickness of the Sirte Shale ranges from a few hundred meters to as much as 900 m in the troughs. These rocks are within the oil-generating window between depths of 2,700 and 3,400 m in the central and eastern Sirte Basin (Futyan and Jawzi, 1996; fig. 1). In figure 1, the outlines of the active pods of thermally mature Upper Cretaceous source rock are drawn reflecting depth of burial of at least 2,865 m (9,400 feet) (Mikbel, 1979; Goudarzi, 1980; Gumati and Kanes, 1985; Ibrahim, 1996), where conditions are considered favorable for oil generation (time temperature index (TTI)=15, vitrinite reflectance (Ro)=0.7; Gumati and Schamel, 1988; Montgomery, 1994; fig. 10). Parsons and others (1980) reported total organic content (TOC) values ranging from 0.5 to 4.0 percent with an average of 1.9 percent TOC for 129 samples from the Upper Cretaceous source rocks. Baric and others (1996) presented organic geochemical data for a 500 m section of Sirte Shale in wells on the Zelten Platform (southern Sirte

Figure 11. Postulated petroleum migration pathways for oil sourced from Upper Cretaceous shales, which also provide a regional seal in Sarir arm area of eastern Sirte Basin. Modified from Ambrose (2000).

Figure 12. Postulated pre-Upper Cretaceous source areas and migration pathways of minor nonmarine source rocks in eastern Sirte Basin. Modified from Ambrose (2000).

Basin), in which total organic carbon (TOC) exceeds 0.5 percent and ranges as high as 3.5 percent; and hydrogen indices (HI) generally exceed 300 milligrams of hydrocarbon per gram of organic carbon (mg HC/g org.C) and reach as much as 600 mg HC/ g org. C). Organic matter is dominantly Type II, and the shales are oil prone. El-Alami (1996b) documented Upper Cretaceous source rocks ranging from 0.10 to 7.86 percent TOC in the Etel and Rachmat Formations (Cenomanian-Turonian) and recorded an average of 1.28 percent TOC for the Sirte Shale in the Abu Attifel (Sirte Graben) in the eastern Sirte Basin.

Several other potential source rocks of ages other than Late Cretaceous have been considered; Burwood (1997), for example, identified source potential in four mudstones within deeper parts of the Sirte Basin including the Sirte Trough. These potential source rocks occur in the Sirte Shale (Upper Cretaceous), a lower part of the Nubian Formation (Triassic–Lower Cretaceous), the Harash Formation (Paleocene), and the Antelat Formation (Eocene, Gir Formation equivalent) (figs. 7, 8). Silurian age source rocks, the Tanezzuft Formation, may be potential in Algeria where present in deeper areas off the flank of the ancestral Sirte Arch, and in the offshore area where the Silurian may be present (Futyan and Jawzi, 1996; Klitzsch, 1996, Gumati and others, 1996; fig. 6).

El-Alami (1996b) concluded that the mudstones within the Nubian (Sarir) Formation (particularly in the Lower Cretaceous part) are mature enough to generate oil in the deep parts of the Sirte Basin, but "their richness does not appear to be sufficient to cause generation of large amounts of hydrocarbons" (p. 347). Ambrose (2000) considered the Upper Cretaceous "Tethyan" shale system to be the dominant source rock, with particular emphasis on the Sirte Shale as being the primary source rock in the eastern Sirte Basin. He further concluded that potential Triassic source rocks are of limited distribution but as yet are not well known (compare figs. 11 and 12).

Geochemical data based on analyses of 81 oils from Libya (GeoMark, 1998) indicate that the Sirte Shale is the dominant source rock in the Sirte Basin province. Sirte oils are low sulfur and of relatively high gravity; for example, median oil gravity is 36°, ranging from 30° to 43° API, and median sulfur content is 0.3 percent (Petroconsultants, 1996; GeoMark, 1998; fig. 13). The oil generally has low gas/oil ratios (median 300 ft^3/ barrel, U.S. Geological Survey World Energy Assessment Team, 2000).

Although as many as four oil families can be identified, all but three of the 81 samples analyzed by GeoMark (1998) can be linked to a single oil family (Jerry Clayton, written commun., 1998) based on (1) pristane/phytane ratios (>1.0) to $\delta C13$ aromatic content, (2) sulfur content, (3) API gravity, and (4) $\delta C13$

Figure 13. Oil geochemistry plots utilizing data from GeoMark (1998) for 81 oil samples from 55 fields in Sirte Basin. *A*, Pristane/phytane ratios; *B*, Sulfur percentages; *C*, API gravity.

Figure 14. Sirte-Zelten Total Petroleum System events chart. Significant rock units noted on chart include GH, Gargaf/Hofra Formation—Cambrian-Ordovician sandstones; TZ, Tanezzuft Shale—Silurian; N, Nubian or Sarir Sandstone—Jurassic–Early Cretaceous; R, Rakb Group—Cretaceous, Turonian-Campanian; S, Sirte Shale Member of Rakb Group, primary source rock—Campanian; Z, Zelten Group carbonates—Paleocene; H, Hon Evaporite Member of Gir Formation—Eocene-Ypresian; G, Gialo Formation carbonates—middle Eocene–Lutetian; A, Arida Formation—Oligocene; M, Marada Formation—Miocene.

saturates vs. δC13 aromatic characteristics (fig. 13). El-Alami (1996b), Jerry Clayton (written commun., 1998), and Ambrose (2000), concluding that the Upper Cretaceous Sirte Shale is by far the dominant source of oil for the Sirte Basin province, also recognized that there may be contributions from other Upper Cretaceous source rocks in a composite total petroleum system, the Sirte-Zelten. (See Glossary in U.S. Geological Survey World Energy Assessment Team, 2000.)

The remaining three oils analyzed by GeoMark (1998) appear to be younger (Tertiary, most probably reflecting a Paleocene/Eocene source); however, they may also reflect biodegradation of the Upper Cretaceous source (Jerry Clayton, written commun., 1998).

Tertiary petroleum systems may possibly exist in the deeper part of the Sirte Basin (for example, the Sirte or Ajdabiya graben of Baird and others, 1996, figs. 1, 6) and in offshore areas. A distinctly different oil—lower gravity (<25° API), high sulfur (as much as 4.5 percent), and pristane/phytane ratios <1.0—is found in lower Tertiary reservoirs, particularly Eocene sequences (for example, Kalash Limestone, Gir or Kheir Formations, figs. 7, 8). Tertiary carbonates may contain indigenous hydrocarbon sources particularly in Eocene rocks (Gir Formation) that could potentially have contributed about 1 billion barrels of recoverable oil reserves in the Pelagian Basin (Bouris, Ashtart, Sidi el Itayem fields, fig. 3) to the northwest of the Sirte Basin (Bishop, 1985,1988; Rodgers and others, 1990). However, few data are available on these potential source rocks in the Sirte Basin. Abugares (1996) concluded that hydrocarbons in the Gir Formation are actually sourced by Sirte Shales. El-Alami (1996b) and MacGregor and Moody (1998) suggested a secondary contribution, where mature, from the Paleocene Heria Shales, which are depositionally similar to the Sirte Shale; they also recognized the possibility of other Tertiary-age source rocks, including the Kheir and Harash Formations (Paleocene/Eocene, figs. 7, 8).

As shown on the events chart (fig. 14), hydrocarbon generation commenced about 50 million years ago (Ma) in the deeper basins, about 40 Ma in many other areas, and may continue to the present day. Geothermal gradients generally range from 1° F / 100 ft to 1.8° F / 100 ft; in general the horsts and grabens have roughly equivalent thermal regimes relative to the primary source rock (Gumati and Schamel, 1988). Along the southwest and west margins of the province are extrusive igneous deposits (fig. 2) whose presence tends to diminish the hydrocarbon potential of these areas (Busrewil and others, 1996; Hallett and El Ghoul, 1996).

Overburden Rock

As shown on the events chart (fig. 14), the Upper Cretaceous Sirte Shale is the source rock deposited generally in grabens that had formed during a period of active rifting in the Sirte and Tibesti arms of the rift system (fig. 2). During the Cretaceous, there were apparently two distinct rifting stages related to different limbs of a triple junction that were active at different times. In the eastern part of the Sirte Basin, the development of a series of east-west-trending horsts and grabens in the Sarir arm (fig. 2) was accompanied by syn-rift deposition of Early Cretaceous clastics called the Nubia or Sarir Sandstone. These clastic materials were deposited within the rift basins, and some formed significant stratigraphic traps adjacent to horst blocks such as Messla and Sarir fields (Ambrose, 2000; figs. 15–18).

Northwest-southeast-trending horst and graben structures formed in the Sirte arm of the triple junction from the Late Cretaceous to the end of the Paleocene in the central and western Sirte Basin, with the younger trends extending offshore (fig. 2; Van der Meer and Cloetingh, 1996; Guiraud and Bosworth, 1997). Overburden was largely deposited during the post-rift sedimentation stage (Oligocene and younger). Pre-rift and early syn-rift deposition was largely clastic whereas later syn-rift deposition was dominated by carbonate deposition. According to Hallett and El Ghoul (1996) (1) the deepest troughs, such as the Sirte (also called Ajdabiya Graben, fig. 2), have more than 7,000 m of sediment, of which 5,500 m is of Tertiary age (fig. 5); and (2) 80 percent of the drilling in the province has been on platform (horst) areas at depths less than 3,000 m.

Reservoir Rock

The distribution and quality of reservoirs in the Sirte Basin are most directly related to major tectonic events in the region, specifically reservoirs related to pre-rift, syn-rift, and post-rift sequences (figs. 7, 8). The current configuration of the Sirte Basin, deepening from west to east and also offshore, significantly influenced reservoir development. The basin is unusual in that oil is produced from Precambrian (fractured basement), Cambrian-Ordovician, Triassic through Lower Cretaceous, Paleocene, and Eocene rocks. Charging of multiple reservoirs from Upper Cretaceous source rocks along faults, principally along horst blocks, is illustrated in figure 9. Carbonate reservoirs, mostly of Tertiary age, contain 42 percent of the petroleum; and clastics, mostly of pre-Tertiary age, contain 58 percent (Harding, 1984; Petroconsultants, 1996). Carbonates of the Paleocene Zelten Group contain 33 percent of the known petroleum; this is the single largest reservoir interval. However, the clastics of Early Cretaceous age (Nubian or Sarir Sandstone) contain 28 percent, and clastics of Cambrian-Ordovician age (Gargaf, Hofra or Amal Group) contain 29 percent of known petroleum volume (fig. 9).

Montgomery (1994) divided the stratigraphy of the Sirte Basin into four megacycles (fig. 7). The oldest, of Paleozoic age, consists mostly of nonmarine clastics and some volcanic rocks, bounded by a Precambrian unconformity below and the Hercynian unconformity of Late Permian and Early Triassic age above; local thicknesses are as much as 1,500 m. Cambrian-Ordovician sandstones, variously called Gargaf (western Sirte Basin), and Hofra Formation or Amal Group (central Sirte Basin; fig. 7) are important reservoirs. These reservoirs produce oil in 23 fields, at least 5 of which are giant accumulations—Amal, Raguba, Nafoora, Samah/Bel Hadan, Waha fields (fig. 1). Following deposition of the Cambrian-Ordovician, uplift occurred and much of the Paleozoic section was eroded from the central Sirte area (Massa and Delort, 1984; Anketell, 1996, fig. 6). However, Cambrian-Ordovician reservoirs are preserved particularly in fault blocks related to subsequent rifting, and possibly in some of the offshore areas as well. The Cambrian-Ordovician reservoirs are commonly tightly cemented orthoquartzites (Roberts, 1970;

Figure 15. Tectonic elements and oil fields in eastern Sirte Basin. Sarir Sandstone isopachs are shown in main depocenters (modified from Ambrose, 2000). Cross section *A–A'* shown in figure 16.

Barr and Weegar, 1972; Brennan, 1992). Production is enhanced by fracturing as noted by Roberts (1970) at Amal field and Brennan (1992) at Raguba field. In a few areas, Silurian, Devonian, and Carboniferous clastics are preserved and are potential reservoirs (fig. 6).

The Nubian (Sarir) deposits, ranging from Triassic/Late Jurassic? to Early Cretaceous in age, constitute the second major megacycle in the Sirte Basin province (Montgomery, 1994; El-Hawat and others, 1996; this report, figs. 7, 8) and are the producing interval in at least 72 fields in the eastern Sirte Basin (Petroconsultants, 1996). These clastic strata are the primary reservoirs in several giant fields including Messla, Sarir, Amal, and Abu Attifel fields (fig. 1). The reservoirs are continental sandstones, both alluvial and eolian deposits, although Ambrose (2000) identified significant reservoirs in the Upper Sarir Sandstone that are fan delta deposits. El-Hawat and others (1996) divided the Nubian Sandstone into three members that reflect the interfingering of alluvial deposits with Tethyan marine sediments as the Sirte rift system began to develop in Neocomian-Barremian time (El-Hawat, 1996; Ambrose, 2000). East-west-trending sinistral shear zones (strike-slip) strongly controlled deposition of the Nubian sequence according to Anketell (1996) and Abdulghader (1996), and Ambrose (2000) documented the sedimentological pattern and heterogeneities within the Nubian sequence that may have enhanced hydrocarbon potential of the Sarir Sandstone in the eastern Sirte Basin.

Figure 16. Stratigraphic cross section *A–A'* in Calanscio-Hameimat Trough (line of section shown in fig. 15). Note subdivisions (members) within the Sarir Sandstone and the combined structural-stratigraphic trap at Sarir-C field (modified from Ambrose, 2000).

The Nubian (Sarir) Formation is highly variable in thickness (maximum as much as 2,500 m); that variation reflects the infilling of low areas (grabens) that partially extend across some Cretaceous horsts and formed prolific stratigraphic/structural traps such as Sarir field (Sanford, 1970; Lewis, 1990) and Messla field (Clifford and others, 1980; Koscec and Gherryo, 1996; Ambrose, 2000; this report, figs. 15–18). Lewis (1990) suggested that Sarir field is a complex of individual fields, Sarir C alone containing 6.5 BBO EUR. A cross section from Messla field by Ambrose (2000), shown in figures 15–18, portrays the major stratigraphic truncation that occurs in the Sarir Sandstone across the structural high and the opportunity for additional exploration targets near these terminations, such as in the Upper Sarir fan delta deposits. Abdulghader (1996) documented average porosity of 27.5 percent for the main Sarir reservoir. Lewis (1990) documented average porosity of 18–19 percent, and average permeability of 200–300 millidarcies at Sarir field.

The third megacycle, largely composed of marine deposits, of Late Cretaceous and early Tertiary ages, encompasses the entire Sirte Basin, and depositionally followed the early nonmarine graben fill of the Sarir (Nubian) sediments in the eastern Sirte Basin. As summarized in Montgomery (1994), two major Upper Cretaceous transgressive and regressive cycles and two Paleocene cycles of sedimentation characterize this later syn-rift fill

Figure 17. East-west structural cross section across western margin of the Messla High (modified from Ambrose, 2000). Note that faulting caused erosion of different members of the Sarir Sandstone along the highs.

Figure 18. Schematic structural cross section from Sarir Trough across Messla High and into Hameimat Trough showing hydrocarbon habitat of the Sarir Sandstone (modified from Ambrose, 2000). Note truncation and stratigraphic trap potential in various members of the Sarir Sandstone. Scale is approximate.

sequence (fig. 7). Sedimentation was largely controlled by northwest-southeast-oriented horst and graben structures. Erosion along the Sirte Arch in the central Sirte Basin has removed evidence of the older sediments, including the Lower Cretaceous clastics, although the hydrocarbon potential is largely undeveloped in structurally low areas within the central Sirte Basin.

The first Upper Cretaceous depositional cycle consists, in ascending order, of (1) a transgressive sequence comprising the Bahi Formation; (2) carbonates, commonly represented by dolomites of the Lidam Formation; and (3) a regressive sequence of carbonates, evaporites, and shales that now characterize the Etel Formation (a potential source rock interval, figs. 7, 8). A second transgression resulted in the deposition of shallow marine sediments (Rachmat Formation) followed by deposition of deep marine sediments (Sirte Shale). Shallower water sequences in the younger Cretaceous Kalash Limestone are in turn overlain by shales (Hagfa Shale, similar lithologically to the Sirte Shale) and carbonates (Beda Formation) of Paleocene age. The Beda Formation is a significant reservoir, commonly consisting of calcilutite, calcarenites, oolites, and skeletal debris along the south margin of the Sirte Basin; and significant production has taken place in fields such as Dahra and Hofra and in many fields on the Az Zahrah (Dahra and Beda) and Zelten (Al Janamah) platforms (Bebout and Poindexter, 1975; Brady and others, 1980; this report, figs. 2, 5).

Continued sedimentation during Paleocene time resulted in deposition of the Zelten Formation, which is notable for its carbonate build-ups and reefs that grew on the structurally elevated horsts such as the Az Zahrah (Beda and Dahra) Platform and the Zelten (Al Janamah) Platform. As previously discussed, the Zelten Formation is the single largest reservoir interval in the Sirte Basin province. Carbonates, mostly Upper Cretaceous, Paleocene, and Eocene, are the dominant reservoirs in 150 fields encompassed in the area shown as assessment unit 20430102 in figure 1. Carbonate deposition in the late syn-rift sequences took place particularly during Paleocene time on the platforms along the south margin of the Sirte Basin. Carbonates are important reservoirs in many giant oil fields such as Intistar, Beda, Defa, Waha, Haram, Zelten (Nasser), Hofra, and Nafoora (Belazi, 1989; Roohi, 1996b; figs. 1, 19).

The upper Paleocene regression of this megacycle is represented by the deposition of shallow marine carbonates (Harash and Kheir Formations) followed by transgressive deposits of the Facha Dolomite (fig. 7). These were ultimately overlain and subsequently sealed in a final regression of this megacycle by the evaporites of the Gir Formation (Hon Evaporites Member). The carbonates in the upper part of the Gir Formation are the stratigraphically youngest potential reservoirs, containing about 1 percent of the proven hydrocarbon reserves in the Sirte Basin. Stratigraphic traps within the Eocene strata, including nummulitic banks and dolomite zones in the Facha Dolomite (fig. 7) as well as possible indigenous, high sulfur (3 percent), heavy oil shows in tests near Beda-Haram, between Intisar and Amal fields, and in the eastern Sirte Basin (Ghori and Mohammed, 1996, fig. 1) indicate that the Eocene sequence may be an exploration target in the deeper portions of onshore grabens and offshore (Abugares, 1996).

The final megacycle represents the post-rift fill of Oligocene and younger age and is of minor potential for hydrocarbons because no commercial shows of hydrocarbons have been found in rocks younger than Eocene.

In general, clastic reservoirs are dominantly of Early Cretaceous and older (pre-rift, early syn-rift) ages in the eastern Sirte Basin, whereas carbonate reservoirs are dominantly uppermost Cretaceous, Paleocene, and Eocene (syn-rift or late syn-rift) elsewhere in the Sirte Basin province. The assessment units, discussed later, were delineated using these criteria.

Seal Rock

Although carbonates and shales dominate much of the Tertiary sequence, the evaporite and salt deposits of the Eocene Gir Formation (Hon Evaporites Member; Abugares, 1996; fig. 7) are of the utmost importance to petroleum accumulation in the Sirte Basin province because they form essential seals for the hydrocarbons migrating out of the Upper Cretaceous into reservoirs of many ages along the faulted horsts and grabens (Harding, 1984; Montgomery, 1994; Abugares, 1996; figs. 7, 9). The formation shows rapid changes in thickness, reaching a maximum of 1,305 m in the Marada Trough. It contains dolomite, anhydrite, and halite, but also shows abrupt lithologic changes. In some areas, halite forms 35 percent of the total section, as in the Zallah Trough (Abugares, 1996), but the salt component decreases dramatically around the onshore margins of the Sirte Basin, which might help to explain the absence of significant oil fields near the outcrop belt and the high risk of drilling in the offshore area.

Trap Style

Shown on the oil and gas field map for the Sirte Basin (fig. 1) are the 237 fields that were considered in this study. Of these fields, 221 are oil fields and 16 are gas fields (Petroconsultants, 1996). Known petroleum volumes of 43.1 BBOE rank the Sirte Basin province as the 13th in the world, exclusive of the U.S. (15th if U.S. provinces are included). It is dominantly an oil province with 36.7 BBO, 37.7 TCFG (6.3 BBOE), and 0.1 BB NGL (Klett and others, 1997). Twenty-three fields are major oil fields (>100 MMBOE), and 16 fields rank as giant oil fields (>500 MMBOE).

The dominant trap style is structural (84 percent), with the remainder considered stratigraphic or a combination of the two (Clifford and others, 1980). As examples of combined traps, bioherm developments in the Paleocene Zelten Group are found on horst blocks, and clastic stratigraphic traps such as at Sarir or Messla field are superimposed on structures (figs. 15–18). Similarly, bioherm development in Paleocene sediments of the Zelten Group in the Zelten field (Bebout and Poindexter, 1975), which occurs on a major horst, is shown to represent the carbonate assessment unit (20430102). An example of such a carbonate field is shown for Idris field in the northeastern Sirte Basin (Terry and Williams, 1969; this report, fig. 19).

Petroleum Assessment

The discovery history of the Sirte Basin started relatively late (as discussed earlier) because Libya did not really become an

Figure 19. Stratigraphic cross section through Zelten Formation (Paleocene) bioherms, Idris "A" field, northeastern Sirte Basin, representing reservoirs in carbonate assessment unit (modified from Terry and Williams, 1969).

independent country until 1951. Giant fields were found between 1956 and 1961, including Amal, Sarir, Raguba, and Zelten platform fields (Carmalt and St. John, 1986; Brennan, 1992; fig. 1). Three distinct discovery segments are seen on cumulative oil plots—a steep segment from 1956 to 1961, an intermediate segment from 1962 to 1970, and a nearly flat segment since 1970 (fig. 20). The discovery process has been interrupted by political events, including sanctions against Libya that prohibited U.S. company involvement in exploration in Libya since 1981. Montgomery (1994) and MacGregor and Moody (1998) have contended that the Sirte Basin has a significant future potential, citing the fact that the North Sea is three times more heavily explored than the Sirte Basin as a comparison.

Four assessment units within the Sirte-Zelten total petroleum system (two established, two hypothetical) were defined for the present study; they are as follows:

Southeast Sirte Clastics (20430101) is an established unit and includes Cretaceous and older (Cambrian-Ordovician, Precambrian) fields in the onshore area of the eastern Sirte Basin (fig. 1).

Central Sirte Carbonates (20430102) is an established unit and contains fields producing from carbonates of the Upper Cretaceous, Paleocene, and Eocene platforms, mostly onshore, with potential for production to water depths of about 200 m (fig.1). Offshore production has been established in the water depth range of 200 m or less in the Gulf of Sirte (figs. 1, 2). Some minor calcarenite Middle Cretaceous production is also included in these fields.

Offshore Sirte Hypothetical (20430103) extends from water depths of 200 m to 2,000 m and does not contain any established fields, although hydrocarbon shows have been encountered. Both positive and negative petroleum factors are recognized for this area. On the positive side is the likely presence of thermally mature Upper Cretaceous and possibly Silurian and Eocene source rocks, and the likelihood of both carbonate and clastic reservoirs being present. On the negative side, tectonic complexity is considerable, including a subduction zone and numerous extrusive magmatic features that may have compromised preservation of the total petroleum system (figs. 4, 5). To address such circumstances (and uncertainties), the world petroleum assessment (U.S. Geological Survey World Energy Assessment Team, 2000) takes into account three geologic risk elements pertaining to rock characteristics (source, reservoir, and seal), migration and trapping conditions, and timing of geologic events as well as an additional risk involving accessibility for exploration. Two of the three geologic risk factors are applied (1.0 indicating no risk) in this assessment unit: (1) rocks (0.8 or an 80 percent chance of success), and (2) timing of geologic events (0.6 or a 60 percent chance of success).

Southeast Sirte Hypothetical (20430104): Although there have been more than 65 wildcat tests in the southeastern Sirte Basin, none had hydrocarbon shows, according to Petroconsultants (1996). This area is therefore also considered to be a

Figure 20. Cumulative plot of volume of known oil (produced and remaining) versus field discovery year for Southeast Sirte Clastics Assessment Unit (from U.S. Geological Survey World Energy Assessment Team, 2000).

Table 1. Sirte-Zelten, Total Petrolem System 204301—assessment results summary.

Figure 21. Volumetric assessment results for geologically risked assessment units in Sirte-Zelten Total Petroleum System in Sirte Basin province 2043.

Figure 22. Volumetric assessment results for geologically risked and unrisked assessment units in Sirte-Zelten Total Petroleum System in Sirte Basin.

Figure 23. Comparison of U.S. Geological Survey World Energy Assessment Team (2000) mean risked estimates for oil, natural gas, and natural gas liquids versus Masters and others' (1994) mean estimates, Sirte Basin province 2043.

hypothetical assessment unit. The Southeast Sirte Hypothetical (20430104) represents the possibility of hydrocarbon charging dominantly shallow clastic reservoirs along major fault systems. Potential reservoirs include Campanian marine bar sandstones (Hammuda, 1980; Montgomery, 1994).The entire risk (0.5 or a 50 percent chance of success) for this assessment unit is taken in the risk element involving the sourcing of petroleum for reservoir rocks, because reservoirs and geologic structures appear to be abundant. Lateral migration would be required to charge reservoirs in this assessment unit.

Field growth has occurred in the Sirte Basin, as documented by Montgomery (1994); for example, Mabruk field has recently added more than 1 billion barrels of new reserves (fig. 1). For estimation of undiscovered field sizes, a Lower U.S. 48-field-growth model was used, as described by Schmoker and Crovelli (1998). Proprietary reserve data from North Africa presented to us from World Energy consortium members are consistent with the Lower U.S. 48-field-growth algorithm as defined by Schmoker and Crovelli (1998).

The last assessment reported by the U.S. Geological Survey for undiscovered oil and natural gas was given by Masters and others (1994), who reported mean undiscovered petroleum resources for Libya as 7.1 BBO, with a 95 percent to 5 percent fractile range of 3.5 to 13.3 BBO; mean undiscovered gas volume of 23.9 TCF, with a 95 percent to 5 percent fractile range of 8.9 to 48.9 TCF of gas; and mean undiscovered 0.4 BBNGL. Ahlbrandt and others (1998) tested several methods for calculating undiscovered resources in the Sirte Basin. The discovery process method calculated a median estimate of 12.2 BBOE, and the fractal method calculated an estimate of 47.5 BBOE. The median value of Masters and others' (1994) assessment, which was a geologically based Delphi estimate, was 10.7 BBOE and a mean of 11.5 BBOE.

The results of the current resource estimates are shown in table 1 and in figures 21 and 22. These estimates are derived from geologic inputs to the Monte Carlo probabilistic model developed for the World Energy Project (Charpentier and Klett, 2000). Risking structure and other methodological considerations are provided in chapters within the recent world assessment (U.S. Geological Survey World Energy Assessment Team, 2000).

Following is a summary of the unrisked assessments for the two established assessment units and the risked assessments for the two hypothetical assessment units in the Sirte Basin province (figs. 21, 22). The mean geologically risked (GR) estimates compare favorably with the estimated mean of Masters and others (1994). The current mean resource estimates are 11.63 BBOE (unrisked) and 8.98 BBOE (risked; fig. 23).

Compared to Masters and others (1994), less natural gas is estimated for the Sirte Basin as a result of the present study. This reduction is in large part due to reduced amounts of gas associated with Sirte Basin oils calculated on the basis of very low gas/oil ratios (GOR median used in this assessment is 300; U.S. Geological Survey World Energy Assessment Team, 2000), reflecting data available to us from Petroconsultants (1996) and GeoMark (1998). The geologically risked numbers reflect levels of uncertainty for the two hypothetical assessment units.

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