Stellingen behorende bij het proefschrift:

_The structural, paleogeographical and hydrocarbon systems analysis of the Ghadamsis and Murzuq Basins, West Libya, with emphasis on their relation to the intervening Al Qarqaf Arch._

_Yahia Ahmed M. Al Festawi, TU Delft, September 18, 2001_

1. De grootste concentratie van koolwaterstof voorkomt veelal naast en boven opwellingen voor die zich in of bij sedimentaire bekkens bevinden. (Dit proefschrift)

2. De beste manier om onzekerheid te beperken bij bestudering van de ondergrond is om een probleem te benaderen met behulp van verschillende niet-gerelateerde methodes, met gegevens die op verschillende manieren vergaard zijn. (Dit proefschrift)

3. De beperkingen op het publiceren van gegevens van olievelden belemmeren het behalen van voordelen die anders uit regionale gegevensbestanden afgeleid zouden kunnen worden. (Dit proefschrift)

4. Regionale gegevens over grondwater chemie en drukverdeling worden vaak genegeerd in olie exploratie hoewel deze van cruciaal belang kunnen zijn voor het begrijpen van de migratie en accumulatie van olie en gas. (Parke Dickey in vele van zijn publicaties)


6. De gehele kostbare inspanning van acquisitie en analyse van exploratie gegevens wordt dikwijls gecomprimeerd in een enkel getal (NPV, OIP) dat wordt doorgegeven aan het management. Besluiten worden derhalve vaak in isolatie genomen met een fractie van de beschikbare gegevens. Geautomatiseerde besluitvorming en risicoanalyse kunnen deze flessenhals ontwijken, en een platform creëren waar alle informatie gewogen wordt en alle mogelijke alternatieven in een prospect tegelijkertijd worden geëvalueerd.

7. Er zijn slechts twee noodzakelijke ingrediënten voor exploratie: geluk en geld.

8. Niet de zee, noch zand of ijs bedekking, maar door mensen ingestelde natuurreservaten vormen de laatste grens in olie exploratie.

9. Grondwater is van grotere waarde voor woestijnbewoners dan ruwe olic.


11. Een trein stopt bij een treinstation, een bus stopt bij een busstation en werk stopt bij een werkstation. (Prof. ir. K.J. Weber, Technische Universiteit Delft)

12. Het uitvoeren van promotieonderzoek en het hebben van een gezin is als een oorlog op twee fronten; de geschiedenis leert dat dit niet langer dan een paar jaar volgehouden kan worden.
Propositions pertaining to the dissertation:

The structural, paleogeographical and hydrocarbon systems analysis of the Ghadamis and Murzuq Basins, West Libya, with emphasis on their relation to the intervening Al Qarqaf Arch.

Yahia Ahmed M. Al Festawi, TU Delft, September 18, 2001

1. The largest concentration of hydrocarbon accumulations is frequently found near and over arches in or adjacent to sedimentary basins. (This thesis)

2. In subsurface analysis the best way to reduce uncertainty is to tackle a problem by using several unrelated methods, with data gathered in several different ways. (This thesis)

3. The restrictions on publishing oil field information prevent the reaping of benefits that otherwise could be derived from comprehensive regional databases. (This thesis)

4. Data on regional water chemistry and pressure distribution are often neglected in hydrocarbon exploration although these can be of crucial importance in the understanding of the migration and accumulation of oil and gas. (Parke Dickey in many of his publications)

5. The risk of overlooking potentially important information during the visual or digital interpretation of data is considerable, and difficult to control. (From: Spatial data integration for mineral exploration resources assessment and environmental studies: a guide book, IAEA Publication, December, 1994, p.155).

6. The entire costly effort of acquisition and analysis of exploration data is often condensed to a single figure (NPV, OIP) that is passed on to management. Therefore decisions are often made in isolation on a fraction of the available information. Computerized decision and risk analysis may avoid this bottleneck and establish a platform where all information is weighted and all possible alternatives in a prospect can be evaluated simultaneously.

7. There are only two essential ingredients for exploration: luck and money.

8. Not the sea, not sand or ice sheets, but human-declared nature reserves form the last frontier to oil exploration.

9. Groundwater is more valuable than crude oil to desert inhabitants.

10. The Internet is the virtual end of distance.

11. A train stops at the train station, a bus stops at the bus station and work stops at a workstation. (Prof. ir. K.J. Weber, Delft University of Technology)

12. Doing Ph.D. research while having a family is like fighting on two fronts; history shows that this cannot be sustained for more than a few years.
The structural, paleogeographical and hydrocarbon systems analysis of the Ghadamis and Murzuq Basins, West Libya, with emphasis on their relation to the intervening Al Qarqaf Arch.
Dit proefschrift is goedgekeurd door de promotor:

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Cover image: Combination of Landsat TM mosaic and shaded relief map of aeromagnetic coverage of West Libya
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INTRODUCTION
1.1 Background of the research

The Paleozoic Ghadamis Basin, which forms the northern part of the study area, is one of the major depositional basins of North Africa, extending into large areas of the eastern Algerian desert and southern Tunisia. It is delineated in the north by the Nefusah Uplift and to the east and the south by the Hun Graben and Al Qarqaf Arch, respectively. South of Al Qarqaf Arch, the Murzuq Basin is located, bounded by the Tibisti Uplift to the east and southeast and by the Tihembokah Arch in Algeria to the west. The basin extends southwards into Niger where it is known as the Djadu Basin before terminating against the Pre-Cambrian Hoggar Massif. Al Qarqaf Arch is a major SW-NE structural feature, separating the Ghadamis Basin to the north from the Murzuq Basin to the south. The thickness of the sedimentary cover lying on the axis of the arch is less than that on any other arch in Libya. The degree of influence of the arch on the structural and stratigraphical framework of the two basins and on the occurrence of hydrocarbon systems has not been well studied as yet.

Arching is a dynamic phenomenon that starts with the uplifting of part of the cratonic crust. If the arch continues to grow, it may spread over hundreds of kilometres. In many continents, records indicate that during Early Paleozoic times arching was the dominant intracratonic structural style. The paleogeographical effects of the arches determine the nature, size and trends of hydrocarbon traps in such regions.

According to Levorsen (1954), arches are broad uplifts of low relief, characterized by a small total thickness of overlying sediments. Such features form centres or axes away from which all formations dip, and consequently towards which any oil and gas would converge. The stratigraphical sequence is frequently interrupted by truncation and unconformable onlap and by faulting, local folding and facies changes. While most producing provinces seem to be closely associated with sedimentary basins that have thick sedimentary sequences, on closer inspection many prolific provinces appear to be related to intrabasinal basement uplifts, or second-order basins.

Mapping the arch structures of Libya, which separate most Libyan sedimentary basins one from another, can significantly enhance the understanding and modelling of their tectonic formation and deformation history. These arches were probably effective in localizing truncation, unconformities and the onlap of depositional sequences (Missalatti, 1986). Hence, they are likely to be focal points for oil migration and accumulation, especially in stratigraphical traps.
Chapter 1: Introduction

Al Qarqaf Arch is a major SW-NE trending structural feature in western Libya, which developed during the Hercynian Orogeny and separates two large Paleozoic basins, the Ghadamis Basin to the north and the Murzuq Basin to the south. The arch represents the highest basement surface in the area and includes the northernmost exposure of Pre-Cambrian in the African Craton (Goudarzi, 1980). The reason that the thickness of the sedimentary cover on the axis of the arch is less than that on any other arch in Libya may be due to an epeirogenic uprising and subsequent erosion along Al Qarqaf Arch, which may have been active for a long time after the Late Paleozoic. Of all Libyan arches, Al Qarqaf Arch is the best-exposed arch to be studied and separates two major hydrocarbon-producing sedimentary basins.

Exploration started in 1956 in the Ghadamis Basin and later in the Murzuq Basin. So far, no comprehensive study of all available information has been undertaken that would enable a regional analysis of the significance of Al Qarqaf Arch for the structural and stratigraphical framework of the Ghadamis and Murzuq Basins and of its implications for hydrocarbon exploration. Moreover, many water wells have been drilled in the eastern Jabal Al Hassawanah of Al Qarqaf Arch. Together with fieldwork observations and an analysis of the hydrocarbon seeps that are found along the arch, this could give important clues to the development of Al Qarqaf Arch.

1.2 Location

The research deals mainly with the western Paleozoic basins of Libya. The area lies between the plain of Hamada Al Hammra to the north, the Tihembokah Arch to the west, the Murzuq Sand Sea to the south and the Tripoli-Tibesti Arch and the Hun Graben to the east (Figure 1.01). The geographical boundaries are defined between the following coordinates: 24° 00’ and 31° 00’ N latitude and 10° 00’ and 15° 00’ E longitude.

1.3 Objectives

The study will focus on analyzing the influence of Al Qarqaf Arch on the stratigraphical and structural framework of the Paleozoic rocks in the adjacent Ghadamis and Murzuq Basins and its implication for hydrocarbon accumulations in the region. The objective and scope of this research is essentially fivefold:

1. Literature survey of arches worldwide, with special emphasis on Paleozoic arches.
2. Multisource investigation, mapping and analysis of the tectonic basement structures and their surface expressions in the area of Al Qarqaf Arch and the adjacent Ghadamis and Murzuq Basins, using remote sensing, aeromagnetic, seismic and well log data.

3. Analysis of the influence of Al Qarqaf Arch on the distribution of facies and on the depositional history and tectonic evolution of the Silurian and Devonian units, which are the main source and reservoir rocks in the Ghadamis and Murzuq Basins.

4. Analysis of hydrocarbon systems (e.g. play maps) in the Ghadamis and Murzuq Basins in relation to Al Qarqaf Arch.

5. Mapping and analysis of hydrocarbon seeps along Al Qarqaf Arch and its significance for hydrocarbon exploration in the area.

Figure 1.01 Generalized map of Libya and surrounding countries, showing location of the study area.
1.4 Data and methodology

Tables 1.01 and 1.02 summarize the data used in the study. A digital database was constructed for the data collected and integrated in different parts of the study. Different types of remote sensing data were used in different parts of the research. About 12 Landsat TM images, 182 Spot XS images and four Radar ERS-1 images were digitally enhanced and used for mapping structural features, lineament analysis and stratigraphy of the area. Landsat TM, Spot XS and Radar ERS-1 were merged for mapping surface structures, partly covered by sand sheets, in the central part of Al Qarqaf Arch. Landsat TM images were also used to map fault patterns in the area of hydrocarbon seeps along the southern part of Al Qarqaf Arch.

As a first step of the digital integration of spatial data, geometric correction and co-registration of all data types on a common cartographic projection has been applied. The UTM (zone 33N) was used as projection zone. The Landast TM, Spot xs and ERS-1 images were geometrically corrected by an image to map registration procedure.

Aeromagnetic data derived from a compilation of the African continent, and compiled at 1000 m terrain elevation (AMMP, 1992), were also digitally acquired and enhanced, and were subsequently used for mapping the structural framework of the area. The techniques applied include total intensity, analytic signal and second vertical derivative. These data are an excellent tool for both structural mapping and basement configuration mapping, especially in combination with remote sensing imagery.

Seismic sections were used along the western part of the Murzuq Basin for mapping the fault and fold patterns. Unfortunately, no good seismic sections were made available for the Ghadamis Basin. Tectonic displacement maps derived from seismic isopach maps were used in the study to map tectonic displacement in the central part of the Murzuq Basin.

About 120 well logs (lithology, gamma ray) distributed over the entire area of study were used for constructing structural, isopach, sand percentage and sand/shale ratio maps of Cambro-Ordovician, Silurian, Devonian and Carboniferous units (see Figure 3.03 for the locations of these wells). These units are the most important producing horizons in the Ghadamis and Murzuq Basins. The depths of basement data derived from some 54 oil and water wells that reach the basement were used to construct a structural contour map of the basement.
A digital database of reservoir characteristics, such as reservoir types, age, traps, thicknesses, lithology, source rock, etc., was constructed for about 70 oil and gas wells. This database was used to analyze the patterns of hydrocarbons in the area. Different image and data analysis systems were used to process and enhance the data: ER-Mapper® and Erdas® were used for remote sensing image analysis; Geosoft Oasis® was used for aeromagnetic data analysis; and Rockware software® was used for constructing different subsurface maps, rose diagrams and stereograms. Freehand® was used for drafting the maps and sections.

<table>
<thead>
<tr>
<th>Type</th>
<th>No of scenes</th>
<th>Path/row</th>
<th>Combination</th>
<th>Analysis and product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat TM (30 m resolution)</td>
<td>12 (186*186 km for each scene)</td>
<td>189-040/041/042, 188-040/041/042, 187-040/041/042, 186-040/041/042</td>
<td>Bands 1,4,7 (RGB)</td>
<td>Structural and lithological mapping. Lineament analysis.</td>
</tr>
<tr>
<td>Spot XS (20 m resolution)</td>
<td>182 (60*60 km each scene)</td>
<td></td>
<td></td>
<td>Bands 3,2,1 (RGB)</td>
</tr>
</tbody>
</table>

Table 1.01 Specifications and analysis of remote sensing images used in this study.

1.5 Innovative aspects of the proposed study

1. Literature survey of arches worldwide.

2. Relation of Al Qarqaf to the Ghadamis and Murzuq Basins.

3. No comprehensive basin-wide study published as yet.
4. Integration of data from various sources: geophysical (aeromagnetic, seismic), remote sensing (Landsat TM, Spot XS, Radar ERS-1), petroleum exploration (well data, oil field data) and water well data.

5. Modern techniques of basin analysis.

6. Significance for other (Paleozoic) basins with arches.

7. Comparison of the Ghadamis Basin (partly explored) with the Murzuq Basin (relatively unexplored). Both basins are underexplored. As a comparison: about 500 wells were drilled in an area of some 500,000 km² for the Ghadamis and Murzuq Basins, where as more than 4000 wells were drilled in the Sirt Basin (about 375,000 km²).

<table>
<thead>
<tr>
<th>Type</th>
<th>Format</th>
<th>No</th>
<th>Analysis and product</th>
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<tbody>
<tr>
<td>A. Geophysical:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Aeromagnetic</td>
<td>Raster</td>
<td>Entire area (23° to 33° N and 08° to 16° E).</td>
<td>* Basement topography and depths map.</td>
</tr>
<tr>
<td>1 km resolution.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Seismic:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Tectonic displacement map (derived from seismic isopach maps).</td>
<td>Hard copy</td>
<td>Two regional seismic sections in Murzuq Basin.</td>
<td>* Stratigraphic and structural cross sections.</td>
</tr>
<tr>
<td>2. Seismic sections.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Well logs:</td>
<td>Hard copy</td>
<td>120 well logs.</td>
<td></td>
</tr>
<tr>
<td>* Lithology logs.</td>
<td></td>
<td></td>
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<tr>
<td>* Gamma ray logs.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Oil and gas well data:</td>
<td>Hard copy</td>
<td>Data for about 70 oil and gas fields.</td>
<td>* Maps and analysis of: 1. Reservoir types and ages. 2. Trap types and distribution. 3. Ultimate oil recovery maps. 4. Source rock types and distribution.</td>
</tr>
<tr>
<td>* Source rock data.</td>
<td></td>
<td></td>
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<tr>
<td>* Reservoir data.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>E. Fieldwork data:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Paleocurrent measurements.</td>
<td></td>
<td></td>
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</tbody>
</table>

*Table 1.02 Data summary of types of data, formats, numbers, analysis and products.*
1.6 Research questions

The main objective of this research is directly related to the issue of the influence of arches on hydrocarbon migration and accumulation. With this in mind, answers to the following research questions were sought:

1. How are the Paleozoic arches of the world distributed and what is their relation to adjacent sedimentary basins and to hydrocarbon accumulations?

2. What is the effect of basement structures in areas of arches on sediment thickness patterns, with particular regard to the Ordovician, Silurian and Devonian rocks of the Ghadamis and Murzuq Basins?

3. What are the surface structural and stratigraphical expressions of the basement in the Ghadamis and Murzuq Basins, and what is their significance for hydrocarbon migration and accumulation?

1.7 Structure of the thesis

To achieve the goals to the aforementioned research questions, all available geological data, geophysical (seismic, aeromagnetic) data, remote sensing images, well logs of oil and water wells, and oil field data have been interpreted and integrated. The thesis comprises seven interrelated chapters. Each chapter presents the analysis and results of part of the research. The following is a description of the chapter contents.

Chapter 1 is an introduction to the research programme, and gives an extensive summary of the different parts of the research.

In Chapter 2, arch structures are described. Arch structures are areas of broad uplift on a regional scale. They have developed throughout the geological history of the Earth and are usually a basement doming. Basement structures such as arches are common features in many foreland basins. They are as important as basins in the tectonic history of cratons and occupy similar surface areas. They are also one of the most important producers of second-order basins. In many continents, records indicate that arching was a dominant structural style during the Early Paleozoic time. The paleogeographical effect of arch development in adjacent sedimentary basins is clearly observed in many areas. Hydrocarbons are present around many of these arches, in both structural and stratigraphical traps. It is recorded that arches or uplifts produce reeфаl
belts in carbonate basins (e.g. the Peace River Arch, western Canada) and will produce pinchouts in the case of clastic sedimentary areas (e.g. Hassi Maessoud, Algeria). These structures are significant controls on the distribution of reservoirs and become focal points for hydrocarbon migration and accumulation. Areas of arches are characterized by several structural processes, such as faulting and folding, which keep the areas higher than the adjacent basins; thus the areas of arches or uplifts are more exposed to erosional activity than the surrounding areas. The analysis includes the characteristics of arch structures, occurrences of arches around the world, examples of arches located within different Paleozoic hydrocarbon-producing sedimentary basins, and the characteristics of oil fields associated with these structures. Al Qarqaf Arch is used to compare a number of important characteristics with those of some other arches. The chapter also includes a tectonic and stratigraphical framework of Al Qarqaf Arch and the adjacent parts of the Ghadamis and Murzuq Basins.

In Chapter 3, the basement configuration of Al Qarqaf Arch and adjacent parts of the Ghadamis and Murzuq Basins are mapped and analyzed (see Figure 3.03). The analysis includes the mapping of basement topography, using both magnetic data and 54 well logs that reach the basement. Aeromagnetic data covering western Libya were processed in order to enhance the tectonic features of the basement and to map the architecture of the Ghadamis and Murzuq Basins and the intervening Al Qarqaf Arch. The faulting patterns of the Pre-Cambrian basement and the overlying sediments were analyzed. Different aeromagnetic data processing techniques were used to enhance the aeromagnetic images of the area. These include analytic signal and second vertical derivative. The tectonic interpretation of aeromagnetic images, integrated with remote sensing, can be used to define details within known productive areas as well as analogous locations for hydrocarbon exploration elsewhere. Regional seismic sections in the Murzuq Basin were used to study the faulting and folding patterns in the area. However, no seismic sections were available in the Ghadamis Basin for correlation purposes. Surface structures that express the basement configuration were also mapped using remote sensing images. A tectonic model of the area was constructed using magnetic and seismic interpretations, as well as rose diagrams of the lineaments interpreted from remote sensing images. Combined analysis of remote sensing, aeromagnetic and well data has enabled identification of basement features that form the framework of the Paleozoic Ghadamis and Murzuq Basins and the intervening ENE-WSW trending Al Qarqaf basement high in northwestern Libya.
Chapter 1: Introduction

Subsurface lithological contrast, expressed in magnetic anomalies as well as surface lineaments derived from various remote sensing data, was interpreted with respect to the regional tectonics. The well data were used to verify the trends observed. The surface lineaments on the Landsat TM, Spot XS and Radar ERS-1 images of the area were tested for expression in the subsurface (see Figures 3.06 and 3.07). The surface lineaments were integrated with aeromagnetic and seismic data. The combined study reveals that the data sets confirm and supplement one another in identifying subsurface basement structures.

In Chapter 4, the paleogeography of Ordovician, Silurian and Devonian formations in the parts of the Ghadamis and Murzuq Basins adjacent to Al Qarqaf Arch is mapped. Particular emphasis is given to the Cambro-Ordovician, Silurian and Devonian rocks because of their reservoir and source rock potential. The Cambro-Ordovician, Silurian, Devonian and Carboniferous history of Al Qarqaf Arch and the adjacent Ghadamis and Murzuq Basins is shown by a series of cross sections, isopach maps and sand percentage maps based on electrical and gamma ray log correlation of more than 120 wells distributed throughout the area. These maps and sections were used to determine the stratigraphy and paleogeography of the Cambro-Ordovician, Silurian, Devonian and Carboniferous systems. The paleogeography and facies developments of these sequences and megacycles are directly connected with the Caledonian and Hercynian orogenic events. The depositional boundaries between the different cycles are marked by major erosional or non-depositional unconformities related to these orogenic events.

Chapter 5 includes the results of mapping and analyzing the pattern of hydrocarbon distribution and characterization of the hydrocarbons in the Ghadamis and Murzuq Basins. This chapter also contains an analysis of reservoir characteristics, such as reservoir type, age, traps, source rock, etc., of all oil and gas wells in the Ghadamis and Murzuq Basins. Next, these criteria were analyzed according to their locations relative to Al Qarqaf Arch. Furthermore, the hydrocarbon migration in the two basins was analyzed. Figure 5.02 shows the combined information on the reservoir and hydrocarbon features in the basins.

In Chapter 6, the hydrocarbon seeps located along Al Qarqaf Arch are mapped and analyzed. The work includes mapping the spatial distribution of these seeps and the geochemical analysis of soil samples collected from the area.

In Chapter 7, general conclusions and recommendations are presented.
CHAPTER 2

ARCH STRUCTURES AND HYDROCARBON EXPLORATION
Chapter 2: Arch structures and hydrocarbon exploration

2.1 Introduction

Basement structures such as domes and arches, together with fault and shear zones, are the most common features in many basins. These structures often exert significant control on the distribution of potential reservoirs and become areas of hydrocarbon migration and accumulation (Figures 2.03 and 2.04).

The term “arch” has been defined by several authors; for example, Park and Jaroszewska (1994) write: “the arch or uplift is a structure caused by the upward movement of a part of the Earth’s surface within a stable zone or craton. The terms arch, uplift, swell, dome have been used synonymously. Arches are typically of the order of 500-1000 km across. Many exist for long periods of geological time, undergoing slow and perhaps spasmodic upwards movements and, through subsequent erosion, provide a supply of sediments to surrounding basins.”

Arches or uplifts are areas of dynamic phenomena, which start with the folding of part of the cratonic crust. This folding then continues growing laterally over hundreds of kilometres till it is usually terminated by faulting. This phenomenon has occurred throughout the geological history of the Earth. In many continents, records indicate that arching was the dominant structural style during the Early Paleozoic time.

Some studies on arches and their importance as hydrocarbon exploration targets have been published (e.g. Billo, 1985; Stephen and Mary, 1990). The main objectives of this analysis are:

1. State models of arch formation.
2. Distribution of arches around the world.
3. Types of structural and stratigraphical traps associated with arches.
4. The influence of the stage of arch formation on trap style and orientation.

As we have seen in Chapter 1, arches are common in Libya. They separate Libyan sedimentary basins from one another. By analyzing arches from different parts of the world, common characteristics such as their interactive relation with adjacent sedimentary basins and their influence on trap formation and migration routes will help
Chapter 2: Arch structures and hydrocarbon exploration

in the construction of a model of the role of arch structures in hydrocarbon exploration. This model will be used in a later stage in the case of Al Qarqaf Arch and adjacent parts of the Ghadamis and Murzuq Basins to locate the most promising prospective areas for hydrocarbon exploration.

2.2 Models of arch formation

Arch structures are regional geological areas that have their origin in multiple deep-seated processes (Harding and Lowell, 1979). Many continental uplifts are associated spatially with rift zones. Among such structures are the East African and Ethiopian Platforms, the Rhenish Shield of Western Europe and the Voronezh-Ukraine Uplift of the Russian Platform.

The arch structures can be formed as a result of different tectonic processes. For example, the Sabine Arch is formed by compression on the Texas-Louisiana border, where the shape of the arch is compatible with an origin by folding and the arch movement is broadly contemporaneous with crustal shortening in the nearby Cordilleran Orogenic Belt (Jackson and Laubach, 1992). The authors propose that the Sabine Arch is a fold caused by Late Cretaceous and Early Tertiary compression of the northern Gulf of Mexico Basin.

Some arch structures are formed along fault zones. For example, the Peace River Arch in northwestern Alberta and northeastern British Colombia (Canada) is a cratonic arch overprinting the pre-existing Pre-Cambrian basement structure (O'Connell et al., 1990). The original arch structure at the Upper Proterozoic continental margin was possibly formed by uplift related to the cratonward extension of an oceanic fracture zone. The extensional history of the Early Carboniferous graben complex suggests a possible origin in a failed rift setting. Flexural uplift can occur adjacent to thick sediment accumulations by significant sedimentary loading, as in the Gulf of Mexico Basin (Stephen and Mary, 1990). The style of deformation of the regional arches of the West Siberian Basin is more likely to be extensional than compressional (James, 1995).

Stephen and Mary (1990) document the relation between the Sabine Arch and its adjacent sedimentary basins. In the area of the arch, they studied the second Paleocene episode of motion between the arch and adjacent basins and noted that the tilting of units, the sub-aerial exposure of the arch crest, and the depositional thickening of
Chapter 2: Arch structures and hydrocarbon exploration

Tertiary units in adjacent basins manifest this motion. Thickening of delta plain sediments in the East Texas Basin and thinning across the arch mark the late Paleocene onset of the uplift.

Several structural processes such as faulting and folding characterize areas of arches, and the erosion activity in these areas is more extensive than in the surrounding basins. This will make the stratigraphy of arch areas or uplifts incomplete, with truncated unconformities, thus making the establishment of the stratigraphical column quite difficult. The arch structures can be formed as a result of compressional or extensional deformation of the Earth’s crust. It is recorded that arches or uplifts produce reefal belts in carbonate basins (e.g. the Peace River Arch, western Canada (Edwards et al., 1994)), and produce pinchouts in the case of clastic sedimentary areas (e.g. Hassi Maessoud and Hassi R’Mel in Algeria (Boote et al., 1998)). In the West Siberian Basin, the sediments are draped over the uplifted blocks in the form of large arches (James, 1995). The oil fields are in very irregularly shaped domes spaced along the tops of these arches. There are numerous oil fields in areas near the margins of the basin, producing from the Jurassic just below a Pre-Cretaceous unconformity. According to James (1995), the sedimentary fill of the West Siberian Basin records an episode of rifting from Late Permian to Middle Jurassic times, followed by post-rift subsidence from the Late Jurassic onwards. The rifting process initiated the regional arches on which many of the basin’s oil and gas fields are located.

2.3 Types of arches

According to their depth, arches can be classified into two types: buried and near surface (Figure 2.01 and Table 2.01). Each type has its peculiar hydrocarbon traps and migration and accumulation systems. Table 2.01 summarizes the correlation between the two types.

2.3.1 Buried arches

This type is located at considerable depth and is covered completely by sediments, as in the case of Hassi Maessoud (Algeria), the West Siberian Basin (Russia) and the Kuwait Arch (Kuwait). Hydrocarbon accumulations associated with this type are trapped mainly on broad anticlines and/or reefs on the crest of the arch and often form giant fields, as in the case of Hassi Maessoud (Figure 2.07), the Burgan field (Figure
Chapter 2: Arch structures and hydrocarbon exploration

2.09) and the West Siberian fields (Figure 2.10). In many cases, the source rocks are located near the area of the arches and short-distance migration of hydrocarbons is most probable. Trap types are mainly large anticlines, reefs and pinchouts against unconformities; fault traps may also be expected (Figure 2.05). The faults in this type are more important in accommodating the migration than in trapping the hydrocarbons.

![Buried arch](image1)

![Near surface arch](image2)

**Figure 2.01** Theoretical illustration of cross sections of the buried and near surface arches.

### 2.3.2 Near surface arches

In this type, the core of the arch is close to the surface, and in many cases the basement is only partly covered by the sediments or even partly exposed on the surface, as in the case of the Cincinnati Arch (USA; Figure 2.04), El Baul Arch (Venezuela; Figure 2.02 and Table 2.02) and Al Qarqaf Arch (this study). Hydrocarbon accumulations associated with this type are characterized by long-distance migration from adjacent sedimentary subbasins, where there are good conditions for source rocks to produce hydrocarbon and accumulations in the flanks of the arch (Figures 2.03, 2.04 and 2.05). Relative to the buried arch type, the hydrocarbon accumulations in the areas of near surface arches are smaller in size and reserves. This can be explained by the smaller structures associated with near surface arches, the smaller size of the traps, and the increased chance of leaking reservoirs. Expected traps associated with the near surface arches range from structural traps (simple anticlines, faulted anticlines, normal and reverse faults), stratigraphical traps (pinchout, onlap) to combination traps (Figure 2.05).
### 2.3.3 Comparison of the characteristics of buried and near surface arches

<table>
<thead>
<tr>
<th>Buried arch</th>
<th>Near surface arch (perching arch)</th>
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</thead>
<tbody>
<tr>
<td><strong>Traps</strong></td>
<td></td>
</tr>
<tr>
<td>1. Broad anticlines</td>
<td>1. Structural (simple anticlines, faulted anticlines, faults)</td>
</tr>
<tr>
<td>2. Pinchout</td>
<td>2. Stratigraphical: pinchout, onlap, unconformity (erosion and non-deposition)</td>
</tr>
<tr>
<td>3. Lateral porosity</td>
<td></td>
</tr>
<tr>
<td>4. Unconformity</td>
<td>3. Combination traps</td>
</tr>
<tr>
<td>5. Local fault truncation</td>
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<tr>
<td>6. Reefs</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Faults</strong></th>
<th>Trapping, migration</th>
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</thead>
<tbody>
<tr>
<td>Faults have limited role in reservoirs (mainly in migration)</td>
<td></td>
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</table>

<table>
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<tr>
<th><strong>Migration</strong></th>
<th>Mainly long-distance migration (from adjacent subbasin)</th>
</tr>
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<tr>
<td>Short-distance migration</td>
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<thead>
<tr>
<th><strong>Accumulation</strong></th>
<th>Flanks of the arch (relatively small-size fields)</th>
</tr>
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<tbody>
<tr>
<td>Crest and adjacent to the arch (giant fields are expected)</td>
<td></td>
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</tbody>
</table>

**Table 2.01** Correlation between characteristics of buried and near surface arches.

### 2.4 Distribution of arches around the world

The parameters controlling the occurrence of hydrocarbons in areas of arches range from the influence of traps, source beds and cap rock, the timing of specific events, the age of reservoir rocks, to the preservation of hydrocarbons—or a combination of these parameters. The greatest concentration of reserves in terms of trap type in the North African sedimentary basins are in broad arches, as typified by Hassi
Chapter 2: Arch structures and hydrocarbon exploration

Maessoud and Hassi R’mel (Balbucchi and Pommier, 1970). Major uplifts in Qatar and Kuwait are associated with several super-giant oil and gas fields at the Cretaceous level (Ghawar Anticline, Qatar Arch, Burgan Khrais Trend, etc.; Christian, 1997).

Hydrocarbons are found along or near many arch structures around the world. Some 23 arches distributed around the world (Figure 2.02 and Table 2.02) were classified, studied and investigated. Some of these arches are given the names of the basins where they are located, others are given different names.

2.5 Hydrocarbon migration around arches

Several authors have studied the influence of arches on hydrocarbon migration and accumulation. Good examples of the importance of arches as focal points for hydrocarbon migration and accumulation are the Hassi Maessoud and Hassi R’Mel oil fields, which are classified as super-productive. These are located on the crests of broad arches, which encouraged extremely efficient lateral migration focusing and an important entrapment style (Boote et al., 1998).

In the case of the Kuwait Arch, the arch structure became the focus of petroleum migration in the Late Cretaceous and Tertiary (Menahi, 1994). In the Asahan and Tiga Arches of the Sumatra Basin in Indonesia, migration occurred on both flanks of the Tiga Puluh Arch during the Late Miocene (Courteney, 1994). According to Pratsch (1985), the lateral and vertical migration of hydrocarbons is influenced by basin geometry (regional structure). Where attractive porosities occur in areas of preferred (focused) hydrocarbon migration (on regional highs, basin flanks or intrabasinal “highs”), major fields may be found. The combination of lateral migration of hydrocarbons and faults in areas of arches will produce hydrocarbon seeps along these arches, as in the case of the Western Canada and the Eastern Venezuelan Basins (Link, 1952). The same observation can be made in the case of Al Qarqaf Arch, Libya (see Chapter 6).
Figure 2.02 Map showing the locations of arches listed in Table 2.01: 1) Al Qarqaf Arch; 2) Massi Massoud Arch (Algeria); 3) Tasiemzane Arch (Tunisia & Algeria); 4) Kuwait Arch (Kuwait); 5) Qatar Arch (Qatar); 6) Asahan and Tiga Arches (Indonesia); 7) Yashir and Shaklotia Arches (Turkmen, Uzbek and Afghanistan); 8) Tazhong Uplift (China); 9) arches of West Siberian Basin (Russia); 10) El Baul Arch (Venezuela); 11) La Libertad Arch (Guatemala); 12) Guaire-Arch (Colombia); 13) Broome Arch (Australia); 14) Sweetgrass Arch (Canada); 15) Cincinnati Arch (USA); 16) Sioux Arch (USA); 17) Bend Arch (USA); 18) Wisconsin Arch (USA); 19) Wiggins Arch (USA); 20) Casper Arch (USA); 21) East Peace River Arch (Canada); 22) Barrow Arch (USA); and 23) Las Animas Arch (USA).
<table>
<thead>
<tr>
<th>No</th>
<th>Arch name</th>
<th>Type</th>
<th>Country</th>
<th>Geological setting</th>
<th>Basin name</th>
<th>Basin sediments</th>
<th>Trap types</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al Gharqaf Arch</td>
<td>Near surface</td>
<td>Libya</td>
<td>African Plate</td>
<td>A. Ghadamis Basin</td>
<td>Paleozoic clastic sediments</td>
<td>A. Structural (faults)</td>
<td>This study</td>
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<td></td>
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<td></td>
<td>B. Murzuq Basin</td>
<td></td>
<td>B. Stratigraphy ( unconformity and pinchout)</td>
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<tr>
<td>2</td>
<td>Hassi Messoud</td>
<td>Buried</td>
<td>Algeria</td>
<td>African Plate</td>
<td>Ghadamis Basin</td>
<td>Paleozoic clastic</td>
<td>A. Structural (faults and/or broad anticlines)</td>
<td>Boot et al., 1996</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td>B. Stratigraphic traps (pinchout and truncation)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Taktzemane Arch</td>
<td>Near surface</td>
<td>Tunisia &amp; Algeria</td>
<td>NW extension of the African Plate</td>
<td>Ghadamis Basin</td>
<td>Cambrian to Triassic</td>
<td></td>
<td>Fabrizio, 1996</td>
</tr>
<tr>
<td>4</td>
<td>Kuwait</td>
<td>Buried</td>
<td>Kuwait</td>
<td>Arabian fold step</td>
<td>Mesopotamian Foredeep Basin</td>
<td>Tertiary and Late Cretaceous sed, rock</td>
<td>Structural (near vertical fault system and structural closures)</td>
<td>1. Menahi, 1994</td>
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<td></td>
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<td>2. Wara, 1990</td>
</tr>
<tr>
<td>5</td>
<td>Qatar Arch</td>
<td>Buried</td>
<td>Qatar</td>
<td>Arabian Plate</td>
<td>A. N. Gulf Salt Basin</td>
<td>Jurassic to Cretaceous Carbonate</td>
<td>A. Horst-block anticlines</td>
<td>Aditya and Al Sarahiji, 1994</td>
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<td></td>
<td></td>
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<td></td>
<td>B. S. Gulf Salt Basin</td>
<td></td>
<td>B. Salt-involved structures</td>
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</tr>
<tr>
<td>6</td>
<td>1. Asahan Arch</td>
<td>Buried</td>
<td>Indonesia</td>
<td>Eurasian Plate</td>
<td>A. N. Sumatra Basin</td>
<td>Eocene to Pleistocene sandstone</td>
<td>A. Structural (anticlines)</td>
<td>Courteney, 1994</td>
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<tr>
<td></td>
<td>2. Tigi Arch</td>
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<td></td>
<td>B. S. Sumatra Basin</td>
<td></td>
<td>B. Stratigraphic</td>
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<tr>
<td>7</td>
<td>1. Yashtiar Arch</td>
<td>Buried</td>
<td>Turkmen, Uzbek</td>
<td>Eurasian Plate</td>
<td>Amu-Darya Basin</td>
<td>Carbonate (Upper Jurassic age)</td>
<td>C. Combination traps</td>
<td>Clarke, 1988</td>
</tr>
<tr>
<td></td>
<td>2. Shakhmolla Arch</td>
<td>Buried</td>
<td>and Afghanistan</td>
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<td>8</td>
<td>Tazhoring Uplift</td>
<td>Buried</td>
<td>Turkmen, Uzbek</td>
<td>Eurasian Plate</td>
<td>Tarim Basin</td>
<td>Paleozoic sediments range from marine to non-marine clastics</td>
<td>A. Structural (faults)</td>
<td>Wang et al., 1992</td>
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<tr>
<td></td>
<td>(Central Uplift)</td>
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<td></td>
<td></td>
<td></td>
<td>B. Stratigraphic ( unconformity)</td>
<td></td>
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<tr>
<td>9</td>
<td>1. Surug Arch</td>
<td>Buried</td>
<td>Russia</td>
<td>Eurasian Plate</td>
<td>West Siberian Basin</td>
<td>Production from Cretaceous sandstone</td>
<td>A. Structural (faults)</td>
<td>1. James, 1995</td>
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<tr>
<td></td>
<td>2. Alichar Arch</td>
<td>Buried</td>
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<td>B. Stratigraphic</td>
<td>2. roofs and Nenimchako, 1992</td>
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<td>3. Kond Arch</td>
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<tr>
<td>10</td>
<td>El Baul Arch</td>
<td>Near surface</td>
<td>Venezuela</td>
<td>South American Plate</td>
<td>A. Berinas-Apure Basin</td>
<td>Cretaceous through to Pleistocene</td>
<td>A. Structural (anticlines associated with thrust faults)</td>
<td>Keer, 1987</td>
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<td></td>
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<td></td>
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<td>B. Eastern Venezuelan Basin</td>
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<td>B. Stratigraphic (up dip pinchout)</td>
<td></td>
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<tr>
<td>11</td>
<td>La Libertad Arch</td>
<td>Near surface</td>
<td>Guatemala</td>
<td>South American Plate</td>
<td>A. North Peten Basin</td>
<td>Cretaceous Carbonate</td>
<td>Asymmetric anticlines associated with faults</td>
<td>Vinao, 1982</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td>B. South Peten Basin</td>
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<tr>
<td>12</td>
<td>Guaica Arch</td>
<td>Buried</td>
<td>Colombia</td>
<td>South American Plate</td>
<td>A. Putumayo Basin</td>
<td>Shallow marine sandstone</td>
<td>A. Thrust-related faulted anticlines</td>
<td>Clara and David, 1996</td>
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<td></td>
<td>B. Llanco Basin</td>
<td></td>
<td>B. Combination</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Broome Arch</td>
<td>Buried</td>
<td>Australia</td>
<td>Indian-Australian Plate</td>
<td>Canning Basin</td>
<td>Early Ordovician to recent carbonate</td>
<td>A. Structural (faults)</td>
<td>Virginia, 1991</td>
</tr>
</tbody>
</table>

Table 2.02 Selected arches and their hydrocarbon characteristics.
<table>
<thead>
<tr>
<th>No</th>
<th>Arch name</th>
<th>Type</th>
<th>Country</th>
<th>Geological</th>
<th>Basin name</th>
<th>Basin sediments</th>
<th>Trap types</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 14 | Sweetgrass Arch | Buried    | Montana, Canada           | North American Plate                 | Williston Basin | Cambrian to Cretaceous sandstones    | A. Structural  
B. Stratigraphy (unconformity) | Gerhard et al., 1982 |
| 15 | Cincinnati Arch | Near surface | North Dakota, USA        | Western Periphery of Phanerozoic of the North American Craton | Illinois Basin | Cambrian to Devonian carbonate | A. Structural (faults)  
B. Stratigraphy | Crockett et al., 1990 |
| 16 | Sioux Arch    | Near surface | Dakota, USA               | North American Plate                 | Williston Basin | Cambrian and Cretaceous sandstones | Structural (faults)     | Peterson, 1993      |
| 17 | Bend Arch     | Near surface | Texas, USA                | North American Plate                 | Fort Worth Basin | Jurassic, Cretaceous and Tertiary sediments | Structural            | Kaiser et al., 1997 |
| 18 | Wisconsin Arch | Near surface | South Indiana, West Kentucky, USA | North American Plate | Illinois Basin | Ordovician and Devonian rocks | Structural (anticlines and faulted anticlines) | Barnes et al., 1996 |
| 19 | Wiggins Arch  | Buried     | Southern Mississippi, USA | North American Plate                 | Mississippi Salt Dome Basin | Jurassic and Cretaceous carbonate | 1. Stratigraphic  
2. Combination | Cagia and Khan, 1983 |
| 20 | Casper Arch   | Buried     | Wyoming, USA              | North American Plate                 | Wind River Basin | Paleozoic to Cenozoic carbonate and clastic | A. Structural traps (faults)  
B. Stratigraphic (pinchout) | Gries, 1983          |
| 21 | East Peace River Arch | Buried       | Alberta, British Columbia, Canada | North American Plate | Western Canada Basin | Triassic rocks (carbonate and evaporite sed) | A. Stratigraphy  
B. Combination | Edwards et al., 1994 |
| 22 | Barrow Arch   | Near surface | Alaska                    | North American Plate                 | A. Canada Basin  
B. Colville foreland Basin | Paleozoic sediments | A. Stratigraphy  
B. Structural | Montgomery, 1996 |
| 23 | Las Animas Arch | Near surface | SE Colorado, USA          | North American Plate                 | A. Denver Basin  
B. Hugoton Embayment | From Upper Cambrian to Cretaceous sediments | Structural (faults, faulted anticlines) | Higley, 1987 |

Table 2.02 Selected arches and their hydrocarbon characteristics (continued).
Figure 2.03 Cross section along the Barrow Arch, showing the influence of the near surface arch on the adjacent sedimentary basin and hydrocarbon accumulations in the area (for location see Figure 2.02, modified after Bird and Molenaar, 1992).

Figure 2.04 Map showing the hydrocarbon accumulations on the flanks of the Cincinnati Arch (USA), as an example of near surface arches (for location see Figure 2.02, after Levorsen, 1954).
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2.6 Types of structural and stratigraphical traps associated with arches

Hydrocarbon accumulations associated with arch structures occur in both structural and stratigraphical traps. Harding and Lowell (1979) described arches or uplifts as structural features resulting from multiple deep-seated processes. Correlation of the locations of arch structures and known hot-spot tracks indicates that some of the arches are located along hot-spot tracks, as in the case of Al Qarqaf Arch (Libya).

Arches are suitable areas for producing different styles of traps (Figures 2.02, 2.03 and 2.07). Syndepositional faulting across the Broome Arch (Virgina, 1991) and along its flanks produced horst blocks, grabens and half-grabens, and potential structural traps. In many arch areas, the folding was apparently caused by uplifts of blocks of basement. In the West Siberian Basin, the sediments are draped over the uplifted blocks in large structures (James, 1995). The oil fields are in very irregularly shaped domes spaced along the tops of these arches. The model extracted from the analysis of arches (Figure 2.06) indicates that large fields occur on the top of buried arches, as in the case of the Kuwait Arch (Figure 2.09), and smaller fields occur on the flanks of both near surface and buried arches (Figures 2.05 and 2.06).

Kopaska-Merkel et al. (1994) noted a strong association between unusually porous upper Smackover reservoirs and proximity to the Wiggins Arch (USA). This is interpreted as a possible result of the arch acting as a positive element to increase and focus the flow of subsurface brines along its margins. It is also significant, as these authors point out, that over 35% of all liquid hydrocarbons produced from the Smackover in Alabama come from reservoirs located along the northern portion of the arch.

Generally, the location of traps in arch areas is strongly related to the depth of the basement in the area and how deep the arch is buried. For example, in the case of buried arches such as the Kuwait Arch and the arches of the West Siberian Basin, the reservoirs are located along the crest of the arch. In the case of near surface (partly exposed) arches such as Al Qarqaf Arch (Libya), the reservoirs are located along the flanks of the arch (Figure 2.05).
Figure 2.05 Schematic diagram showing types of traps associated with buried and near surface arches.

Figure 2.06 Schematic diagram showing the development of preferred reservoirs and hydrocarbon migrations in areas of arch structures.
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2.7 Examples of arches associated with oil fields

Several arches or uplifts located in different sedimentary basins have been the subject of investigation by various authors in order to study the arching mechanism and its influence on the sedimentary basins. In this section, several examples of arches will be described and compared with Al Qarqaf Arch. This comparison is summarized in Figure 2.02 and Table 2.02.

2.7.1 Hassi Maessoud and Hassi R’mel area (Algeria)

The Hassi Maessoud fields, classified as super-productive, are located on the crests of broad Paleozoic arches, which encouraged extremely efficient lateral migration focusing and a very high impedance entrapment style (Boote et al., 1998). They are located in the eastern part of the Algerian Sahara Desert. Hydrocarbon accumulation occurs in combination traps on the flanks. The closure is structural, while on the crest the reservoir is truncated by the unconformity base of the Triassic. The arch formed during the late phase of the Hercynian (Late Paleozoic) Orogeny; this was followed by erosion that cut down to the Cambrian on the crest.

![Diagram of Triassic/Illizi petroleum province](image)

**Figure 2.07** Schematic cross section of Triassic/Illizi petroleum province, showing hydrocarbon accumulations in Hassi Maessoud and Hassi R’Mel oil fields and their relative location to the buried arch (for location see Figure 2.02, after Macgregor, 1996).

According to Boote et al. (1998), the principle uplift of the area must have taken place during the Devonian (final phase of Caledonian movement) and ended with the Late Paleozoic (Hercynian) orogeny. This uplift was followed by intense erosion and
fracturing subsidence. A new phase of subsidence of the northern Algerian Sahara began early in the Mesozoic. This subsidence resulted in the burial of Maessoud-El Agreb beneath 3000 m of Mesozoic sediments, which now overlie the Hassi Maessoud structure. The Cambro-Ordovician reservoirs of the Hassi Maessoud area comprise quartzitic sandstones, which rest unconformably on a granitic basement and are capped by the Hercynian Unconformity. The traps will be of faulted and/or gently folded types. The source rocks are the Silurian shales; the reservoirs are sealed by Silurian shale and/or Triassic evaporites (Djarnia and Fekirine, 1998).

2.7.2 Qatar-South Fars Arch (Qatar-Iran)

The Qatar Arch is situated on the northeastern edge of the relatively stable Arabian Platform. Possibly the Qatar Arch already divided the Arabian Basin from the Pre-Cambrian (Murris, 1980). West of this arch, some of the structures seem to be related to the movement of the Infra-Cambrian Hormuz Salt. The north Bahrain area forms a homoclinal slope westwards from the Qatar Arch, and only a few gentle structural closures or noses are present. During the Pre-Cambrian, Arabia was part of the super-continent of Gondwana.

Figure 2.08 Distribution of Infra-Cambrian to Cambrian salt basins and the location of the Qatar-Fars Arch and the hydrocarbon accumulations in the area (modified from Murris, 1980).
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The Pre-Cambrian-Cambrian rocks now form the basement in Arabia and record three major orogenic sequences: the Kibran, Hejaz and Najd. Four salt basins can be identified (Murriss, 1980): (1) the Dhufar-Ghaba in south Oman, (2) the Fahud, (3) the southern Gulf and (4) the northern Gulf. The salt of these basins exerted a major structural influence throughout the Phanerozoic, with each basin having its own style of salt tectonics, which is determined by differences in overburden thickness and lithology. According to Murriss (1980), the northern Gulf salt basins where the Qatar Arch is located contain large elongated pillows and salt swells, whereas the giant Burgan field occurs where halokinetic movement is combined with basement horst block structures. Several regional unconformities can be recognized in the Paleozoic record of this area. These are related to gentle epeirogenic events, the most important of which occurred during the Late Cambrian, Early Devonian and Early Carboniferous (Murriss, 1980). The region was stable from the Permian until the time of the Zagross Uplift, so all the reservoirs were in trap position almost from the time of deposition until at least the Late Tertiary (Abdulrahman and Christopher, 1986).

2.7.3 Kuwait Arch (Kuwait)

The Kuwait Arch is an excellent example of the relationship between an arch structure and the occurrence of oil and gas fields (Figure 2.09). Kuwait lies at the northeastern edge of the Arabian Foreland, on the southwestern flank of the Arabian Gulf geosyncline (Beydoun, 1991). The Kuwait Arch trends approximately N-S, plunges in Kuwait to the north and has a maximum width of approximately 25 km (Figure 2.09; Menahi, 1994). Several oil fields are located in the area of the Kuwait Arch. For example, the Bahara oil field is located north of Kuwait Bay, astride the Kuwait Arch, and within an overall structural closure that includes the Greater Burgan field (Ahmadi, Magwa and Burgan), the Khashman, Dharif and Abduliyah oil fields to the south, and the Sabiriyah and Raudhatain oil fields to the north of Bahara. The structure of the Bahara oil field is defined as gentle, comprising a number of separate fault-related structural culminations developed on the Kuwait Arch axis (Menahi, 1994). Traps in the area are near vertical fault systems and structural closures. Milton (1965) noted that subsurface data indicate that the main Kuwait structures have been growing steadily since at least the Cretaceous, and are possibly as old as Late Jurassic. Both normal and reverse faults may be expected since the region was essentially a passive
margin until about 15 Ma, when compression commenced as a result of collision between the Arabian and Eurasian Plates (Hempton, 1987).

Figure 2.09 Relationship between locations of oil fields in Kuwait and the Kuwait Arch (modified after Menahi, 1994; for location see Figure 2.02).

2.7.4 Arches of West Siberian Basin (Russia)

The West Siberian Basin is the one of the largest petroliferous basins in the world (Figure 2.10; James, 1995). It underlies a vast region of outcropping Cretaceous and younger sediments, which extends more than 2000 km in the N-S direction and 1500 km E-W (James, 1995). In terms of gas reserves, the basin is also the largest in the world. When production peaked in 1987, the basin was producing more than 10% of the world’s daily oil consumption (Peterson and Clarke, 1991).
According to James (1995), the structure of the West Siberian Basin must be considered at two scales. The first involves Permian-Middle Jurassic grabens and the regional arches or "megaswells" expressed at Cretaceous level. The latter are typically hundreds of kilometres long and tens of kilometres wide. The second scale includes disharmonic folds in Pre-Neogene rocks and reverse faults on the western margin of the basin. These features have fold wavelengths and fault heaves, respectively, of less than 1 km. Disharmonic folding is reported at many locations in the basin and also on the Siberian Platform, but the folds appear to be a superficial phenomenon. They are not described from depths greater than a few hundred metres at most. At least some of the West
Siberian Arches increased their amplitude after the Jurassic. The expression of these arches at Cretaceous and shallower levels cannot be explained in terms of compaction alone; tectonism must be invoked. This deformation resulted in arches that are uplifted relative to the inter-arch areas. The bulk of the petroleum is produced from Upper Jurassic and Cretaceous clastic reservoirs in both structural and stratigraphical traps. These traps generally occur on the crests and flanks of regional structural arches (Figure 2.02; James, 1995). The type and relative locations of the oil fields in the area are conformable with the model of arch trapping type (Figures 2.05 and 2.06). Peterson and Clarke (1991) mentioned subtle structural movements in Jurassic and later times, and claimed that arches are products of the reactivation of faults that bound Triassic rifts.

2.7.5 Al Qarqaf Arch (Libya)

Al Qarqaf Arch can be considered as a typical example of a near surface arch, where part of the arch core is exposed in the area of Jabal Al Hassawanah (see Figures 3.08 and 4.14). In the next sections, this arch will be described in detail. Al Qarqaf Arch and its adjacent Ghadamis and Murzuq Basins dominate western Libya.

Paleozoic rocks occupy much of the southern part of Libya. They crop out along the western, eastern and northern peripheries of the Murzuq Basin and in the vicinity of Jabal Awaynat-Arkenue and the hills of Jabal Dalma in the region of Al Kufrah Basin, as well as in Jabal Nugi in the Tibesti region. This study will focus only on the Paleozoic rocks outcropping along the peripheries of the Murzuq Basin, and their subsurface equivalent in the Ghadamis Basin in particular (Figure 4.14). On the western flank of the Murzuq Basin, Paleozoic rocks are exposed in the Ghat-Awaynat area (see Figure 4.02). They consist of Cambro-Ordovician, Silurian, Devonian and Carboniferous sediments. The Cambro-Ordovician thickness has been reported to be 580 m. A thickness of 500 m of Silurian graptolite shales was measured near Ghat. Overlying the Silurian shale are two sandstone units.

Typically, the Ghadamis and Murzuq Basins are broad shallow intracratonic basins. They are characterized by extensional basement-controlled faulting along NW and NE trends (Goudarzi, 1980; Missallati and Bayoumi, 1983). Doming and vertical movements along the reactivated basement faults during the Caledonian and Hercynian Orogenies resulted in two major unconformities, the Caledonian and Hercynian
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Unconformities. Other major structures are to a large extent inherited from reactivated Pre-Cambrian structural alignments.

The Tibisti Massif bounds the Murzuq Basin to the east, where Pre-Cambrian and Paleozoic rocks are cut by NE-SW trending faults (Figure 2.11). To the west are the Pre-Cambrian Hoggar Massif and the NS trending Tihembokah Arch. Here N-S and NW-SE trending faults occur. Farther north, the Hassi Atchan Arch forms the prolongation of the Tihembokah Arch. The Tihembokah, Ben Ghenemah and Hassi Atchan Arches were periodically active from Cambrian through Devonian times, keeping the same N-S orientation. Prior to the deposition of the Paleozoic sediments within the Ghadamis and Murzuq Basins, the basement was repeatedly tectonized and nearly peneplaned. At the time, it formed a single northerly inclined intracratonic basin (intra-Tassilian surface).

Structurally, both basins are presently delineated by NW-SE and NE-SW structural highs (Figure 2.11), forming the uplifted and faulted flanks of both basins, with associated exposures of Pre-Cambrian massif (crystalline and granitic rocks) and Tertiary basalt flows extracted along faults intersection (see Chapter 3). From west to east, these are the Hoggar, Tibisti and Awaynat-Arkenue Pre-Cambrian Massifs. They represent the northernmost major exposures of the North African Shield and were extensively subjected to the last Pre-Cambrian thermodynamic episode of the Pan African Orogen, which obliterated to a great extent the imprint of former orogenies and after which the development of a stable craton in North Africa was essentially completed (Sander, 1968).

The N-S and NE-SW structural highs mentioned before originated during the Caledonian and Hercynian Orogenies, which had deformed the African Craton since its early development in Late Pre-Cambrian-Early Paleozoic times. Understanding the importance of these early tectonic events is essential. Tectonic trends formed during the early stages of the structural development of the African Craton play a major part in controlling the orientation, style, mechanism and geographical distribution of the present-day structure, characterizing the general geotectonic setting of Libya as a whole and of the Ghadamis and Murzuq Basins in particular.

A geological study of the Lower Paleozoic in Libya and adjacent areas provides evidence of a close relationship between these tectonic phases and sedimentation (Beuf et al., 1971). The sedimentation in both the Murzuq and Ghadamis Basins was
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controlled initially by basement deformation during the Pan African Orogeny. Locally, thickness and facies variations in the sediments throughout the Paleozoic sequence are observed to be related to the N-S and NE-SW tectonic axes of the Caledonian and Hercynian orogenic phases. These axes were first documented by Klitzsch (1971) and are clearly recognizable. They have been further discussed by Mikbel (1977, 1979), Goudarzi (1980) and others.

The trend (Figure 2.11A) was formed in Early Paleozoic times during the Caledonian Orogeny. They are typically epeirogenic in nature, taking the form of alternating uplifts and troughs that are essentially aligned N-S. From west to east, these are: the Tihembokah-Hassi-Atchan Arch, the Tripoli-Tibisti Arch, the Tripoli-Al Haruj Arch, the Kalanshiyo-Awaynat Uplift and the alternating troughs of the Murzuq-Djadu, Dor El Qussah and Kalanshiyo Basins.

The second trend (Figure 2.11B) was formed in Late Paleozoic-Early Mesozoic times, during the Hercynian Orogeny, as uplifts striking NE-SW to N-S. From south to north, these are: the Ennedi-Awaynat Uplift, the Tibisti-Sirt Uplift, Al Qarqaf Arch and the Nefusah Uplift. Although Klitzsch (1971) did not extend these two sets of structures and trends into adjacent areas, other investigations revealed that the Nefusah Uplift (Anketell, 1980) would appear to have been initiated in Caledonian times.

These two sets of structural trends are of great significance in the tectonic and physiographic history of the area. In Libya and the adjacent areas, these old structural trends formed the backbone or the core of the existing structural provinces and tectonic trends, and played a great part in controlling subsequent sedimentation patterns, tectonic trends, style and mechanism. They control and now define the present existing structural and sedimentary basins of Al Kufrah, Murzuq, Ghadamis and Dor El Qussah, and the Pelagian Basin in northwestern offshore Libya. The Sirt Basin was formed after the collapse of the Tibisti-Sirt Uplift, during the Upper Cretaceous time. The Nefusah Uplift, being parallel to the present coast of northwestern Libya, formed an effective barrier to marine incursions in the Permian and Early Mesozoic times, so that sediments to the south tend to be continental in nature. It also had a major effect on the erosion of earlier formed sediment, due to uplift.
Figure 2.11 Geodynamic evolution of Libya and adjacent areas (data from Anketel, 1980; Burollet, 1967; Goudarzi, 1980; Klitzsch, 1971; Mikbel, 1977, 1979; Missalatti and Bayoumi, 1983).
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2.8 Discussion and conclusions

In this chapter, the definition, tectonic setting and causes of the formation of arches are discussed, together with their hydrocarbon significance. Twenty-three arches distributed around the world have been analyzed and studied (Table 2.02 and Figure 2.02). Al Qarqaf Arch, the subject of this thesis, is introduced with respect to its location and relation to the adjacent Ghadamis and Murzuq Basins. The observations for this chapter are:

1. Arches have developed throughout the geological history of the Earth. In many continents, records indicate that arching was the dominant structural style during the Early Paleozoic time. The arches are formed as a result of different tectonic events. This can range from basement uplift along major basement faults to flexural uplifting in the case of thick sediment accumulations or orogenic belts, while volcanic processes related to hot spots are also quoted.

2. Adjacent sedimentary basins can be influenced by the arch structure. This influence is in the form of faulting and folding of sedimentary units adjacent to the arch. The influence can also take the form of inversion unconformities, pinchouts and the thinning of units against the arch.

3. Analysis of arches indicates that in many cases they are a focal point for hydrocarbon migration and accumulation.

4. Traps for hydrocarbon accumulations include structural, stratigraphical and combination traps (Table 2.02).

5. A model can be extracted from the correlation between all the studied near surface arches, indicating that these arch structures have similarities in trap types and an interactive relation with the adjacent sedimentary basins. The points of similarities can be summarized as:

A. The range of trap types is wider in the case of near surface arches than in the buried arch types (Figure 2.05).
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B. A combination of horizontal and vertical migration with uplifts, erosion and, hence, faults that reach the surface gives a high probability of hydrocarbon seeps along the near surface arches.

These observations will be used in the next chapters to study Al Qarqaf Arch and indicate areas of hydrocarbon exploration interest.
* Parts of this chapter were presented as:

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  Aeromagnetic constraints of the basement structure of Al Qarqaf Arch and adjacent parts of the Ghadamis and Murzuq Basins, NW Libya, and implications for hydrocarbon exploration. Sedimentary Basins of Libya, 2nd Symposium: Geology of Northwest Libya, 6-8 November 2000.

(Colored Figures 3.01, 3.02, 3.04, 3.05, 3.06, 3.08, 3.09, 3.10, 3.11, 3.12, 3.13 and 3.14 are in color plate section at the back of the thesis)
Chapter 3: Surface and subsurface characteristics

3.1 Introduction

Basement highs (also known as arches or uplifts) are a common geological phenomenon separating sedimentary (sub)basins from one another. They have a profound influence on the structural and stratigraphical framework of the adjoining basins throughout the entire overlying sedimentary sequence, as expressed in sequence geometry, facies distribution, unconformities, bedding attitude and structural features (folds, monoclines and faults). This configuration in turn determines the potential for hydrocarbon occurrences within the basin. The geological basement for various basins can be defined in different ways. In this study, the basement is defined as Pre-Cambrian igneous and metamorphic rocks.

Several authors have described the basement structure of Libya. Mikbel (1979, 1981) published maps of the basement configuration and structure of western Libya, describing the major basement structures north of latitude 26° 00’ N and their relation to some oil fields. Goudarzi and Smith (1978) published a structural contour map of Libya (scale 1:2,000,000). Both publications used data (available at the time of the studies) from oil wells that penetrated the basement.

This chapter provides a regional-scale overview of the structural framework and overall architecture of Al Qarqaf Arch and the Ghadamis and Murzuq Basins, using remote sensing, aeromagnetic maps, seismic sections and well log data. The chapter has two primary objectives. The first is to construct a detailed model of the morphology and architecture of Al Qarqaf Arch and adjacent parts of the Ghadamis and Murzuq Basins. The second objective is to map and analyze the surface expressions of basement structures by using remote sensing images. Emphasis will be placed on (1) the integrated analysis of remote sensing and aeromagnetic images, seismic sections and well log data; and (2) the application of several structural models for interpreting the influence of the basement structures and topography on the development of expected traps.

Basement rocks can have large contrasts in magnetic properties, resulting in high-amplitude magnetic anomalies. When the basement rocks are shallow, the strong short wavelength anomalies they produce can obscure any weaker anomalies of similar wavelengths produced by sedimentary rocks. When the basement rocks are deep, their anomalies become broader and can therefore be separated from the more localized anomalies of the shallow sedimentary rocks by appropriate wavelength filtering. Young volcanic units tend to produce strong magnetic anomalies at all wavelengths, which
obscure anomalies from underlying sedimentary units. This phenomenon of magnetic variability in basement rocks and/or configuration of sediment-basement interface is clearly observed in the area. There the near surface volcanic centres and flow edges in the areas of Jabal As Swada and Jabal Al Hassawanah form narrow width anomalies, with high amplitudes approaching 600 to 700 gamma.

3.2 Data

Various types of data are included in this study. About 50 oil and water wells (drilled up until 1996) that reached the basement were used to construct a structural contour map of the Pre-Cambrian basement. The aeromagnetic data used in the study are part of the African Magnetic Mapping Project (AMMP, 1992) and comprise a digital 1km*1km grid of total field anomaly continued upwards to 1 km above topography. A digital terrain model of USGS, with 1 km resolution, was used to describe the topography of the area (Figure 3.01). The remote sensing data set comprises the digital enhancement and interpretation of Spot XS, Landsat TM and ERS-1 images for mapping surface structures (Table 1.01). Seismic data were also used to map tectonic displacement and seismic sections were used to map fault and fold patterns in the Murzuq Basin. In this way, the sparse but exact drilling data set is complemented by the continuous and qualitative interpretation of remote sensing and aeromagnetic data. At the same time, the subsurface information of aeromagnetic and well data is complemented by the observation of surface anomalies.

3.3 Basement configuration based on well logs and aeromagnetic data

3.3.1 Basement topography from well data

Figure 3.01 illustrates the combination of a DEM and the interpolated basement topography of Al Qarqaf Arch and its surroundings. The basement topography was constructed using data from some 54 wells that reached the basement; the map was constructed using a Rockware surfer®. The interpolation has done using kriging and linear interpolation methods. The result was refined by the aeromagnetic trends. The symmetrical geometry of Al Qarqaf Arch is clearly shown. The map shows that the Ghadamis and Murzuq Basins are not completely separated by the arch. The two basins are connected in the area of the Atchan Saddle. The structural contour map of the basement (Figure 3.01) shows that the basement is in the range of 3500 m below sea level in the centre of the Ghadamis Basin and about 3000 m in the centre of the Murzuq Basin. Figure 3.01 shows that the basement topography and its structural trends are well
expressed at the surface, as shown by the elevation map. The shape, geometry and boundaries of the two basins can be easily traced; major faults such as Dor El Qussah are clearly visible on the map.

3.3.2 Basement topography and structure from aeromagnetic data (magnetic modelling)

The aeromagnetic image of the area was filtered to remove any frequency noise that might influence the derivative images. From the total intensity magnetic anomalies, a reduction to the pole anomaly map was made. Several processing methods were applied to this image, including sun shading and second vertical derivative. In addition, estimation of the depth to the magnetic basement was attempted using the Werner and Euler deconvolution (Werner, 1953).

The main objectives of this part of the study were to map, at the scale of basin reconnaissance, the geometry of Al Qarqaf Arch and the adjacent Ghadamis and Murzuq Basins, and to indicate aeromagnetic anomalies and their possible significance for hydrocarbon accumulations in the area. This will be used to indicate areas of exploration interest.

The magnetic data were gridded and modelled using Geosoft®. A regional analytic signal shaded relief map was constructed from the residual total intensity aeromagnetics, using Geosoft® (Figure 3.02). The analytic signal method, produces a particular type of calculated magnetic anomaly enhancement map that is used for defining, the edges (boundaries) of geologically anomalous magnetization distributions (e.g. basement fault block boundaries, basement lithology contacts, fault/shear zones, igneous and salt diapirs, etc.). Analytic signal maxima have the useful property that they occur directly over faults and contacts. A three-dimensional (3D) model or network that represents the basement topography was constructed using Geosoft® (Figure 3.03). Geosoft’s Euler 3D deconvolution processing routines were used to locate and determine depths for gridded magnetic and gravity data. Euler 3D automates 3D geological interpretation by delineating magnetic boundaries and calculating source depths. The data used to calculate depth to magnetic basement included vertical derivative (dz) and horizontal derivative (dx and dy) grids.

Several observations can be made when interpreting the aeromagnetic maps and basement structure contour map. From correlating the geological basement map
constructed from well log data (Figure 3.01) with the depth to the magnetic basement map (Figure 3.03), it can be concluded that the magnetic basement is deeper than the Pre-Cambrian geological basement. This indicates that the basement can be subdivided into a low-magnetic granitic upper part (known from outcrop, Figures 3.08 and 4.14, and wells) and an unknown magnetic deeper part. The analytic signal map of the aeromagnetic anomalies (Figure 3.02) indicates the presence of several lows or subbasins (L1-L8) with sufficient sediments to be of exploration interest. The area of Al Qarqaf Arch can be described as a combination of highs separated from one another by low magnetic anomalies (L5, L6 and L7). The area L5 corresponds to the Atchan Saddle, connecting the Ghadamis and Murzuq Basins. The Ghadamis Basin is characterized by low magnetic anomalies in the southern part (L8) and high magnetic anomalies in the eastern and western parts (H6 = Tihembokah Arch; H7 = Tripoli-Tibisti Arch).

In the Murzuq Basin, several magnetic lows are observed (L1-L4); these lows most probably correspond to NW-SE trending troughs. Some of these are clearly visible in remote sensing images. The area L1 in Figure 3.02 corresponds to the Dor El Qussah subbasin, which is separated from the main Murzuq Basin by the NW-SE trending Ben Ghenemah Arch (represented by H2 in Figure 3.02). Another trough is clearly observed in the southwestern part of the Murzuq Basin (Figure 3.02, area L4). This trough is named as the Serdies Trough in some published maps (Petroconsultants, 1998). Figure 3.02 shows that the Murzuq Basin is expressed in magnetic highs and lows trending NW, perpendicular to the trend of Al Qarqaf Arch. This pattern is probably the result of the presence of a horst and graben configuration, with thick sedimentary packages in the grabens. The faults separating the blocks are likely to form major pathways for hydrocarbon migration (see Chapter 5).

Most if not all discovered hydrocarbon concentrations in the study area are located in the vicinity of high magnetic anomalies (Figures 3.02 and 3.03). Most probably, hydrocarbons are generated in areas of troughs (low magnetic anomalies) and migrate to the high areas. A new feature was detected in the northern part of the Ghadamis Basin, in the form of a low magnetic anomaly (Figure 3.04) about 130 km wide and 300 km long. The area could be a promising target for hydrocarbon exploration, especially with the presence of some oil fields in the area.
Figure 3.03 Modelled basement topography, constructed from aeromagnetic data for parts of the study area, showing the geometry of Al Qarqaf Arch and the Ghadamis and Murzuq Basins. The location and trap types of hydrocarbon accumulations in the area are indicated (for location see Figure 3.02).

3.4 Surface characteristics of Al Qarqaf Arch and adjacent Ghadamis and Murzuq Basins (remote sensing analysis)
3.4.1 Introduction

Lineament analysis using all the enhanced remote sensing images has been particularly valuable in determining regional and local patterns that reveal some episodes of the brittle deformation history of an area (e.g. fractures and faults that are involved in forming traps for hydrocarbons). Lineament maps therefore yield economic payoffs and were used for a regional lineament and tectonic evaluation. Very large lineaments were interpreted using a 1:1,000,000 scale Landsat TM mosaic of Libya. Visual interpretation of the processed images was performed in order to identify and record structural and morphostructural elements such as lineaments, faults, scarps, dikes, silicified zones, semi-circular features, etc. The interpretation was made using scales 1:250,000 and 1:400,000, and was compiled at scale 1:10,000,000 (Figure 3.06). Where possible, the lineaments were geologically calibrated by comparing the interpretation of existing geological maps, geophysical data and field observations.

3.4.2 Remote sensing data types and processing

Remote sensing imagery recorded by satellite sensors is a powerful method for hydrocarbon exploration. The imagery used in this study consisted of (Table 3.01):

1. Some 182 Spot XS images at scale 1:100,000.

   Multispectral mode with 20 m resolution. This mode contains three spectral bands: green (0.5 to 0.59 microns), red (0.61 to 0.68 microns) and near infrared (0.79 to 0.89 microns). This selection has been optimized to allow maximal discrimination of various types of terrestrial targets.

2. Twelve Landsat Thematic Mapper TM images at scales 1:250,000 and 1:400,000.

   In this study, Landsat TM bands 2, 4, and 7 (R, G, B) were combined to make false-colour composite images for geological mapping.

3. Four ERS-1 radar images at scale 1:250,000.

   The information available from microwave remote sensing is different from, but complementary to, that available from the visible and infrared wavelengths. In arid desert environments (as in this study), a major advantage of using SAR (synthetic aperture radar) is its ability under extremely dry circumstances to penetrate sand to some
extent (L-band can penetrate as much as 2 meters of very dry sand to image buried rock structures).

The Spot and Landsat TM provide spectral textural information, while the SAR ERS-1 data provide only textural and surface roughness and humidity information.

3.4.2.1 Digital image analysis

Spectral and textural information provides excellent interpretative assistance through the use of remote sensing images. When viewing various images, the interpreters can readily see different rocks, etc. Digital image processing permits the interpreter to go beyond the intuitive classification of such features and quantify or enhance specific target features, using appropriate image processing software. The digital image analysis of Landsat TM, Spot XS and ERS-1 data was performed using ER-Mapper® image processing. The various digital techniques employed for processing the images include band combination.

Figure 3.06 illustrates the combination of the magnetic (analytic signal) map of the area and the lineament map. The map indicates that most of the lineaments in the area coincide with the magnetic linear features (i.e. most of the lineaments are basement-related features). The continuation of these magnetic features suggests that they are regional fault structures that are not visible on remote sensing images because the areas are covered by extensive sand dunes. The lineament map and corresponding table (Figure 3.06 and Table 3.01) were used to create rose diagrams for different sub-areas (Figure 3.07), using the grid of the 1:250,000 geological map sheet series from the Libya Industrial Research Center (IRC) as a reference. According to this subdivision, 22 rose diagrams were constructed and used for tectonic evaluation of the area. Subsequently, these rose diagrams were compiled into five regional rose diagrams (Figure 3.07). These five rose diagrams represent the lineament trends of the major tectonic elements of the area. The lineament map was overlain with the locations of the oil fields in the Ghadamis and Murzuq Basins (Figure 3.06). The correlation indicates that some of the oil fields are located in areas of dense lineaments, particularly in the southern part of the Ghadamis Basin (see 3.4.5.2 and Figure 3.09). A structural contour map on top of the producing horizon of these fields (Figure 5.08) shows that these oil fields produce from faulted anticlines. Figure 3.09 shows (semi-) circular features located on high magnetic anomalies (see also Figure 3.02, area H7). This suggests that these anomalies are most probably related to basement highs or hidden volcanics. The
oil fields of Algeria (Figure 3.02, area H6) are also located in an area of dense lineaments.

3.4.3 Lineaments of major tectonic elements

3.4.3.1 Al Qarqaf Arch

3.4.3.2 The Tripoli-Tibisti Arch

3.4.3.3 The Tihembokah Arch

3.4.3.4 The Ghadamis Basin

3.4.3.5 The Murzuq Basin

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Table 3.01: Lineaments classified in classes of 10° intervals.
3.4.3.1 *Al Qarqaf Arch*

This arch is a Pre-Carboniferous Hercynian uplift trending in SW-NE direction. This is the main structural element in the area, separating the Ghadamis Basin from the Murzuq Basin. It plunges westwards and exposes Cambro-Ordovician sediments at the crest (Figure 4.14). The arch was periodically a high in Early Paleozoic times, and remained as a discontinuous positive feature. This separation is clearly visible in the Landsat TM mosaic (Figure 3.05) and in the lineament map of the area (Figure 3.06). A 150 km wide zone of lineaments trending SW-NE has been recognized. They vary in length from 1 to 10 km. Lineaments measured in various formations over Al Qarqaf Arch trend dominantly NE-SW in Cambro-Ordovician rocks. This zone of lineaments is characterized by constant width along the arch. However, lack of lineaments in the southwestern part of the arch was observed (Figures 3.05 and 3.06). This is due to recent sand sheets covering the depression in the area of the Atchan Saddle. Interpretation of seismic sections across the southern part of the saddle (Figure 3.10) shows uniform thickness of Cambro-Ordovician, Silurian and Devonian rocks for more than 140 km. This saddle is a SW trending feature that represents the westward extension of Al Qarqaf Arch. The trend of lineaments in this area is mainly ENE-WSW, with both a high frequency and great length (see Table 3.01 and Figure 3.07). The density of the NW-SW lineaments and an increase in the concentration of lineaments along Al Qarqaf Arch confirm that the arch has an elongated shape. A subordinate lineament direction is trending ESE-WNW. Most probably, this direction represents the lineaments influenced by basement structures trending ESE-WNW that are represented in the magnetic map (Figure 3.02, area H7) as a strong magnetic anomaly (trending 110°). The dense area of lineaments along Al Qarqaf Arch is located mainly over an irregular and discontinuous high magnetic anomaly, which suggests these lineaments are basement-related.

3.4.3.2 *The Tripoli-Tibisti Arch*

NW-SE structures were dominant in Paleozoic times. Synsedimentary faulting along the NW-SE trending Tripoli-Tibisti Arch in Paleozoic times (Said, 1974) indicates that most of the faults are probably basement-controlled. Reactivation along these NW-SE trends occurred in Late Cretaceous-Tertiary times, as is evidenced by the Hun Graben. Lineaments of this trend are characterized by a NNW-SSE major trend (Figure 3.07), the maximum interval being 150° to 160°. This trend is characterized by a low frequency of lineaments (236) and the average length of the lineaments is 8.6 km.
3.4.3.3 The Tihembokah Arch

The Tihembokah Arch is a N-NW plunging anticlinal structure. The arch separates the Illizi Basin of Algeria from the Murzuq and Ghadamis Basins of Libya. The arch trends N-S and forms the western termination of the Atchan Saddle between the Murzuq and Ghadamis Basins. Lineaments of this area have a relatively high frequency (481 lineaments). The NW-SE and NE-SW (45° and 150°) directions show a maximum in most of the rose diagrams of the neighbouring sub-areas (Figure 3.07). As a result of this spread, the compiled rose diagram represents this area located at the intersection of Al Qarqaf Arch and the Tihembokah Arch. The lineament trends in the area are strongly influenced by the intersection of the two arches, i.e. the area lineaments cross each other (NW-SE lineament direction representing the Tihembokah Arch and NE-SW lineament direction representing Al Qarqaf Arch). This intersection of lineaments, which may represent subsurface faults, could help in hydrocarbon trapping systems in the area.

3.4.3.4 The Ghadamis Basin

The individual rose diagrams representing this area possess the following characteristics: the lineaments are short and relatively less frequent. The roughly NW-SE (130°) lineament direction is represented as the most frequent in the majority of the rose diagrams (Figure 3.07).

3.4.3.5 The Murzuq Basin

Thick sheets of sand dunes (Figures 3.06 and 3.07) cover most of the Murzuq Basin, which makes it unfavourable for detecting lineaments by remote sensing. The only areas that are not covered by sand dunes are the western and eastern rims of the basin. Lineaments of the western rim have a dominant NW-SE direction. The eastern rim of the basin has relatively few lineaments with mainly NE-SW and N-S directions and very minor NW-SE direction.
Figure 3.07 Rose diagrams of sub-areas based on major geological features (10° interval directions with frequency vs. length) of the lineaments mapped using Landsat TM, Spot XS and ERS-1 images.

3.4.4 Fault and fold patterns

3.4.4.1 Al Qarqaf Arch

Figure 3.08 shows the basement complex outcrops in the central part of Al Qarqaf Arch. Several outcrops of limited extent, made up of gray biotitic granites with white to pink feldspar and metamorphic rocks, represent this Pre-Cambrian window. Weathered basalt cones are scattered all over the area. The tectonic evolution of the area is mainly related to the crossing of the Caledonian NW-SE trending Tripoli-Tibesti Arch with Al Qarqaf Arch (Klitzsch, 1965). This intersection was rejuvenated during Oligocene times.
(Jurak, 1978). The distribution of the weathered basalt cones, lineaments and dikes around the two main Pre-Cambrian windows (Figure 3.08) support this conclusion.

3.4.4.2 The Ghadamis Basin

Circular and semi-circular features were interpreted from remote sensing images and are located in the southern part of the Ghadamis Basin (Figure 3.09). Alezeyer (1985) also observed some of these features. According to him, these features are easily traceable on aerial photographs and can be established in the terrain by arcuate sections of wadies that locally have related sabkhas and scarps. It is likely that these semi-circular features are a result of the subsurface tectonics and are thus of practical interest in hydrocarbon prospecting. Two types of circular features appear from the interpretation of remote sensing images. First, semi-circular or elliptical features, ranging from 12 to 35 km in diameter and located in the southern part of the basin, were detected on the 1:1,000,000 Landsat TM mosaic and on 1:100,000 Spot XS images (Figure 3.09). In general, these features are elongated in a NW-SE direction (140°). The second category is located in the central part of the basin and includes some small circular features that can be detected only on 1:100,000 scale images. These range from 5 to 10 km in diameter. These features coincide with the location of El Hammra and Emsgayet oil fields and are located on the aeromagnetic map in an area of high magnetic anomalies, which are most probably related, as previously mentioned, to the basement high or hidden volcanics of Jabal As Swada (Figure 3.09).

3.4.4.3 The Murzuq Basin

The shape of the Murzuq Basin is clearly visible on the remote sensing image mosaic (Figure 3.05). Its shape is triangular, with a tip oriented to the south (towards the Djadu Basin, which is the continuation of the Murzuq Basin in the Republic of Niger).

The Murzuq Basin is shaped by two main fault systems. The first system, located in east of the basin, is the Dor El Qussah complex fault system. In this area, the fault system is made of faults trending NE-SW. These faults can be traced for long distances on remote sensing images and are well expressed in the aeromagnetic map (Figures 3.02 and 3.06). The Dor El Qussah subbasin is clearly visible and can be mapped in the image. The Brak-Ben Ghenemah Arch, trending NW-SE and separating the Dor El Qussah subbasin from the main Murzuq Basin, is clearly visible on the aeromagnetic image (Figure 3.02, area H2) and the remote sensing image (Figure 3.05).
According to Klitzsch (1964), the Dor El Qussah fault zone was tectonically active from the beginning of the Paleozoic era. In the satellite image of the area (Figure 3.12), the Cambrian rocks are clearly truncated by a denser fault pattern than the younger formations. The Cambrian rocks were also partly folded. The principle tectonism was between Late Carboniferous and Late Jurassic. During the Jurassic, the eastern flank of the Murzuq Basin was lifted and since then the Dor El Qussah has been a mountain chain. In various places, the units are folded parallel to the fault strike (Figure 3.12). The type of faults in the area and the relation between lineaments and fold axis indicate the strike-slip movement model.

Several folded units were clearly observed in remote sensing images of the western part of the Murzuq Basin (Figure 3.11). These folded units are located along the major N-S Tihembokah Arch, separating the Ghadamis and Murzuq Basins from the Illizi Basin in Algeria. Some of these structures are faulted.

Basement-related faulting generally drives strike-slip tectonics in sedimentary cover. When basement faults are reactivated, a zone of rotational bulk strain develops in the sedimentary overburden. The strain is accommodated by a variety of en-échelon structures, including Riedel shears, normal faults, thrusts and folds. In basement-rooted wrench faulting, the first structures to appear are en-échelon Riedel shears. Riedel shears are important kinematic indicators. Figure 3.11 shows an interpreted E-W seismic section. Note the steep to vertical orientation of these faults, their branching and the development of anticlines between them. All these features are indicators of strike-slip or wrench faulting and the development of so-called flower structures. This fault is interpreted as a component of the wrench fault system previously mentioned. These flower structures are interesting structures for hydrocarbon exploration in the Murzuq Basin (see Chapter 5).

From interpretation of the seismic section (Figure 3.11) and correlation with Figure 3.14, which represents tectonic displacement maps based on seismic maps of the central part of the basin, the following remarkable conclusions can be drawn.

1. Most of the faults in the area are basement faults. These faults in the western part of the basin extend to the surface and deform all the overlying units, forming so-called "flower structures". This type of combination of faults and folds is related to strike-slip origin.
Chapter 3: Surface and subsurface characteristics

2. The faults in the Murzuq Basin are trending mainly in the NW-SE and N-S directions, with some trending in the NE-SW direction.

The western limit of the Murzuq Basin is located east of the Hoggar Massif, and it is separated from the Illizi Basin in Algeria by the NW-SE trending Tihembokah Arch. Asymmetric folds are common in the western part of the Murzuq Basin along the Tihembokah Arch (Figure 3.11), and their axes are dominantly NW-SE trending. These folds and faults are located in areas of hydrocarbon-producing fields on the Algerian side of the arch.

3.5 Tectonic implications

3.5.1 Al Qarqaf Arch

Figure 3.13 shows the modelled topography of Al Qarqaf Arch and adjacent areas, resulting from the interpolation with kriging of well data for the area. The figure shows the topography of the area from Late-Cambrian-Early Ordovician till Late Devonian (Tahara Formation). From this figure, we can conclude that Al Qarqaf Arch started from Late Cambrian-Early Ordovician and separated the two basins in Late Devonian. Correlation of the locations of arch structures and known hot-spot tracks in Africa indicates that Al Qarqaf Arch is located along hot-spot tracks. This may suggest that the arch is influenced by the hot-spot tracks. The Ghadamis and Murzuq Basins are not completely separated from each other. The two basins are connected partly in the area of the Atchan Saddle; this connection existed in almost all periods. This observation can also be seen in the seismic section of the southern parts of the saddle (Figure 3.10), where the figure shows a lack of variation in Cambro-Ordovician, Silurian and Devonian rocks for more than 140 km across the saddle.

3.5.2 The Ghadamis Basin

No regional seismic section for the Ghadamis Basin is available to study the fault and fold pattern in the basin. However, the combination of Landsat TM mosaic and the shaded relief map of analytic signal anomalies (calculated from residual total intensity aeromagnetic anomalies) indicates that the basin is characterized by the presence of more than one depocentre. Another observation can be made: there is a strong NE-SW magnetic anomaly (Figures 3.02 and 3.04), most probably representing Al Kabir structure where several oil and gas oil fields are located.
The structural history of the Ghadamis Basin and its elements is essentially characterized by several phases of tectogenesis:

1. Caledonian (end of Silurian time).
2. Hercynian (end of Carboniferous time).
3. Autrichian (Lower Cretaceous time).
4. Alpine (Miocene time)

These tectonic phases produced different types of structural traps and faulting systems (see Chapter 5), having two main regional orientations:

1. SW-NE Al Qarqaf Arch direction.
2. SE-NW Tripoli-Tibisti direction.

All these tectonic movements played a great role in the formation, migration and accumulation of hydrocarbons in the basin.

3.5.3 The Murzuq Basin

The shape of the Murzuq Basin can be described, based on all available maps, together with the constructed cross sections and the tectonic displacement maps of different Paleozoic horizons (Figure 3.14). The important regional structural features are as follows:

1. Pre-Cambrian. There is a very strong NW-SE trending grain in the basement, which may have influenced the tectonic pattern of the Paleozoic and Mesozoic ages.
2. Cambro-Ordovician. Fuerst and Klitzsch (1968) deduced the existence of a Paleohigh occupying the northeastern part of the Murzuq Basin, which they designated the Brak-Ben Ghemah Arch. This arch is trending NW-SE, dividing the Murzuq Basin into two parts: the main Murzuq Basin in the west and the Dor El Qussah subbasin in the east. The surface shape of this subbasin is clearly visible in the remote sensing image (Figure 3.05). Most of the present faults, which are observed in aeromagnetic images and which define the central Murzuq high as a prominent.
approximately N-S trending structural feature, have been active since Cambro-Ordovician times.

3. Silurian. Comparison of the tectonic displacement maps leads to the conclusion that most of the faults active in Cambro-Ordovician times continued to be active during the Silurian.

4. Early Devonian. The tectonic picture in the Early Devonian was more or less the same as in the Silurian.

5. Middle Devonian to Late Carboniferous. Since the aerial density of faults decreases, it is deduced that only part of the faults initiated in the Cambro-Ordovician were continuously active in the Middle Devonian to Late Carboniferous times.

6. Post Carboniferous. This period was relatively quiet; the fault density is low.

The following tectonic conclusions can be reached regarding the Murzuq Basin:

1. The basin has been subject to fault tectonics since Cambro-Ordovician times, and has been active during all the subsequent periods.

2. The faulting that occurred during Cambro-Ordovician and Silurian times was the highest in density, decreasing upwards through younger geological periods. Generally, the displacements in all periods are of the same order of magnitude.

3.6 Discussion and conclusions

In this chapter, aeromagnetic and well log data of Al Qarqaf Arch and the Ghadamis and Murzuq Basins have been processed and interpreted. Several conventional processing techniques were applied to the aeromagnetic image. A regional aeromagnetic basement structure of the area has been mapped and interpreted. The following conclusions can be reached.

1. The integration of multiple data sets for Al Qarqaf Arch and the Ghadamis and Murzuq Basins, including remote sensing images, seismics, aeromagnetics and well data, has given a better understanding of the tectonic process, and the surface and subsurface structural styles resulting from the various deformational phases.
Chapter 3: Surface and subsurface characteristics

2. In the flanks of the Ghadamis and Murzuq Basins, there is a good correlation between the locations of major basement structures mapped using aeromagnetic images, and trends and surface structures mapped in remote sensing images. These positive correlations, especially in the flanks of the Ghadamis and Murzuq Basins, strongly suggest that the sedimentary sections have been influenced by the underlying basement architecture (i.e. the aeromagnetic image indicates an extensive and basement-related fault system).

3. The interpretation of the lineament map of the total area of study (Figure 3.06) and the rose diagrams of the selected sub-areas (Figures 3.07) indicates that contrast between major geological features in the area can be inferred with some degree of confidence from lineament analysis using remote sensing images.

4. The NW-SE trending subsurface arch in the central part of the Murzuq Basin influences most of the structures in this part of the basin.

5. An ENE-WSW fault system is well expressed at the surface in the northern part of the Murzuq Basin and at the southern rim of Al Qarqaf Arch. This trend of faults is most probably influenced by the trend of Al Qarqaf Arch.

6. The geometry of both the Ghadamis and Murzuq Basins is asymmetrical and curved in shape; both basins have more than one depocentre. This may influence hydrocarbon paths and the development of reservoir conditions and trapping systems.

7. The geometry of Al Qarqaf Arch is most likely a combination of small arches. Al Qarqaf Arch does not completely separate the Ghadamis Basin from the Murzuq Basin; it is expressed in the form of high and low magnetic anomalies.

8. A particularly clear example of the importance of the regional basement structure in the concentration of oil reserves exists in the area of study. Most if not all of the discovered oil and gas fields of the Ghadamis and Murzuq Basins are located in areas of magnetic basement highs, which are expressions of deep basement irregularities. Regional oil migration in the area appears to have occurred along these trends. The resultant basin structures were accentuated by regional structural-topographical anomalies, which have become sites of major structural and
stratigraphical traps. This indicates that regional magnetic maps seem to show sufficient detail of the deep structure to define major exploration targets.

9. The magnetic map (Figure 3.02) shows several troughs or subbasins in the Ghadamis and Murzuq Basins, which are areas of sufficient extent and sedimentary thickness to be of exploration interest.

3.7 Recommendations

1. More detailed gravity and aeromagnetic survey and analyses are strongly recommended in order to verify the magnetic and gravity expressions of deeply buried basements, surface anticlines or horsts for exploration purposes. Euler 3D mapping and analysis of sedimentary thickness in the area is also recommended, as is detailed depth to basement mapping using aeromagnetic data.

2. The southern part of the Murzuq Basin has a thicker sedimentary sequence (see Chapter 4). This thick sequence offers good potential for the maturation of hydrocarbons. It is recommended that additional mapping and studies be completed for this area.

3. Backstripping analysis is recommended to investigate the subsidence history of different blocks of the area.
CHAPTER 4

PALEOGEOGRAPHICAL INTERPRETATION OF CAMBRO-ORDOVICIAN, SILURIAN, DEVONIAN AND CARBONIFEROUS SEDIMENTS IN THE GHADAMIS AND MURZUQ BASINS, WEST LIBYA, IN RELATION TO AL QARQAF ARCH

(Colored Figures 4.02 and 4.14 are in color plate section at the back of the thesis)
Chapter 4: Paleogeographical interpretation

4.1 Introduction

At the beginning of the Paleozoic era, large parts of Libya had been peneplaned, as can be observed from Pre-Cambrian rocks wherever exposed. This long period of erosion was general throughout North Africa, from the Atlantic Ocean to the Red Sea. Paleozoic rocks ranging in age from Cambrian to Permian are exposed in many parts of southern Libya. A number of transgressive and regressive cycles occurred during the Phanerozoic. Marine incursions during the Ordovician, Silurian, Devonian, Carboniferous, Late Cretaceous and Tertiary reached far south into Libya (Conant and Goudarzi, 1967). Thus, marine shales, carbonates and evaporites in the northern parts of the country dominate the sedimentary section and it becomes increasingly clastic southwards (in the Murzuq and Kufrah Basins; Gumati et al., 1996).

Al Qarqaf Arch, which separates the Ghadamis and Murzuq Basins, represents an interesting problem in the structural and stratigraphical evolution of these basins. The arch was periodically a high in Early Paleozoic times and remained as a discontinuous positive feature. The stratigraphy and structural setting are quite varied on both sides of Al Qarqaf Arch. The main objective of this research is to map and study the paleogeography of most production horizons (Cambro-Ordovician, Silurian and Devonian) of the Ghadamis and Murzuq Basins and to study a pertinent relation between the tectonic, sedimentary and stratigraphical development, based on the information available from Ordovician, Silurian, Devonian and Carboniferous rocks of the Ghadamis and Murzuq Basins. Particular emphasis will be placed on Ordovician, Silurian and Devonian rocks, given their interest as source and reservoir potential in the area. The Lower Carboniferous Mrar Formation is the only formation from the Carboniferous sequence that will be dealt with, due to its importance as a reservoir in some parts of the Ghadamis Basin. Figure 4.01 represents the overall stratigraphical variations in the Murzuq Basin. The area of study is bound between 9° and 16° E and 25° and 32° N. Fieldwork was restricted to the area of Al Qarqaf Arch where outcrops of Paleozoic rocks are located (Figure 4.02).

The objective was achieved through subsurface well log correlation of more than 120 wells distributed throughout the area. The wells were used to construct isopach, sand percentage and sand/shale ratio maps and regional stratigraphical cross sections.
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Thicknesses of these rocks were estimated by correlating stratigraphical units, seismic sections and outcrop analysis. Data from both published and unpublished reports have been integrated into this analysis.

4.2 General geological setting of Paleozoic rocks


A detailed description of the geology of the whole Paleozoic system is not within the scope of this study. In brief, Paleozoic rocks ranging in age from Cambrian to Permian occupy much of the eastern parts of Libya (Figure 4.02). In the area of study, the Paleozoic rocks crop out along the western, eastern and northern peripheries of the Murzuq Basin. However, this study will focus only on the Paleozoic rocks outcropping along the northern rim of the Murzuq Basin, and their subsurface equivalent in the hadamis Basin in particular (Figure 3.02).

On the western flank of the Murzuq Basin, Paleozoic rocks are exposed in the Ghat-Awaynat area. They consist of Cambro-Ordovician, Silurian, Devonian and Carboniferous sediments. The Cambro-Ordovician thickness has been reported to be 580 m. A thickness of 490 m of Silurian graptolite shales was measured near Ghat. Overlying the Silurian shale are two sandstone units. Together with the shale, they form a transgression-regression cycle of Silurian to Lower Devonian age. On the eastern flank of the Murzuq Basin, the Paleozoic rocks are best exposed in the Jabal Ben Ghenemah and Dor El Qussah areas. They also consist of Cambro-Ordovician, Silurian, Devonian and Carboniferous sediments. The thickness of the Cambro-Ordovician has been reported to be in the order of 600 m. The Silurian Tanezzuft shale is only about 60 m, grading upwards into the sandstone units, thus becoming very thin. In the middle southern Dor El Qussah area, these sandstone units and parts of the shales are eroded. The extent of erosion increases southwards, where the shale and sandstone units are completely eroded over a large area south of 25° N. However, the sandstone-shale
sequence of the Middle Devonian-Carboniferous is very thick in this area, reaching a thickness of 700 to 1000 m.

During the Paleozoic era, two major tectonic pulses affected the region:

1. In the early Paleozoic the Caledonian Orogeny, which formed broad uplifts and troughs with a NW-SE trend.

2. In the Late Paleozoic the Hercynian Orogeny, with an approximately E-W strike.

The stratigraphical setting of the Paleozoic sequence in Libya has been established from outcrop examination and drill-hole correlation. Recent work by oil companies in the areas of the Murzuq and Ghadamis Basins has allowed the establishment of a more refined stratigraphical correlation than hitherto. Five depositional cycles (Figure 4.01) separated by well-marked boundaries have been recognized (Said, 1974; Marmign, 1980; Karasek, 1981). Details of the different sequences and their associated formations are described in the following sections.

The Cambro-Ordovician, Silurian, Devonian and Carboniferous history of Al Qarqaf Arch and the adjacent Ghadamis and Murzuq Basins is shown by a series of cross sections, isopach maps and sand percentage maps. These cross sections and maps are based on electrical and gamma ray log correlations from more than 120 wells distributed throughout the Ghadamis and Murzuq Basins. The intervals represented in the isopach maps are approximate time-stratigraphical units. The sandstone percentages have been estimated from self-potential and gamma ray logs. These maps and sections were used to determine the stratigraphy and paleogeography of the Cambro-Ordovician, Silurian, Devonian and Carboniferous systems.
Figure 4.01 Generalized scheme of depositional cycles and environment.
4.3 Paleogeographical interpretation

4.3.1 Cambro-Ordovician sequence

The Cambro-Ordovician systems in Libya were defined in the area of Al Qarqaf Arch. Occurrences, both in outcrops on the margins of the Ghadamis and Murzuq Basins and in the subsurface, are widespread over a great portion of the North African Craton. Four formations were formally defined by Massa and Collomb (1960). These are Al Hassawanah Formation, the Haoaz Formation, the Melez Chogaine Formation and the Memouniat Formation. The Cambro-Ordovician Al Hassawanah sediments are in direct contact with basement rocks. Basal conglomeratic beds cover the contact in Al Qarqaf Arch (Figure 4.14), while in other places there is a sharp contact with a weathered granite surface. Paleocurrent data of Cambro-Ordovician and Devonian rocks (Figure 4.05) and lithofacies trends indicate progradation towards the northeast, north and northwest over the Pre-Cambrian and Infra-Cambrian erosional surface and suggest a southerly sub-Sahara source. The Memouniat Formation will be the subject of paleogeographical analysis in this study because of its importance as reservoir rock in the Murzuq Basin.

During the Middle Ordovician, the sea completely flooded these older clastics. The Melez Chogaine shale, overlying the Haoaz Formation and separating its basal sandstones from that of the Memouniat Formation, was deposited in this marine environment. During the Late Ordovician, the sea was restricted and the clastics of the Memouniat Formation, deposited by glacial processes, were laid down in the south. The unconformity present at the base of the Memouniat Formation most likely reflects the paleovalley and channel development during this end-Ordovician glaciation (Karasek, 1981).

The upper boundary of the Cambro-Ordovician sequence in the Ghadamis Basin is marked by a dolomitic limestone horizon, with a rich marine fauna developed towards the top of the Memouniat Formation. This horizon is followed by a radioactive zone at the base of the Tanezzuft shale of the Lower Silurian. Lithologically, the strata of this radioactive zone ("hot shales") are similar to the Memouniat Formation of the Upper Ordovician sequence and consist of carbonaceous black shales, frequently associated with intercalations and concretions of calcite and dolomite. Pyrite and carbonized
organic material are also common. The regional cross section (Figure 4.03) shows a thickening of the Cambro-Ordovician section on the southwestern side of the Murzuq Basin. The same observations can be made from the seismic sections (see Figure 3.11).

**Figure 4.03** Schematic N-S cross sections through Al Qarqaf Arch and the Ghadamis and Murzuq Basins.
Figure 4.04 Schematic E-W cross sections through the Murzuq Basin, Al Qarqaf Arch, and the Ghadamis Basin.
Figure 4.05 Paleocurrent data of (A) Cambro-Ordovician rocks and (B) Devonian rocks (from Karasek, 1981).

4.3.1.1. Memouniat Formation

This formation is of Ashgillian age. Massa and Collomb (1960) defined this formation from the western part of Jabal Al Hassawanah. (Figure 4.01). This unit is
widespread and of similar sediment types in both the Ghadamis and Murzuq Basins. The formation is mainly a massive cross-bedded and medium- to coarse-grained sandstone unit. The upper boundary is unconformable with the Silurian Tanezzuft Formation. Generally in the Ghadamis Basin, the formation is thinner in the south (towards Al Qarqaf Arch) than in the northern parts of the basin. In the Murzuq Basin, the occurrence of the formation in the subsurface is widespread (Figure 4.06). The Memouniat Formation is the main producing horizon in the Murzuq Basin and in some places in the eastern part of the Ghadamis Basin (see Figure 5.04). Figure 4.06 shows that most producing areas are located in areas where the sand percentage is more than 75%. The thickness ranges from 20 m in the eastern part of the Murzuq Basin to about 240 m in the northern part of the basin. In the southern parts of the Murzuq Basin, the thickness is decreasing, most probably as a result of a paleo-high area that was exposed to erosion while the surrounding lows were already covered by the overlying transgressive shales.

Paleocurrents indicate a northerly transport direction. Glaciers migrated from north to south over Al Qarqaf Arch area at least once. Hadley (1992) demonstrated periods of sea-level drop and rise associated with glacial advance and retreat. He also indicated evidence of a stronger marine influence from northeast to southwest in the western parts of Al Qarqaf Arch. The formation is a good hydrocarbon reservoir unit in El Hammra oil fields in the south of the Ghadamis Basin (Chapter 5). Sedimentation was associated with the second glacio-marine episode during the late Ordovician (earliest Caradocian) time.

The sand percentage and thickness variation map of the formation (Figure 4.06) indicates an increase in the thickness of the formation and sand percentage towards the northwest of Al Qarqaf Arch, where it reaches about 550 m.
Figure 4.06 Isopach and sand percentage map and thickness variations of the Memouniat Formation.
### 4.3.2 Silurian sequence

The early Silurian period was a time of global sea-level rise as a result of the melting of the ice cap that covered the massifs of Hoggar and Tibisti, and a major marine transgression covered the greater part of North Africa. The Silurian sequence represents a very good example of a transgressive/regressive cycle. The Silurian sediments in the study area are divided lithologically into two major units (Tanezzuft and Acacus). The sequence contains both source and reservoir rocks and represents the most interesting prospect in the northern part of the Ghadamis Basin.

The cross sections (Figures 4.03 and 4.04) indicate regional thickening of the Murzuq Basin, and it reaches about 480 m in the area of the Serdies Trough. In the Ghadamis Basin, the thickness increases towards the northwest and reaches about 900 m in the central part of the basin.

Two formation names have been used to represent the entire Early to Late Silurian sequence in western Libya: the Tanezzuft Formation and the Acacus Formation. Throughout western Libya, the Tanezzuft Formation constitutes the first unit of the prograding Silurian sequence, usually occupying a conformable position on the Late Ordovician (Ashgillian). Silurian rocks in the area of study are exposed around the periphery of the Murzuq Basin. Klitzsch (1968) traced the progressive development of sandy facies and concluded that the regressive phase of the Silurian period is oldest in the south and southeastern parts of the Murzuq Basin. The shoreline had progressively shifted northwards, resulting in the increased thickness of the younger deposits of the Silurian period northwards. The diachronism of these formations, due to the regular progradation of the Silurian sequence, is now well documented (Seilacher, 1969; Bellini and Massa, 1980). Sediments of Silurian age outcrop only on the very western end of Al Qarqaf Arch. These sediments belong to the Early Silurian Tanezzuft Formation. The absence of the Silurian section over all but the very western end of Al Qarqaf Arch is probably the result of non-deposition rather than erosion (Beswetherick et al., 1996). This suggests that Al Qarqaf Arch had become a positive feature by the end of Ordovician times (see Figure 3.14). The Acacus Formation is almost absent in the area of Al Qarqaf Arch. This can be interpreted as a result of the uplift of the arch in Late Silurian, causing the removal of all Acacus sandstone that may have been present.
4.3.2.1 Tanezzuft Formation

The Early to Late Silurian (Ludlovian) Tanezzuft Formation unconformably overlies the Cambro-Ordovician Memouniat Formation and is generally transgressive. The formation is a product of a worldwide transgressive event. The sequence boundary could be the base of the Tanezzuft shale and it is part of a transgressive system track. Shale is predominant. Graptolites and other marine fauna are common. The Tanezzuft Formation is the main source rock in the Ghadamis and Murzuq Basins (see Chapter 5, Section 5.5, and Figure 5.02)

The isopach map of the Tanezzuft Formation (Figure 4.07) shows that the major depocentre of the formation is developed in the northwestern part of the Ghadamis Basin. The map shows thickness thinning towards the eastern and northwestern sides of the basin. The Tanezzuft shales thin over the Atchan and the Tihembokah Arches and are missing over the greater part of Al Qarqaf Arch. Thickness ranges from 60 to 120 m in the Murzuq Basin and reaches about 550 m in the central part of the Ghadamis Basin. According to Klitzsch (1964), the reactivation of the Ben Ghenemah Arch on the eastern flank of the Murzuq Basin has resulted in the erosion of the Tanezzuft sequence and the presence of a pinchout effect, whilst on the northern edge of the basin (and in its central part) well control shows the formation to be represented by shales interbedded with coarser clastics than seen farther north. This formation is extremely rich in organic matter in the Ghadamis and Murzuq Basins and is therefore an ideal source rock in both basins. The sand percentage map of the formation shows that the percentage of sand in most of the area is less than 20% (Figure 4.07).

The occurrence of black, very radioactive shale in the lower part of the formation indicates widespread anoxic conditions, probably associated with low sedimentation rates at the time of maximum transgression.
Figure 4.07 Isopach and sand percentage map and thickness variations of the Tanezzuft Formation.
4.3.2.2 Acacus Formation

The Middle to Late Silurian Acacus Formation conformably overlies the Tanezzuft Formation. Lithologically, the formation consists of a light brown fine- to medium-grained massive cross-bedded sandstone. The formation forms excellent reservoirs in fields of the northern part of the Ghadamis Basin (see Chapter 5, Section 5.3.1, C.2). The thickness of the formation in the basin ranges from less than 60 m in the southern parts of the Ghadamis Basin and the northern parts of the Murzuq Basin to more than 490 m in the northwestern parts of the Ghadamis Basin (Figure 4.08). Eastwards, the formation is thinning on the flanks of Al Qarqaf Arch. The Acacus Formation is the main producing horizon in the northern and central parts of the Ghadamis Basin. Figure 4.08 shows that most of the producing areas are located in areas where the sand percentage is between 25% and 75%.

The isopach map of the Acacus Formation (Figure 4.08) indicates that the depocentre of the formation in the Ghadamis Basin is essentially the same as that of the Tanezzuft Formation. The arches of Al Qarqaf, Tripoli-Tibisti and Ben Ghenemah also influence the thickness of the Acacus Formation. This indicates that the arches of Al Qarqaf and Tihembokah were present during Acacus times. The map shows that the thickness increases towards the northern and northwestern parts of the Ghadamis Basin. The map also shows that the formation is absent over Al Qarqaf Arch and much of the northern part of the Murzuq Basin. Karasek (1981) also notes this. The sand percentage map shows a decrease in sandstone content along the northwest of the Ghadamis Basin and the east of the Murzuq Basin. In the middle of the Ghadamis Basin, there is an increase in sand content. According to Castro et al. (1985), the Acacus sandstone represents the marine regressive stage that followed the marine Silurian transgression (Furst and Klitzsch, 1963). Outcrop studies in the south (Beuf et al., 1971) indicate that the Hoggar Massif was the primary source area for Acacus sediments deposited as far north as the southern part of the Ghadamis Basin. The shape of the sand percentage distribution suggests a fluvial/deltaic system progressing northeastwards into the Ghadamis Basin. According to Castro et al. (1985), the depositional environment of the Acacus Formation is fluvial in the southern Ghat area.
Figure 4.08 Isopach and sand percentage map and thickness variations of the Acacus Formation.

4.3.3 Devonian sequence

The Devonian rocks are the primary targets for oil exploration in the southern and central parts of the Ghadamis Basin, due to the substantial discoveries made from these rocks in eastern Algeria and southern Tunisia. The Devonian is exposed on the south flank of Al Qarqaf Arch (Figures 4.02 and 4.14). However, the Lower Devonian strata
are missing. This absence has been ascribed to non-deposition rather than erosion (Mamgain, 1980). Rapid facies and thickness changes make understanding the Devonian a complex task. The succession in the subsurface of the Ghadamis Basin can be compared directly with outcrop data from the type area of Aouinet Ouenine in the southeast of the Ghadamis Basin. The Devonian system in the area includes the Tadrart, Ouuan Kasa, Aouinet Ouenine and Tahara Formations.

Paleocurrent data of Devonian rocks (Figure 4.05B) and facies trends indicate progradation to the west and northwest in the Ghadamis Basin and towards the southwest in the Murzuq Basin. An easterly source, probably in the vicinity of the Tibisti Massif, Sirt and Al Haruj, is indicated. In general, the regional cross section (Figure 4.03) and the isopach maps of the Devonian formations of the Ghadamis and Murzuq Basins (Figures 4.09, 9.10, 9.11 and 9.12) show the thinning of Devonian rocks towards the northern side of Al Qarqaf Arch. The Devonian rocks show an increase in thickness towards the centre of the Ghadamis Basin and away from the axis of Al Qarqaf Arch, which, based on the paleocurrent data and thickness distribution, would have been established by that time.

4.3.3.1 Tadrart Formation

The Early Devonian (Siegenian) Tadrart Formation is mainly restricted to the Ghadamis Basin (Figure 4.09). It is generally a dark massive cross-bedded sandstone. The formation unconformably overlies the Silurian Acacus Formation. The formation increases in thickness towards the northern part of the Ghadamis Basin. In the Murzuq Basin, the Tadrart Formation is almost absent, particularly in the central part of the basin. The southern and central parts of the Ghadamis Basin produce mainly from the Tadrart Formation (see Chapter 5, Section 5.3.1, D1). The isopach map of the Tadrart Formation (Figure 4.09) shows a general thickening towards the northwest, from less than 30 m to more than 300 m in the centre of the Ghadamis Basin. Al Qarqaf Arch may have been the primary source of the Tadrart sediments in the Ghadamis Basin. The sandstone percentage map (Figure 4.09) shows a decrease in sand percentage north of Al Qarqaf Arch and in the central part of the Ghadamis Basin. In general, the formation appears to have been sourced from the south and southwest. Figure 4.09 shows that most of the producing areas are located in areas where the sand percentage is more than 75%.
In the northwest of the Ghadamis Basin, the Lower Devonian fluvial sandstones of the Tadrart Formation cap the deltaic sediments of the Acacus Formation and are overlain by the Ouan Kasa limestone, dolomite and shales. The Tadrart Formation consists of marginal to deltaic sandstones in the southern parts of the Ghadamis Basin and along Al Qarqaf Arch.

**Figure 4.09** Isopach and sand percentage map and thickness variations of the Tadrart Formation.
4.3.3.2 Ouan Kasa Formation

This formation represents the Early Devonian (Gedinnian to Emsian). The lower boundary of the formation is conformable with the Tadrart Formation, and the upper boundary is unconformable with the Aouinet Ouenine Formation. It consists of a lower carbonate interval with limestone, shale and calcareous sandstone and an upper sandstone and shale interval. In the subsurface of the Ghadamis Basin, the Ouan Kasa Formation is about 10 to $>180$ m thick. Figure 4.10 indicates that the thickness of the Ouan Kasa Formation decreases along Al Qarqaf Arch and the maximum thickness recorded in the area is in the central part of the Ghadamis Basin. The sandstone percentage map shows an increase in sand percentage north of Al Qarqaf Arch ($>75\%$). Clark-Lowes (1985) described the sedimentology of the formation in the type area in detail. He observed several sequences dominated by transgressive deposition. Fluvial sediments are succeeded by estuarine and then shallow shelf deposits, including tidal sand ridges. The interpretation of Figure 4.10 allows us to say that Al Qarqaf Arch was possibly the source and that sand deposition took place near the shore, with fine-grained sediments in the centre of the Ghadamis Basin.

4.3.3.3 Aouinet Ouenine Formation

The Aouinet Ouenine Formation represents the Middle Devonian (Eifelian and Givetian) as well as the Late Devonian (Frasnian and Famennian) stages in the exposed marginal areas of the Ghadamis Basin. The upper contact with the Tahara Formation is conformable; the lower boundary is unconformable with the older unit. The Aouinet Ouenine Formation is a minor producing horizon in the central, eastern and northern parts of the Ghadamis Basin, and some wells in the Murzuq Basin are producing from this formation as well (see Chapter 5, Figures 5.02 and 5.04). Figure 4.10 shows that most producing areas are located where the sand percentage is more than 50%.

Figure 4.11 shows the thickness variations and sand percentage of this formation in the Ghadamis and Murzuq Basins. The map indicates that sediments of the Aouinet Ouenine depositional cycle probably covered most if not all of Al Qarqaf Arch. Also in the Ghadamis and Murzuq Basins, the occurrence of the Aouinet Ouenine Formation is widespread.
Interpretation of Figure 4.11 and the paleocurrents of the formation indicate a source to the east, south of Al Qarqaf Arch. The arch was a slightly positive feature, not emergent but influencing sedimentation. Beds thin and possible onlap the northern margin of the arch. Only part of the formation (Figure 4.05) is present in the eastern outcrop area of the arch (Bellini and Massa, 1980). The paleocurrent direction is to the southwest; north of the arch it is to the northwest.

The formation consists of cross-bedded coarse-grained sandstones with some shale layers. Typically large-scale coarsening-upward cycles represent a prograding delta and shoreface, truncated at the top by transgressive deposits consisting of tidal flats and foreshore deposits (Vos, 1981).
Figure 4.10 Isopach and sand percentage map and thickness variations of the Ouan Kasa Formation.
Figure 4.11 Isopach and sand percentage map and thickness variations of the Aouinet Ouenine Formation.
4.3.3.4 Tahara Formation

This formation represents the latest Devonian (Famennian stage)-Early Carboniferous age. The formation is conformable with the Aouinet Ouenine Formation and unconformably overlain by the Carboniferous Mrar Formation. This unit is significant as it extends geographically throughout North Africa from Libya to Morocco. The formation consists of light and brown sandstone and greenish-gray and brown shales of shallow marine environment. The surface exposures of the Tahara Formation are on the western side of Al Qarqaf Arch (Castro et al., 1985). The Tahara Formation is a minor producing horizon in the Murzuq Basin (see Figure 5.04). Figure 4.12 shows that most of the producing areas are located in areas where the sand percentage is between 50% and 75%.

Figure 4.12 shows the thickness variations of the Tahara Formation. The formation is eroded in the northern part of the Ghadamis Basin and it reaches maximum thickness and shale content in the western parts of the basin. This is confirmed by comparing well logs with outcrop sections. The Tahara Formation covers Al Qarqaf Arch and the Ghadamis and Murzuq Basins, with increasing thickness towards the centre of the Ghadamis Basin. Al Qarqaf Arch is a low positive feature onto which the Tahara rocks thin slightly. The formation is also thinning over the Tihembokah and Atchan arches. In the Dor El Qussah subbasin, the Tahara Formation is eroded. The formation represents a transitional regressive event between the Famennian marine facies below and the overlying Early Carboniferous transgressive marine facies (Conrad et al., 1986).
Figure 4.12 Isopach and sand percentage map and thickness variations of the Tahara Formation.
4.3.4 Carboniferous sequence

No break in deposition has been observed between Upper Devonian and Lower Carboniferous; therefore, the Devonian and Carboniferous formations are treated in common in several places. The Carboniferous sequence is exposed on the southern and northern edges of Al Qarqaf Arch (Figures 4.02 and 4.14).

The Carboniferous outcrops also extend along the margins of the Murzuq Basin. The sequence is eroded in the northern part of the Ghadamis Basin. The most important Carboniferous formation is a thick sequence known as the Mrar Formation. Its thickness reaches 1100 m, recorded in the outcrop of the southern part of the Ghadamis Basin. Besides the Mrar Formation, this sequence also comprises the Assedjefar and Dembaba Formations of Lower and Middle Carboniferous age and the Upper Carboniferous red continental sediments of the Tiguentourine Formation. The Permian is known north of the Nefusah Uplift only. The Lower and Middle Carboniferous sediments represent the culmination of a transgression, which was initiated in the Late Silurian. The Hercynian Unconformity marks the upper boundary of the Paleozoic sequence in the Murzuq and Ghadamis Basins and progressively truncates the Lower Paleozoic sequence northwards towards the Nefusah Uplift. The Mrar Formation will be the subject of analysis due to its importance as a reservoir in the central part of the Ghadamis Basin.

4.3.4.1 Mrar Formation

The Mrar Formation (Late Tournaisian-Visean) consists of interbedded siltstone and shale and is considered as a minor reservoir target in the Ghadamis Basin (see Chapter 5, Figure 5.04). The formation shows a regional N-S facies change, from marine to the north in the PaleoTethys to a progressively marginal marine and continental facies to the south, as in the Murzuq and Djadu Basins. It forms a relatively thick section. Figure 4.13 shows that the thickness of the Mrar Formation increases towards the central part of the Ghadamis Basin, where about 670 m is recorded. The sand percentage map shows that the sand percentage decreases towards the north of Al Qarqaf Arch and towards the west (Tihembokah Arch). The formation represents the early transgressive phase of the Carboniferous over the terminal regressive Devonian unit. Figure 4.13 shows that most of the producing areas are located in areas where the sand percentage is around 50%.
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Figure 4.13 Isopach and sand percentage map and thickness variations of the Mrar Formation.
4.3.5 Other sediments

4.3.5.1 Meso-Cenozoic system

The Mesozoic marine transgression can be dated to Middle Triassic in the Ghadamis Basin; the deposited sediments can be attributed to a shallow-water environment, which lasted up to the Lower Cretaceous. During the Upper Cretaceous, a more widespread marine transgression produced a more typical marine environment in western and northeastern Libya, around Al Qarqaf Arch.

In this period, the Murzuq Basin also emerged. Marine sedimentation continued during the Cenozoic up to the Lower Middle Eocene. A later regressive phase affected a large part of the considered region, creating a lagoonal or lacustrine sedimentary environment during the Oligocene-Miocene.

4.3.5.2 Recent Tertiary sediments

Lacustrine sediments of undifferentiated Tertiary age are located in the Hun and Waddan area. These sediments are made up mainly of variegated lacustrine limestone with frequent chalky interbeds. These Tertiary sediments are present along Wadi El Shatti, where they present a calcareous facies. On the eastern limit of the study area, between the road Waddan-Zalla and the northern boundary of Jabal Al Haruj, undifferentiated Miocene deposits of continental and lagoonal environment (sand, clay and limestones) are present.

4.3.5.3 Basalts

Basalts are the main component of Jabal As Sawada and of Jabal Al Haruj, whose western sector is included in the study area (Figure 3.05). The volcanic deposits are made up of olivine containing phonolitic basalts, and represent a limited thickness that ranges from a few metres to a few tenths of a metre. The age lies between Oligocene and early Quaternary.
4.3.5.4 Quaternary

The Quaternary is represented by the dunes of Idahan Awbari and Ramlat Az Zellaf, which correspond to the last dry post-neolithic phase of the Sahara, and by the alluvial deposits indicated in the Hun Graben.

4.4 Discussion and conclusion

4.4.1 Discussion

The upper boundary of the Paleozoic sequence in the Murzuq and Ghadamis Basins is marked by an unconformity that progressively truncates the Lower Paleozoic sequence northwards. This unconformity is related to the last phase of the Hercynian Orogeny, which represents the second major tectonic event affecting the Paleozoic sequence and can be dated as Middle to Upper Carboniferous through to Permian. Due to uplifting at the close of the Early Silurian, the Tanezzuft shales and Acacus sandstone are missing over Ben Ghenemah and Al Qarqaf Arch. This tectonic uplifting was associated with Early Caledonian movements. Its effects in the Ghadamis Basin were much less pronounced.

The dominantly argillaceous Silurian sediments grade into arenaceous facies northwestwards progressively through time, suggesting that the regression started in the Ghadamis Basin from the southeast during the Late Silurian period. The Late Silurian/Early Devonian are characterized by widespread continental conditions and the emergence of land plants (Hoffmeister, 1959).

Paleocurrent data of Cambro-Ordovician with a N direction and Devonian rocks with NW and SW directions (Figure 4.05) and lithofacies trends indicate transport to the west and northwest during the Early Devonian. This suggests that the source of the Upper Silurian-Middle Devonian sediments are to the east and southeast, in the vicinity of the present Tibisti, and that Al Qarqaf Arch emerged.

Widespread marine transgression marks the beginning of the Silurian period, with shales containing a rich graptolite fauna. After the Middle and Upper Silurian transgression, the area of Al Qarqaf Arch was subjected to the effect of the Caledonian
Orogeny, which started in the middle of the Silurian and persisted into the Devonian. The Devonian period is marked by a great variation in facies and complex cycles of deposition of arenaceous and argillaceous sediments. The rock units of the Tadrart and Ouân Kasa Formations, which constitute the upper part of the Lower Devonian, are post-Caledonian and of continental origin (braided deltaic deposits). During the Middle Upper Devonian and Lower Carboniferous, the area was subject to periodic and frequent cycles of marine transgression and regression. The Middle and Upper Devonian sequence of the Aouinet Ouenine Formation is of marine origin and ends with the regressive sequence of the Tahara Formation. The marine and lagoonal facies, comprising the Mrar, Assedjefar and Dembaba Formations of Lower and Middle Carboniferous age, represent the end of the major transgressive episodes of the Paleozoic in the Murzuq and Ghadamis Basins, which were initiated during the Late Silurian. During the Upper Carboniferous, red continental sandstones were deposited. The Permian transgression is only known north of the Nefusah Uplift. The isopach map of the Tadrart Formation (Figure 4.10) shows that Tadrart sandstone onlapped the Acacus and older formations on the flanks of the major arches and massifs. On the northwestern flank of Al Qarqaf Arch, the Tadrart sandstone unconformably overlies eroded Middle Silurian shales of the lower part of the Tanezzuft Formation.

4.4.2 Conclusions

The marine character in the Paleozoic sequence was first established during the Middle Ordovician period, when the sea completely flooded the older clastics of the Cambrian and Early Ordovician Al Hassawanah and Haoaz Formations, which are mostly littoral to deltaic in origin. The Melez Chograne shale overlying the older clastics was deposited in this marine environment.

From the analysis of regional cross sections, sand percentage maps and isopach maps of Cambro-Ordovician, Silurian, Devonian and Carboniferous periods, the following conclusions can be reached.

1. Isopach and sand percentage maps of the Cambro-Ordovician, Silurian, Devonian and Carboniferous periods clearly illustrate the tectonic influence on the sedimentary fill of the Ghadamis and Murzuq Basins.
2. The total Silurian isopach map (Figure 4.07) indicates a thick section of the Silurian in the southwest of the Murzuq Basin, where more than 490 m of sediments were deposited in the area of the Serdies Trough.

3. Depositional thinning of the Silurian sediments over Al Qarqaf Arch (Figures 4.03, 4.04, 4.07 and 4.08) suggests that it was an intermittently emerging structure throughout the Silurian period.

4. The Tanezzuft shales were deposited in a broad shallow sea, which covered most of North Africa. The well-defined Tanezzuft depocentre (Figure 4.07) is located in the central part of the Ghadamis Basin and most probably extends into Tunisia and Algeria. On Al Qarqaf Arch, the Tanezzuft Formation has been partially or completely eroded. This indicates post-Tanezzuft uplift of the arch. The Acacus Formation (Figure 4.08) was probably more restricted in aerial extent than the Tanezzuft shales. It had approximately the same depocentre as the Tanezzuft Formation.

5. The Acacus Formation is almost absent in the area of Al Qarqaf Arch (Figure 4.08). This can be interpreted as a result of an uplift of the arch in the Late Silurian, resulting in the removal of the Acacus sandstone that may have been present in the arch area.

6. The Devonian section of the area can be understood as a result of a major transgressive event that started in Early-Middle Devonian and progressed into the Carboniferous, the maximum being reached in the Late Lower Carboniferous. Good to very good reservoirs and possible source rocks are present in the Middle to Upper Devonian formations.

7. The sand percentage map and thickness variation of the Aouinet Ouenine Formation (Figure 4.11) indicate a continuing onlap onto Al Qarqaf Arch. Sediments of the formation probably covered most if not all of Al Qarqaf Arch.

8. The sand percentage, sand ratio maps and paleocurrents of the Silurian, Devonian and Carboniferous formations indicate that the main sources of these rocks are southeastern and southwestern (Tibisti and Hoggar Massifs).
9. The isopach maps of different Paleozoic rocks clearly illustrate the influence of tectonics on the sedimentary fill in the Ghadamis and Murzuq Basins.

10. Al Qarqaf Arch was an intermittently active structural feature during most of the Paleozoic era. Most of the formations of the Cambro-Ordovician, Silurian, Devonian and Carboniferous have a decreased thickness in the area of the arch.
CHAPTER 5

HYDROCARBON SYSTEMS OF THE GHADAMIS AND MURZUQ BASINS, WEST LIBYA AND THEIR RELATION TO AL QARQAF ARCH

* Parts of this chapter were presented as:
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Chapter 5: Hydrocarbon systems of Ghadamis and Murzuq Basins

5.1 Introduction

Recent oil discoveries within the Ghadamis and Murzuq Basins indicate the necessity for a renewed examination of the tectonic and stratigraphical framework of both basins. This chapter provides an analysis of the hydrocarbon systems of the Ghadamis and Murzuq Basins. More than 150 exploratory wells have been drilled in these basins, resulting in the discovery of some 50 oil pools in the Ghadamis Basin and some 20 in the Murzuq Basin. Figure 5.01 illustrates the distribution of major known hydrocarbon resources across the region. Most of the hydrocarbon exploration carried out in the Ghadamis and Murzuq Basins has been within their major depocentres.

The primary objectives of this part of the study are to compile a reliable data set of oil and gas fields in the Ghadamis and Murzuq Basins and to develop criteria for subdividing these areas into zones or trends. In this chapter, tectonic processes affecting the sedimentation and facies development of the Paleozoic sequences in the Ghadamis and Murzuq Basins (described in Chapter 4) is evaluated. It is believed that recognition of such processes is essential for a better understanding of the tectonic and stratigraphical framework of the region, and this regional approach is to help to gain an insight in:

1. facies development (source rocks, reservoir rocks, cap rocks, etc.),
2. structural development (migration, traps, etc.),
3. establishing tentative correlation between regional structural patterns and hydrocarbon accumulations.
4. predicting possible hydrocarbon trends.
5. comparing the Murzuq and Ghadamis Basins.

This understanding will be transferred to less explored and currently unproductive areas within the region, in an attempt to highlight areas and fairways of remaining exploration potential.
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Relationships between the stratigraphy and hydrocarbon occurrences within the Ghadamis and Murzuq Basins are summarized in Figure 5.02. The study area covers Al Qarqaf Arch and the adjacent parts of the Ghadamis and Murzuq Basins (Figure 5.01). The data sets used in this study consist of reservoir data of the oil and gas fields that are drilled in the two basins. Recorded attributes for the selected wells in the data sets are (1) location, (2) depth, (3) stratigraphical name of the reservoir, (4) trap type, (5) structural setting, (6) porosity, (7) hydrocarbon types and (8) oil gravity. These data were compiled from well logs and unpublished reports and records of the National Oil Corporation (NOC) and other oil companies. Oil and gas reserves quoted in this chapter are derived from the petroleum exploration (NOC) and production database (Massa et al., 1994).

Hydrocarbons in the Ghadamis and Murzuq Basin have been produced from several Paleozoic sandstone pay-zones (Figure 5.02). The source rock is mainly Silurian shales of the Tanezzuft Formation, supplemented by Devonian and Cambro-Or dovician shales. The main producing horizons in the Ghadamis Basin are the Silurian Acacus Formation in the northern and central parts of the basin and the Devonian Tadrart Formation in the southern and central parts of the basin. Other intervals with minor production are found in several parts of the basin. In the Murzuq Basin, the Ordovician Memouniat Formation is the main producing horizon; other Devonian formations are also producing (Figure 5.04). Structural traps are the most common types of trap in the Murzuq Basin; traps in the Ghadamis Basin range from combination traps in the southern and northern parts of the basin (close to the rims of the basin) to structural traps in the central part of the basin. Minor discoveries are found in stratigraphical traps in the western part of the basin. All discovered oils are naphtenic crude. Oil gravity ranges from 32° to 45° in the Murzuq Basin and between 34° and 47° in the Ghadamis Basin. The reservoirs in the Ghadamis and Murzuq Basins range in depth from about 610 to 1830 m subsea. (All depths stated in this chapter are below sea level.)

5.2 Exploration history

Libya is one of the world’s major hydrocarbon provinces, with reserves in the order of some 17*10^6 M^3 (Klett et al., 1997) plus significant gas. Hydrocarbon accumulations have been found in the Ghadamis Basin (318*10^6 M^3) and the Murzuq Basin (238*10^6 M^3 of reserves; Gumati et al., 1996). Many areas in Libya are under-
explored and excellent potential remains for new discoveries. Exploration for hydrocarbon in western Libya was started in the 1950s by a number of companies along the Algerian border. According to Massa et al. (1995), exploration activities in the Ghadamis Basin started in earnest when Libya passed its petroleum law of 1955. Libya’s first oil discovery was made by East Standard in 1957 in the western part of the Ghadamis Basin and was a continuation of a Paleozoic trend that had yielded some big discoveries in eastern Algeria. Little information exists on the exploration activities that took place prior to 1956.

Following an early phase of field studies in the Ghadamis Basin, three distinct periods can be recognized in the chronology:

1. **Phase 1 (exploration between 1956 and 1962):** This phase was characterized by the activity that began as a result of the first exploration concession being granted in the western parts of the Ghadamis Basin. A number of oil companies began work on magnetic, seismic acquisition and surface geological mapping. Several concessions were granted by 1958, followed by the drilling of several exploration wells in the basin. Interest was stimulated by the giant find on the Algerian side of the Ghadamis Basin. From 1960 onwards, several oil companies (BP, Wintershall, Esso, Gulf, Mobil, Oasis-America, Pan-American, Shell and Total) held concessions in the Ghadamis Basin (Figure 5.01). The Libyan-American oil company drilled the first exploration well in 1956. Several producing wells were drilled during this period, for example the wells of concession 66 (concession NC8A in Figure 5.01), which established El Hammra and the Emsgayet oil-producing area (Gulf company) and the oil fields of Tlacsin (Shell Libya) and El Milaghi in the northern parts of the Ghadamis Basin (Figure 5.01).

2. **Phase 2 (exploration between 1962 and 1969):** Little attention was given to the Ghadamis Basin during this period because most of the oil companies concentrated on the Sirt Basin of central Libya, where most of the (giant) exploration discoveries in Libya were made.

3. **Phase 3 (exploration from 1969 to the present time):** During this period, extensive exploration activities were undertaken in the basin, including advanced seismic acquisition, processing and interpretation. During this period, the concession
licenses were rearranged. Companies such as Shell, Occidental and Elf acquired exploration blocks in the Ghadamis Basin. Few new hydrocarbons were found; most of the activities were concentrated on the oil fields already developed.

In 1999, Agip Eni, through its affiliate Agip North Africa B.V., reached final agreement with the National Oil Corporation (NOC), the Libyan State Oil Corporation, on the implementation of a project for the development of gas, condensate and oil reserves in block NC169 (Figure 5.01). The Wafa field in the Ghadamis Basin (located 550 km southwest of Tripoli along the Libyan-Algerian border) will be connected to the Zwarah plant along the coast by means of gas and liquid pipelines. At the beginning of 2000, Eni, through Agip North Africa, signed a contract to supply four billion cubic m/y of Libyan natural gas to the Italian market. According to this contract, which covers a 24-year period beginning July 2002, the gas will be transported through a sea line. This is currently in the planning stages and will be built and managed by a joint company in which Agip North Africa and NOC will hold a 75% and 25% share, respectively.

The 15 wells of Gulf Company, which were drilled in the early 1960s, established the oil fields of El Hammra and Emsgayet in the southern part of the Ghadamis Basin (Figure 5.01), with an initial flow rate of around 1200 b/d. Some of these oil fields were connected to a small capacity pipeline constructed in 1968. A 32-inch pipeline, completed in 1984 and with a capacity of 120,000 b/d, carries the hydrocarbons produced in El Hammra oil fields 381 km north to the Zawiyah refinery on the Mediterranean coast. Pipeline capacity was increased, and all fields of El Hammra and Emsgayet were connected to the pipeline in 1985. To date, most of the small scattered fields in the Ghadamis Basin have yet to be connected to a pipeline.

Exploration for hydrocarbons in the Ghadamis Basin has been mostly confined to positive elements close to the peripheral areas of the basin. Large parts of the basin, especially the west-central portions, are as yet untested. Exploration efforts have revealed quite a few accumulations of oil so far (Figures 5.01 and 5.05). However, none of these is comparable to the giant accumulations in the Cretaceous-Paleocene clastic-carbonate reservoirs of the Libyan Sirt Basin or in the highly prolific Cambrian clastic reservoirs of the Hassi Maessoud oil field of Algeria. Figure 5.06 shows the ultimate oil recovery of hydrocarbon occurrences discovered in the Ghadamis and Murzuq Basins.
The Murzuq Basin has also had an exploration history since the late 1950s. Gulf Oil, Amoseas, British Petroleum and Wintershall drilled exploration wells during the 1960s but with very limited success. In the case of the Murzuq Basin, the exploration history can be grouped into two main phases: the period between 1957 and 1968 and the period between 1977 and the present time, with a gap between 1968 and 1977. Production operations are centred on discoveries made in two locations: the Atchan Saddle area and the Awbari and Murzuq production areas (in the north-central part of the basin).

1. **Phase 1 (exploration between 1957 and 1968):** During this period, most of the exploration activities were concentrated along the northern margin of the basin. During this period, a total of five wells were drilled (Massa et al., 1995). Four of these wells were dry and the fifth showed oil in the north of concession NC101. As exploration moved to the Sirt Basin of north-central Libya, the Murzuq Basin was virtually forgotten. Not much seismic was shot in the area during this period because of the thick sand cover and the remoteness of the area relative to other basins such as the Sirt and Ghadamis Basins.

2. **Phase 2 (exploration between 1977 and the present time):** The Murzuq Basin was under-explored due to its relative remoteness in comparison with the other basins, but since 1980 the area has been the object of extensive exploration activities by many companies. According to Thomas (1995), PetroBras was awarded concession NC58 (NC174 in Figure 5.01). This was a relatively large permit, encompassing most of the west-central Murzuq Basin. In one well, A1-NC58, a minor subcommercial oil discovery was made in Cambro-Ordovician sandstone reservoirs. Permit NC58 was relinquished in the early 1980s. Rompetrol, the state oil company of Romania (NC115), and BOCO, the state oil company of Bulgaria (NC101), were subsequently awarded exploration permits on the northwestern and north-central flanks of the basin, respectively. Oil discoveries were made on both permits in the Ordovician Memouniat Formation. In late 1994, a group led by Repsol as operator was formally awarded the ex-Rompetrol Murzuq concession. Plans are being made for field development and oil pipeline construction to the El Hammra terminus in the southeast of the Ghadamis Basin, where a pipeline system to the coast is already in place.
BOCO, holder of permit NC101, acquired a seismic survey and has drilled 18 exploration and appraisal wells since 1981. Sixteen prospects have been drilled, resulting in the discovery of five oil accumulations in Cambro-Ordovician reservoirs and two minor oil accumulations in Devonian reservoirs. Lasmo was awarded the open acreage (NC174) between the Rompetrol and BOCO permits in 1990. In 1985, Rompetrol shot good quality seismic (8100 km of 2D seismic) and approximately 2700 line km of seismic was shot in 1990. In 1992-93, four wildcats were drilled. This programme fulfils the work commitments on the licence. Most recently, Lasmo Oil Company discovered an oil field in the area of NC174 (Elephant prospect) in the Murzuq Basin (Figures 5.01 and 5.05). The F-NC174 discovery well (Figure 5.11) cut about 100 m of oil pay in the excellent quality reservoir sands of the Cambro-Ordovician Memouniat Formation, with an average porosity of 16%. DSTs from below 1500 m aggregated 7500 b/d of high-quality 38° gravity crude (Petzet, 1999). The reservoir comprises high net/gross ratio quartz and subarkosic arenites of Late Ordovician age, belonging to the Memouniat Formation. The primary porosity has been partially occluded by extensive quartz overgrowths, but enhanced by partial dissolution of potash feldspar. This dissolution has particularly enhanced the permeability of many layers, with the result that the reservoir properties over most of the field are excellent (Compton et al., 1999). Agip-Eni has reported a series of oil finds in its various concessions in the Ghadamis and Murzuq Basins, such as the Wafa field in the west of the Ghadamis Basin (NC169). Repsol is currently leading a European consortium for exploration and production in the area. Mid-1999, the newly discovered El Sharara field, located 60 km north of the Elephant field, registered an output of 44° API with less than 0.6% sulphur content. Original expectations were that the Murzuq Basin production would reach about 200,000 bbl/d by the end of 1998, but some problems, including difficulties with the pipeline to the port of Zawiyah west of Tripoli, delayed achievement of this target. Currently, the Zawiyah refinery is processing oil from El Sharara field. Some other discoveries have good production capacities, such as the B, A and H fields in concession NC115. According to Petzet (1999), a 30-inch 250,000 b/d capacity pipeline to the El Hammra terminus is to be constructed in 1999 and will be linked to the pipeline from El Hammra oil field to the Zawiyah refinery.

Thus, several large oil fields have so far been discovered in the Murzuq Basin in the region of the Atchan Saddle. To the east, some smaller accumulations have been found. The area in which active exploration has been carried out is the northern part of
the basin. A number of wells have penetrated closures without hydrocarbons. The presence of fresh water in the potential reservoir formations may indicate reservoir flushing. Nevertheless the remaining unexplored area is likely to contain prospective structures. The type of prospect to be expected is described in the rest of this chapter.

Figure 5.01 Index map of the study area showing concessions, names and locations of main hydrocarbon-producing fields in the Ghadamis and Murzuq Basins.
5.3 Distribution of known hydrocarbon accumulations

5.3.1 Ghadamis Basin systems

The Paleozoic source rock and reservoir sequence combine together to create two hydrocarbon systems in the Ghadamis Basin, one in the southern part of the basin close to Al Qarqaf Arch and the other in the northern flank of the basin (Figure 5.04). Several formations are considered as source rocks for hydrocarbons in the Ghadamis Basin, with different levels of maturation, the Silurian and Devonian shales constitute the main source rock intervals of the Ghadamis Basin. Silurian rocks also form the main source for the hydrocarbon accumulations to be found in eastern Algeria and southern Tunisia. Major reservoirs in the Ghadamis Basin range in age from Early Paleozoic to Early Mesozoic (Figure 5.02). The reservoirs comprise the following systems:

A. Cambrian system

The sandstones that are present at this level show a high degree of lateral continuity (Massa et al., 1994). A sizeable decrease in thickness occurs in areas of positive axes such as Al Qarqaf and Tihembokah Arches. To date, no hydrocarbon productive zone associated with the Cambrian has been noted in the area.

B. Ordovician system

This system was deposited in a marine environment (see Chapter 4, Section 4.3.1). The hydrocarbon reservoirs of the system are the upper parts of the sandstone units of the Memouniat Formation. Relative to the Silurian Acacus and Tadrart producing horizons, the Ordovician Memouniat Formation is a minor system in the Ghadamis Basin, with few producing wells (Figure 5.04). Some wells in the central and eastern parts of the basin (Figure 5.04) are producing oil from the sandstones of this formation, trapped in structural traps (Figure 5.07). The porosity of the producing horizons ranges from 5% to 10% (Massa et al., 1994). Only the upper part of the formation has been found to bear oil in these wells. The net pay in well A1-NC40 was only about 10 m. The Tanezzuft shales form the seal.
Figure 5.02 Stratigraphic and hydrocarbon accumulations correlation chart of the Ghadamis and Murzuq Basins, illustrating the different reservoirs and source rocks. Source of data: Karasek 1981; Missaliati, 1986; Massa et al 1994; Sola et al, 1996; Echikh 1998; and hydrocarbon field reports.
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C. Silurian system

The Lower Silurian Tanezzuft shale is regarded as the most consistently mature organic-rich source rock in the Ghadamis and Murzuq Basins (Massa et al., 1994). The Silurian system is the main hydrocarbon-producing system in the northwestern and central parts of the Ghadamis Basin. This system offers both the best source rock (the Tanezzuft Formation) and reservoir (the sandy layers of the Acacus Formation). The formations of this system are:

C.1 Tanezzuft Formation

This formation is the product of a worldwide transgressive event (Chapter 4, Section 4.3.2.1). Figure 5.12 shows that the thickness of the Lower Silurian Tanezzuft Formation decreases on the flanks of the Ghadamis and Murzuq Basins. This formation is less important as reservoir rock in the Ghadamis Basin. Nonetheless, good reservoirs are found in the sandy layers of the top of the Tanezzuft Formation and are producing in the central and northwestern parts of the Ghadamis Basin, where about 20 m of sandstone proved to have an average porosity of 20%. Figure 5.13 shows the log profiles of the basal parts of the Tanezzuft Formation from some wells in the centre and flanks of the Ghadamis and Murzuq Basins. The figure shows the “radioactive marker” hot shale of the zone. The lowermost part of the Early Silurian Tanezzuft Formation is characterized by strong gamma ray log curve deflection. The lower part of the Lower Silurian Tanezzuft Formation in well logs is characterized by high gamma radiation associated with high uranium content. The homogeneous character of this stratigraphical succession, which was accumulated over relatively long time, indicates that the Lower Silurian sediments were deposited on an extensive, flat, stable platform at slow rate in very calm water (see Chapter 4, section 4.3.2.1). The very slow rate of sedimentation at the beginning of the Silurian at reducing sedimentary conditions facilitated the concentration of the uranium at the base of the sequence. Hassan and Massa (1975), showed that an abnormal enrichment in uranium was the main source of the radioactivity of these radioactive zones which were deposited in a reducing environment of the euxinic basins. Uranium concentration in this typical profile exceeds 100ppm, associated with vanadium concentration of more than 2000ppm and ZN, NI and Ba concentration in the range of 100 to 1000ppm.
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C.2 Acacus Formation

The Acacus Formation is a major reservoir in the northwestern and central parts of the Ghadamis Basin (Figure 5.04). The Acacus sandstones represent the marine regressive stage that followed the marine Silurian transgression (Chapter 4, Section 4.3.2.2). The sandstone intervals within the formation are good reservoirs, with a porosity between 15% and 20% in the western part of the basin (area NC100 in Figure 5.01) and increasing towards the central part of the basin (area NC7 in Figure 5.01).

The thickness of the formation in the area of the main Ghadamis depocentre is in the order of 700 m, but closer to the basin margins the unit can disappear altogether. The depth of the top of the Acacus Formation varies between 1500 and 2300 m within the basin. Oil from the Acacus Formation is obtained in the western parts of the Ghadamis Basin. In the southern part, the formation had already been eroded during the Caledonian Orogeny. The net sandstone thickness of the formation ranges from about 10 m in the central parts of the basin to about 60 m in the northwest. Figure 5.03 shows the log profile of the Acacus Formation in the Ghadamis Basin. The gamma ray logs shows several cycles of coarsening upwards (in the order of 10 m each). As we have seen in Chapter 4 (Section 4.3.2.2), the Acacus Formation is part of a complex deltaic system. Figure 5.03 shows that the Acacus Formation occurs as sand layers of varying thickness, separated by shale intervals. According to oil companies working in the basin, the Acacus reservoir bodies can extend over areas of 10 to 20 sq km. The shale levels within the Acacus Formation, especially in its upper part, constitute the seal for underlying reservoirs.

According to trap type, Acacus producing areas in the Ghadamis Basin are grouped into two classes (Figure 5.07):

1. Northwestern part of the basin: producing from stratigraphical traps or a combination of stratigraphical and structural traps.

2. Central part of the basin: producing from structural (anticlinal traps).
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D. Devonian system

This system can be considered as the main reservoir in southern parts of the Ghadamis Basin. However, the Devonian shale has less value as a source rock for hydrocarbon in the Ghadamis Basin than the Silurian shales. Several oil and gas discoveries have been made in Devonian reservoir sandstones (Figure 5.04). This system consists of the following formations:

D.1 Tadrart Formation

The Tadrart Formation consists of marginal to deltaic sandstone in the southern parts of the Ghadamis Basin (Chapter 4, Section 4.3.3.1). This formation is considered to be one of the best Devonian reservoir units in the southern part of the Ghadamis Basin (Figure 5.04). The oil fields of El Hammadra in the southern part of the Ghadamis Basin are producing from this formation. The porosity of the formation in the centre of the basin ranges from 13% to 18% and is located at depths of 1100 to 1990 m (from south to north; Figure 5.10). The porosity of the sandstones of the Tadrart Formation differs not only from one horizon to another, but also laterally within a single horizon. The shaley layers of the overlying Early Devonian Ouain Kasa and Aouinet Ouenine Formations are considered as the best seals for the Tadrart reservoirs. Formation water salinity measurements for the Tadrart Formation in the southern parts of the Ghadamis Basin show that salinities are very low (less than 2000 PPM) throughout the southern half of the Ghadamis Basin. There is, therefore, an abnormal relationship between salinity and oil occurrence in the area: high salinity and no oil in the northwest and low salinity with oil in the southeast. This indicates that the oil in the southeast of the basin was emplaced after the erosional stripping and flushing of the Tadrart Formation, and after the deposition of the Aouinet Ouenine Cap. No clear trend in porosity variation has been found but the porosity of this formation ranges from 12% in some wells of concession NC8, located in the southern part of the basin, to 20% in some wells in concession NC2 (Figure 5.01; Shah et al., 1993). Figure 5.03 shows the log profile of the Tadrart Formation in the Ghadamis Basin. As in the case of the Acacus Formation, the gamma ray logs of Tadrart Formation shows several cycles of coarsening upwards. As in the case of the Acacus Formation, the Tadrart Formation occurs as sand layers of varying thickness, separated by shale sections. The net sandstone unit thickness of the formation

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increases towards the south of the Ghadamis Basin, where it reaches ±40 m in some wells of concession NC8.

D.2 Aouinet Ouenine Formation

The Aouinet Ouenine Formation is a prograding delta and shoreface deposit (Chapter 4, Section 4.3.3.3). This formation contains minor producing reservoirs in the central part of the Ghadamis Basin (Figure 5.3). Porosity ranges from 6% to 25%. Traps are mainly stratigraphical and produce oil and gas. The oil gravity ranges between 40° in the centre of the basin and 47° in the western parts of the basin. The sandstone net thickness is in the range of 70 m.

D.3 Tahara Formation

The formation represents a transitional regressive event between the Famennian marine facies below and the overlying Early Carboniferous transgressive marine facies (Chapter 4, Section 4.3.3.4). The Tahara Formation is the upper reservoir of the Devonian sequence (Figure 5.04). The thickness of the formation ranges between 50 and 70 m. The Tahara Formation is missing in the northern and southern areas of the Ghadamis Basin. Porosity ranges between 15% and 19%. The depth of the Tahara varies between 880 and 1370 m within the basin. The shaley intervals within the Aouinet Ouenine Formation provide the seal for the Tahara sandstone.
Figure 5.03 Log profiles of the the Memouniat Formation (well NC174), the Tadrart Formation (well NC40) the Acacus Formation (Well NC118). All depths are in feet.
E. Carboniferous system

The Carboniferous rocks are of minor importance for hydrocarbon in the Ghadamis Basin. The main formation of this system is the Mrar Formation.

E.1 Mrar Formation

This formation represents the early transgressive phase of the Carboniferous over the terminal regressive Devonian unit. The formation contains a high percentage of sandstone. This formation is producing from some wells in the central parts of the Ghadamis Basin (Figure 5.04). There are no porosity data available for this formation. Oil and gas are trapped in structural (anticline) traps trending NW-SE. The oil gravity ranges between 40° and 43° and the net sandstone thickness ranges between 10 and 30 m.

F. Triassic system

The Early Mesozoic (Triassic) system is represented by the Ras Hamia Formation, which is producing oil from wells in the central part of the Ghadamis Basin (Figure 5.04). There are no porosity data available for this formation. The depth of the top of the formation varies from 910 to 1520 m. This target is not present in the southern part of the basin. The shale levels within the Ras Hamia Formation could represent a good seal for underlying reservoirs. The net sandstone thickness of the Ras Hamia reservoir is around 30 m.

5.3.2 Murzuq Basin systems

The factors that contribute to the hydrocarbon systems of the Murzuq Basin are source, reservoir and sealing mechanisms that are basically associated with the Paleozoic interval from Late Ordovician to Early Carboniferous (to Cretaceous).

The Paleozoic succession of the Murzuq Basin provides both source rocks and reservoir rocks. The positions of both the main source rock units (of Silurian and Devonian age) and the main reservoir rock units (of Silurian and Early Carboniferous age) are shown in the generalized map of the Ghadamis and Murzuq Basins (Figure 5.02).
In the Murzuq Basin, hydrocarbon accumulations are known to be present mainly in members of the Memouniat Formation, just below the Tanezzuft shales. Hydrocarbons are also present in Devonian sandstones of the Aouinet Ouenine and Tahara Formations (Figure 5.04). The hydrocarbon reservoirs of the Murzuq Basin can be described as follows:

A. Cambro-Ordovician system

This system is the major known commercial hydrocarbon system in the Murzuq Basin and is represented by the Memouniat Formation (Figure 5.04), which was deposited in a shallow marine environment and is producing in the central and northwestern parts of the basin. Oil accumulated in structural anticlinal traps that formed most probably as a result of regional wrench faulting (see Chapter 3). Figure 5.03 shows the log profile of the Memouniat Formation in the Ghadamis Basin. The gamma ray logs is smooth in shape and indicate that the sandstones of the formation are homogeneous. Porosity ranges from 8% to 17%, and can be as high as 25% in concession NC115. The net sandstone thickness ranges between 20 m in the central part and 76 m in the northwestern part of the basin. Very low porosities characterize the Memouniat Formation in the central parts of the Murzuq Basin (Meister et al., 1981). This may lead to less prospectivity in the central parts of the basin. Tanezzuft shales act as a top seal to the Memouniat reservoir sandstone.

B. Silurian system

In the Murzuq Basin, this system is considered as a major source rock (see Section 5.4.3 of this chapter). To date, no reservoirs have been discovered in the basin. This could be interpreted as a result of non-deposition or erosion of the system over large parts of the basin.

C. Devonian system

The uplift and erosion that characterize the Devonian sequence of the Murzuq Basin area and which were associated with the later episodes of the Caledonian Orogeny caused coarser clastic deposition of a continental type rather than a predominance of marine (shale) sequences (Massa et al., 1994). Only the thinly laminated shales in the middle and upper parts of the Ouân Kasa Formation and parts of the Aouinet Ouenine
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Formation appear to present favourable conditions for source rock occurrence in the basin. The Early-Middle Devonian formations have been assessed as having TOC values in the range of 0.8% to 1.2% (Al Muzughi and Al Magtouf, 1981). Source rock material in the Devonian appears to be of only secondary importance.

The Aouinet Ouenine Formation is a minor hydrocarbon system in some areas in the northwestern part of the basin, with an average porosity of about 10%, net sandstone thickness of 18 m and oil gravity of about 40°. In the central area of the basin and in the northwestern part of the Atchan Saddle, the Tahara Formation is a producing reservoir with a gross unit thickness of about 70 m, an average porosity of 17% and oil with a gravity of about 42°. Traps are mainly structural (Figure 5.07).

D. Carboniferous system

As in the Ghadamis Basin, the Carboniferous succession in the Murzuq Basin area is characterized by a marine deltaic sequence in the Early Carboniferous, marine carbonates in the Middle Carboniferous and evaporitic and continental sequences in the Late Carboniferous and Early Permian. Most significant in terms of source rock potential are the marine deltaic sequences of the Early Carboniferous. This succession of carbonate with evaporite on top may lead to a trapping situation and is an interesting subject for further study.

5.4 Comparison of the hydrocarbon systems in the Ghadamis and Murzuq Basins

5.4.1 Introduction

Stratigraphy and hydrocarbon occurrence relationships within the Ghadamis and Murzuq Basins are summarized in Figure 5.02. Comparison of the hydrocarbon systems in the two basins indicates that there are some points of similarity and also some differences.
5.4.2 Distributions of reservoirs in the Ghadamis and Murzuq Basins

5.4.2.1 Spatial and stratigraphical distribution

Figure 5.04 presents the regional distribution of the reservoirs in the Ghadamis and Murzuq Basins. In the north part of the Libyan part of the Ghadamis Basin, the Upper Silurian Acacus Formation is the most productive horizon, and in the southeast of the basin the Lower Devonian Tadrart Formation. In the central part of the basin, there is a combination of different reservoirs, ranging from the Acacus Formation to the Lower Carboniferous Mrar Formation. The reason for this, according to Alvares (1956), is apparently to be sought in the source-cap relationship (Figure 5.18). The middle Acacus shale units have apparently acted as a cap, confining oil generated in the Tanezzuft shale to Lower Acacus sands, and preventing it from reaching the reservoirs of the Upper Acacus/Tadrart. As the Middle Acacus shale dies out to the southeast, the lack of barriers permits Tanezzuft oil to reach the Tadrart reservoirs (Figure 5.18).

In the Murzuq Basin, the Cambro-Ordovician Memouniat Formation is the most important producing horizon. Two clusters of reservoirs are producing in the basin, the first one located in the central part of the basin (Figures 5.01 and 5.03) and the other one located in the area of the Atchan Saddle.

5.4.2.2 Depth distribution

Figure 5.05 shows N-S cross sections with the reservoirs in the area. Most of the discovered hydrocarbon fields in the Ghadamis and Murzuq Basins are almost similar in depth, ranging from 600 to 2200 m in both basins. The correlation with the depth to top of basement map indicates that the discovered hydrocarbon fields are located in areas where the depth of the basement ranges from 1220 to 2740 m subsea in the Ghadamis Basin and from 610 to 2440 m subsea in the Murzuq Basin.
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Figure 5.04 Map showing regional distribution of reservoirs in the Ghadamis and Murzuq Basins.
Figure 5.05 Cross sections showing the depths of reservoirs in the Ghadamis and Murzuq Basins.
5.4.2.3 Field size distribution

Figure 5.06 represents the distribution of trap types and the initial recoverable reserves. The fields of the two basins have been subdivided into four groups, with less than 50, 50 to 100, 100 to 150, and more than $150 \times 10^6$ barrels of initial recoverable reserves. In the north and central Ghadamis Basin, the discovered hydrocarbon fields range in size between 50 and 100 MMBO. In the northern part of the Ghadamis Basin, the traps are mainly a combination of structural and stratigraphical traps. The size of the fields increases to the south, where fields reach more than 150 MMBO close to Al Qarqaf Arch. Most of the traps in the south are combination traps. Mixed types of traps also characterize the central part of the Ghadamis Basin. All the traps of the Murzuq Basin are structural, with two groups of reservoirs. The first is located in the area of the Atchan Saddle and is characterized by fields that have recoverable reserves of between 50 and more than 150 MMBO. The other group is located in the northeastern part of the Murzuq Basin and is characterized by fields of smaller size, generally less than 100 MMBO.

5.4.2.4 Play type distribution (classification of traps)

As we have seen in Chapter 2, interaction between near surface arches and adjacent sedimentary basins can produce several types of traps (Chapter 2, Section 2.3 and Figures 2.05 and 2.06). Analysis of well and seismic data over the Ghadamis and Murzuq Basins indicates the existence of a wide variety of structural and stratigraphical trap types of different age. Three main classes of traps have been identified in the area (Figure 5.07 and 5.07).

It is interesting to compare the actual traps encountered in the Ghadamis and Murzuq Basins (Figure 5.07) with the general model of trap types associated with near surface arches (Chapter 2, Section 2.6 and Figure 2.05). In the Ghadamis Basin, we indeed find structural traps in the centre of the basin and combination to stratigraphical traps towards the flanks. Most of the productive structures in the Ghadamis Basin have a SW-NE orientation, especially in the southern parts of the basin where the influence of Al Qarqaf Arch is strong (see Chapter 3, Sections 3.4.3 and 3.4.4). In the Ghadamis Basin, all Acacus Formation oil has been found in structural traps. Trap development in the Ghadamis Basin has been assumed to be related to tectonism in the latter part of the
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Silurian (Caledonian) and in the Carboniferous and Permian (Hercynian). In the case of the Murzuq Basin, the story is different because all of the traps identified are structural and most of the faults trend NW-SE (almost perpendicular to the direction of Al Qarqaf Arch). As we have seen in Chapter 3, this is a result of major wrench fault tectonics on the western flank of the basin (Figure 3.11). The influence of the wrench faulting is stronger than the influence of Al Qarqaf Arch in the Murzuq Basin. However, on the basis of hydrocarbon seeps on the south side of Al Qarqaf Arch one may also expect arch-related traps (see Chapter 6).
Figure 5.06 Trap styles and ultimate oil recovery of hydrocarbon occurrences in the Ghadamis and Murzuq Basins (number of fields in this figure is less than in Figure 5.07 due to lack of information on the ultimate oil recovery of some oil fields; see Figure 7.01 for areas of hydrocarbon exploration interest).
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**Figure 5.07** Map showing regional distribution of traps of oil fields in the Ghadamis and Murzuq Basins (see Figure 5.08 for trap types and their abbreviations).

<table>
<thead>
<tr>
<th>A. Structural Traps:</th>
<th>B. Stratigraphic Traps:</th>
<th>C. Combination Traps:</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRB:</td>
<td>STA:</td>
<td>CT:</td>
</tr>
<tr>
<td>Faulted anticlines</td>
<td>Stratigraphic trap</td>
<td>Pinch outs, unconformity, cut-offs, regional compression faults and arching of porous horizon provided both simple and combination traps.</td>
</tr>
<tr>
<td>SRC:</td>
<td>STB:</td>
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<tr>
<td>Normal faulted</td>
<td>Stratigraphic sandstone truncation by the Paleozoic unconformity.</td>
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<td>structures.</td>
<td>STC:</td>
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<td></td>
<td>Pinch out</td>
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**Figure 5.08** Types of traps in the Ghadamis and Murzuq Basins. See Figures 2.05 and 2.06 for correlations with the model extracted for traps associated with near surface arch type.

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A. Structural traps

Most of the large hydrocarbon accumulations discovered in the Ghadamis and Murzuq Basins occur in structural traps. In the Murzuq Basin, most structural traps of the Murzuq Basin were probably formed before or coincident with the first phase of oil generation in the Late Paleozoic. Figure 5.11 shows a TWT structural map (Middle Devonian Unconformity) showing N-S en-échelon fault blocks. The fault system is part of the 10° wrench fault (Figure 3.11). The seismic windows A and B of Figure 3.11 show flower structures associated with the wrench fault (see Chapter 3. Sections 3.4.4.3 and 3.6, and Figure 3.11). The figure shows that the oil in the area of the Elephant oil field is trapped in a reverse faulted anticline over basement uplift.

The structural history of the area of both basins has produced a wide variety of structural traps of different ages.

A.1 Simple low relief anticline (SRA)

This trap type is present mainly in central and northern parts of the Ghadamis Basin (Figures 5.06 and 5.07). These anticlines are generally broad low-relief structures and were formed during the Silurian and Devonian (Echikh, 1998).

A.2 Faulted anticline (SRB)

This type of faulting corresponds to the model of traps associated with the near surface arch (faulted anticline type in Figure 2.05). In this form of trap, entrapment was achieved by the faulting of anticlines (Figures 5.09 and 5.10). This type of structure is found in the southern part of the Ghadamis Basin, close to Al Qarqaf Arch. In this area, the beds have a regional NNW dip and are arranged in large tilted fault blocks, bounded to the south by major ENE trending faults, which are downthrown to the south. Oil and gas has accumulated in anticlines on the footwall side of the faults, the accumulations being locally sealed by these faults. These fields are made up of several pools, some of which are divided into "sub-pools" separated by saddles or faults. In many cases, the faulted anticlines appear on the surface, as we have seen in Chapter 3 (Section 3.4.4.2), as circular and semi-circular features, which are interpreted from remote sensing images and are located in the southern part of the Ghadamis Basin (Figure 3.09). It is likely that these semi-circular features are a result of the subsurface tectonics and are thus of
practical interest in hydrocarbon prospecting. Two types of circular features appear from the interpretation of remote sensing images. They are located in the southern part of the basin and range from 5 to 35 km in diameter. These features coincide with the location of El Hammra and Emsgayet oil fields and are located on the aeromagnetic map in an area of high magnetic anomalies.

A.3 Normal faulted structures (SRC)

This type of trap is mainly related to the faulting of layers due to basement uplifting. In the Ghadamis Basin this type was formed during the Hercynian events. To date, available data indicate the presence of this type in the central and northern parts of the Ghadamis Basin (Figure 5.07). This type is mostly expected in flanks of Al Qarqaf Arch (see Chapter 5, Section 3.4.4.2 and Figure 3.09).

Figure 5.09 Schematic sections illustrating the mechanism of faulted anticlines and normal faulted structures associated with arch structures and basement blocks.
Figure 5.10 A) General subsurface structural map on the top of the Lower Devonian Tadrart sandstone, El Hamra field area, Ghadamis Basin (for location see Figure 5.01). B) geological cross section A-B in Ordovician to Devonian rocks (Hammuda, 1981)
Figure 5.11 A) TWT structural map (Middle Devonian unconformity), C.L.20 msec, showing N-S en-échelon fault blocks. The fault system is part of the 10° wrench zone. B) Seismic windows, the seismic sections showing flower structure in concession NC58 (window A) and reverse faulted anticline formed over a basement uplift (window B). Well F1-NC174 is a well in the giant Elephant field, while the other well is a dry hole in a smaller but well-defined closure to the south.
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B. Stratigraphical traps

The traps formed by lateral change in the reservoir. Two types of stratigraphical traps have been observed (Figures 5.06 and 5.07), namely:

B.1 Stratigraphical truncation on unconformity (STB)

This type consists of sandstone reservoirs that are truncated by the Paleozoic unconformity. It is present in the central and northwestern parts of the Ghadamis Basin. According to Echikh (1998), in this type, hydrocarbons are trapped against the subcrop of the Silurian Acacus reservoirs against Triassic shales.

B.2 Permeability pinchout traps (STC)

In the Ghadamis Basin, this type of trap is present in the western part of the basin, close to the Tihembokah Arch (Figure 5.07). The sandstone bodies of the Aouiniet Ouenine Formation are considered as the main target in this area, where they pinch out into shale. The extensive shale layers within the formation provide the seals. No information has been released on the reservoir characteristics.

C. Combination traps (structural-stratigraphical traps)(CT)

This is a combination of any two or more of the above. This type of trapping includes pinchouts, unconformity, fault-bounded closures, regional compressional faults and arching. A number of oil fields belong to this type in the Ghadamis Basin, such as the example shown in Figures 5.07 and 5.08.

5.4.3 Seals

In the Ghadamis and Murzuq Basins, stratigraphical units possessing seal rock properties are like the reservoir rock and source rocks to be found at various levels within the Paleozoic succession. The Early to Late Silurian (Ludlovian) Tanezzuft shales are the regional seal deposited across the Murzuq Basin (Figure 5.02). Figure 5.18 shows the model of the relationship between source rock, reservoir rock and sealing in the central and southern parts of the Ghadamis Basin. Some layers of the Acacus Formation serve as a good seal for the hydrocarbons of the formation in the
central and northern parts of the Ghadamis Basin (Figure 5.18). The Tadrart reservoirs in the Ghadamis Basin have as their top seal the shales that occur at the base of the overlying Early Devonian Ouankasa Formation (Figure 5.18). The extensive shales of the Early Carboniferous Mrar Formation provide seals for the Tahara reservoir. The shale levels within the Ras Hamia Formation could represent a good seal for the underlying reservoirs. In general, the Paleozoic units of the Murzuq Basin contain more coarse clastic reservoir intervals than seals and source rocks. The Tanezzuft shales act as a regional top seal to the Memouniat reservoirs in the Murzuq Basin. The sub-regional seals of the Murzuq Basin have a smaller range. Some layers of the Middle to Late Devonian Aouinet Ouenine Formation and Early Carboniferous Mrar Formation form the seals in some parts of the basin. Therefore, the extent of the seal rocks over the Murzuq Basin is a limiting factor in its petroleum play.

5.5 Hydrocarbons

5.5.1 Source rocks characterization and correlation

Oil source rocks in the Ghadamis and Murzuq Basins have been identified in the Lower Silurian Tanezzuft shales. This formation is Early to Late Silurian (Ludlovian), unconformably overlies the Cambro-Ordovician Memouniat Formation and is generally transgressive. The formation is the product of a worldwide transgressive event. The sequence boundary is probably the base of the Tanezzuft shale that is part of a transgressive system track. The isopach map of the Tanezzuft Formation (Figure 4.07) shows that the thickness of the formation is increasing towards the depocentres of the basins. The Tanezzuft shales thin over the Atchan and Tihembokah Arches and are missing over the greater part of Al Qarqaf Arch. Its thickness ranges from 60 to 120 m in the Murzuq Basin and reaches about 550 m in the central part of the Ghadamis Basin (see Chapter 4, Section 4.3.2.1). The basal Tanezzuft shows a gradational section of rhythmic alternations of euxinic, good oil-source shales and sandstones. The recognizable “hot shales” gamma ray readings record the basinwide occurrence of the shale unit (Figures 5.10 and 5.11). Generally, a high degree of lateral and vertical variation in organic content is found in the formation. The formation contains a rich mixture of organic matter that is mainly marine and well preserved (Figure 5.14), of type II kerogen, with up to 10.71% TOC (Total Organic Carbon) and petroleum potential maximizing at 33.56 kg of HC/t of rock. The geochemical analysis (TOC,
Rock Eval Pyrolysis and Organic Petrography) performed on about 800 cuttings taken from 11 wells distributed in the Ghadamis Basin (PRC, 1998) indicates that besides the Tanezzuft Formation there are other types of source levels encountered around the Ghadamis Basin. They correspond to the hot shales of the Middle to Late Devonian Aouinet Ouenine Formation. As for the Aouinet Ouenine Formation, the main source potential lies in its argillaceous facies. Values for TOC in the Aouinet Ouenine Formation range from 1.2% to 10%, with an average of around 3%. Some shale levels of the Acacus Formation, especially in the centre of the Ghadamis Basin, are also considered to have good source rock characteristics and also act as effective seals for hydrocarbon accumulations in the Acacus sandstone reservoir units. The analysis shows fair to high TOC and petroleum potential and the formation can be regarded as good source rock.

In the Murzuq Basin, several potential Paleozoic source rocks exist. Al Muzughi and Al Magtouf (1981), utilizing subsurface data from well A1-NC58 of the Murzuq Basin (for location of well A1-NC58 see Figure 5.05), have described the geochemical analysis of the Paleozoic section of the Murzuq Basin. The source rocks in the basin are found at different levels. These are Silurian, Devonian and Carboniferous in age. In fact, as in the Ghadamis Basin, the most significant source rock is the widespread oil-prone Lower Silurian Tanezzuft Formation. However, Figure 5.12 shows that the Tanezzuft is almost absent in the eastern part of the Murzuq Basin and across the Ben Ghememah uplift. In the northern part of the Murzuq Basin, the TOC of the Tanezzuft shales is in the range of 4.9% to 8.4% (Meister et al., 1981; Figure 5.02) and fairways would appear to be present in the Murzuq Basin, where good to excellent source rocks are present. According to Meister et al. (1981), the Mrar Formation in some wells of the northern part of the Murzuq Basin shows a TOC range of 2.16% to 2.3%.
Figure 5.12 Isopach map (A) and panel diagram (B) of the Tanezzuft Formation in the Ghadamis and Murzuq Basins.
Figure 5.13 Log profiles of the Lower parts of the Tanezzuft Formation from the Ghadamis Basins (A and B) and Murzuq Basin (C and D). (all depths are in feet) For locations of wells see Figure 5.10; profile D from Meister et al., 1991.
Figure 5.14 HI vs. OI diagram of cores for one of the NC100 wells in the Ghadamis Basin (PRC, 1998).

There is a lack of information on the geothermal gradient for the Ghadamis and Murzuq Basins. Based on new well data, Burdon (1980) found geothermal gradients ranging from 22.8° to 39.1° C/km in the Murzuq Basin. No literature exists on the effects of volcanic areas such as Jabal Al Hassawanah and Jabal As Swada on the maturation of sedimentary organic matter in the Ghadamis and Murzuq Basins. However, according to Marco et al. (1985), for a basin like the Murzuq, a lack of evidence of intrabasinal igneous activity suggests that past subsurface temperatures were probably much the same as those of today.
5.5.2 Oil characterization

Figure 5.15 shows that all the hydrocarbons in the Ghadamis and Murzuq Basins are low in gravity, ranging between 34° and 43° API (American Petroleum Institute). Most of the discovered oil in the Murzuq Basin ranges in gravity between 34° and 42° API. In the area of the Atchan Saddle, the gravity is higher and ranges between 45° and 47° API (Massa et al., 1994). Meister et al. (1981) characterized a crude oil in the basin of 40° API, with 0.05% sulphur content and a gasoline range (C4-C7) fraction characterized by strong normal paraffin and cyclohexanes and a relatively low methylcyclopentane content.

![Map showing variations in gravity of hydrocarbons in the Ghadamis and Murzuq Basins.](image_url)
5.5.3 Hydrocarbon generation, migration and trapping

The generation and expulsion of hydrocarbons of varying thermal maturation can be explained with reference to a source rock's thermal history (Figure 5.16). Burial history curves of three wells in the Murzuq Basin show important geological horizons and key Time Temperature Index (TTI) lines. These curves were used to estimate theoretical maturity and to determine the likely time of hydrocarbon generation. The Time Temperature Index has been computed using Lopatin’s method (Waples, 1980). This method is applied to three wells in the Murzuq Basin. The calculations and graphics indicate that the base of the Silurian sediments reached a Time Temperature Index of 15 at respectively 50, 107 and 112 million years before present for wells A, B and C (Figure 5.16). This means that Silurian rocks would have attained sufficient thermal maturity to start generating oil only since Cretaceous to Early Tertiary times. Peak generation was probably in Late Mesozoic (Early Cretaceous) time. Generation in source rock units younger than the Silurian was somewhat later. The Devonian may not have produced hydrocarbon until Cretaceous time. In general, traps older than Jurassic would be expected to be most favourable for oil accumulation (Massa et al., 1994). Migration distance for the discovered fields in the Murzuq Basin, according to Meister et al. (1981), must have been in the order of 150 to 200 km (Figure 5.18). It is generally assumed that lateral migration played an important role, since much of the shale underneath the producing areas is insufficiently mature to have provided hydrocarbon to the overlying reservoir zones. In view of the hydrocarbon seep at the northern margin of the Murzuq Basin, it is possible that the process is still continuing to the present day (see Chapter 6). Generally, the migration of hydrocarbon in the Murzuq Basin from the centre to northern parts of the basin would include lateral migration from the Silurian source to the Ordovician Memouniat reservoirs. Other types of migration can be expected, such as lateral migration along zones of continuous porosity in the top of Ordovician reservoirs, and upward migration from the Silurian source along faults is expected (Figure 5.21). Figure 5.17 presents burial history curves for the centre and margin of the Ghadamis Basin. In the Ghadamis Basin, moderately good source intervals have been identified within the Middle to Upper Ordovician (Scott, 1992). These rocks are now situated in the gas window (Figure 5.17). Generally, the highest-quality source rocks are the black shales.
Chapter 5: Hydrocarbon systems of Ghadamis and Murzuq Basins

Figure 5.16 Burial history curves of three wells in the Murzuq Basin, showing important geological horizons and key Time Temperature Index (TTI) lines (after Marco et al., 1985). For the Ghadamis Basin, see Figure 5.17.

This wedge of claystones shows northward progradation. As a result, proximal facies to the south are poorer in source quality, as are the younger parts of the succession. According to Figure 5.17, Silurian source rocks are in the late stages of maturity towards the margin of the Ghadamis Basin, and well into the gas generation phase within the centre of the basin. The existence of gas fields along the Libyan-Algerian border (the large Alrarr East gas field in Algeria and the Wafa gas field in Libya; Figure 5.01)
indicates that in that region the source rock is in the gas window. This demonstrates the strong inversion along the Tihembokah Arch. Other fairly rich source rock exists in the Upper Devonian part of the succession, as in the case of the Silurian succession. This interval is in the late stages of thermal maturity, except close to the basin margin.

Fresh-water flushing is a key factor in the hydrocarbon accumulations in the Murzuq Basin. Several hydrological studies have been undertaken in the Murzuq Basin. Dubay (1980), Pallas (1980) and Sinha and Bandey (1980) focused on the groundwater aspects of the fresh-water influx into the Paleozoic or Mesozoic rocks in the basin. Burdon (1980) pointed out that hydrological investigations over the last three decades have generally led to the conclusion that the area of Ghat, located on the southwestern side of the basin, acts as the main groundwater infiltration and aquifer recharge area. The high topographical elevation of the Cambro-Ordovician sequence makes the outcrops and rising highlands to the south around the Hoggar Massif (see Figure 4.02) a prime candidate for being a recharge area for the Cambro-Ordovician aquifers in the subsurface. It can be concluded that the main factor influencing hydrocarbon migration from the central part of the Murzuq Basin towards the northern parts is the hydrodynamic factor. All the studies reviewed lead to the conclusion that the hydrocarbons that were generated in the central parts of the Murzuq Basin moved generally northwards to fill any traps in their paths. Figure 5.18 shows the migration routes and trapping in the Murzuq Basin. The hydrocarbon seeps encountered along Al Qarqaf Arch (see Chapter 6) confirm the evidence of dysmigration. In this study (Chapter 6), the interpretation placed on their observations is that meteoric water has flushed Cambro-Ordovician and Devonian sandstones and that Al Qarqaf Arch acted as a barrier to these meteoric waters (see Chapter 6). According to the model, this means that the possibility exists, in parts of the basin with low structural traps, for dynamic trapping.
Figure 5.17 Burial history curves for the centre (A’) and margin (B’) of the Ghadamis Basin. The zone of maximum hydrocarbon generation is between vitrinite reflectance values of 0.55% Ro and 0.75% Ro (after Scott, 1992) (for location see Figure 5.16).
Figure 5.18 Schematic cross sections showing hydrocarbon migration routes and trapping in (A) the Ghadamis Basin (after Alvares, 1956) and (B) the Murzuq Basin (after Meister et al., 1991).
Figure 5.19 A) West Netherlands Basin, location map of oil and gas fields. B) SW-NE cross section through the IJselmonde/Ridderkerk field (after de Jager et al., 1996).
Figure 5.20 A) Sirt Basin, location of the Messlah oil field. B) Composite isopach map of net pay sands. C) E-W cross section along the northern part of the Messlah oil field (after Arabian Gulf Oil Company, 1980).
5.6 Future trends

Hydrocarbon prospectivity increases towards the basin margins, where traps tend to be structural and structural/stratigraphical. The structures tend to be low-amplitude anticlinal closures, and hydrocarbon columns are small. Most stratigraphical traps found so far are associated with the regional Hercynian Unconformity, which facilitates the overstep of dipping Paleozoic reservoirs by basal Mesozoic seals.

In the Murzuq Basin, the Late Ordovician Memouniat Formation is the primary prospective horizon. As we have seen in Chapter 3, the Murzuq Basin is bounded by two major wrench zones. This type of faulting will produce flower structures, which are potential traps. As an example of this trap type, a hydrocarbon field of the western Netherlands Basin is illustrated in Figure 5.19. In the western part of the Murzuq Basin, a similar structural configuration exists. Some wells have oil shows (Figure 5.11) and the area is still under exploration. The hydrocarbons of the recently discovered giant Elephant oil field are trapped in a reverse faulted anticline formed over a basement uplift of compressional origin, with dip closure to the north, east and south. The structure resulted from several pulses of uplifts (Compton et al., 1999). It can be concluded that the western and northern parts of the Murzuq Basin are highly prospective for hydrocarbon exploration (see Chapter 7). The eastern parts of the basin are less prospective due to the lack of source rock (see Chapter 4, Section 4.3.2.1 and Figure 4.07). As we have seen before, the structural and the hydrocarbon systems of the Ghadamis and Murzuq Basins are quite different with respect to the influence of Al Qarqaf Arch. The influence of Al Qarqaf Arch on the structural and trapping systems in the Ghadamis Basin is stronger than that in the Murzuq Basin (see Chapter 7, Figure 7.01). As we have seen in this chapter, the central part of the Murzuq Basin is characterized by the very low porosities of the Memouniat Formation and the eastern part of the basin is characterized by the absence of source rock. This leads to the conclusion that these two areas are less prospective compared with the northern part of the basin and the Atchan Saddle.

Therefore, potential oil and gas plays expected to be present in both basins include the following:
1. Pinchout of the reservoir units of the Late Silurian Acacus Formation could occur as the section thins against the Al Qarqaf Arch axis at the southern edge of the Ghadamis Basin. The same could occur in the northern parts of the Murzuq Basin with the Cambro-Ordovician Memouniat Formation. As an example of this stratigraphical trap type, the Messlah oil field of the Sirt Basin is illustrated in Figure 5.20. The major trapping mechanism in this field is the pinchout of the Mesozoic non-marine Sarir sandstones against the Messlah high.

2. Structural doming of porous horizons along wrench faults on the western and central parts of the Murzuq Basin.

A sketch summary of the play concepts of the two basins is shown in Figure 5.21, in which one can see the distribution of the major resources and source rocks and the principle migration routes.

5.7 Recommendations

1. A study of the distribution and maturity of all possible source rocks, and source rock-cap rock relationships, in particular around Al Qarqaf Arch.

2. Investigation of the formation water salinities in the two basins, which may give clues to the nature and age relationships between oil emplacement, erosional stripping and fresh-water flushing. In some areas, oil may be emplaced after the erosional stripping and fresh-water flushing of the reservoir rocks. In such cases, anomalous salinity values are expected.

3. There are not enough data available to establish the pattern of diagenesis for the reservoir rocks occurring in the area, so further analysis is recommended.

4. Detailed work on the role of faults in migration in both basins is highly recommended.

5. The role of wrench faults in the trapping of oil in the Murzuq Basin should be investigated in more detail by integrated interpretation of seismic data over a large area.
Figure 5.21 Sketch summary of play concepts of the Ghadamis and Murzuq Basins (see Figure 5.15 for detailed relationship between source, reservoir and seals in the central and southern parts of the Ghadamis Basin).
CHAPTER 6

SPATIAL DISTRIBUTION AND GEOCHEMICAL ANALYSIS OF HYDROCARBON SEEPS IN AL QARQAF ARCH, WEST LIBYA, AND ITS IMPLICATIONS FOR HYDROCARBON EXPLORATION

* Parts of this chapter were presented as:
Y.A. Al Fasatwi, M.S. Hroud and M.M. El Kelani

(Colored Figures 6.02, 6.03, 6.04, 6.05 and 6.06 are in color plate section at the back of the thesis)
Chapter 6: Hydrocarbon seeps near Al Qarqaf Arch

6.1 Onshore hydrocarbon seepage (literature survey)

A hydrocarbon seepage is defined as a visible evidence at the Earth’s surface of present or past leakage of oil, gas or bituminous substance from the subsurface (Hunt, 1996). Seeps are commonly found adjacent to major hydrocarbon fields. This is because most seeps are fed by these natural underground reservoirs of hydrocarbons. Hydrocarbon seepages and their links with onshore oilfields, also with considerable horizontal migration, are well documented.

Hunt (1996) described hydrocarbon seeps, their origin, examples and application for hydrocarbon exploration. Parts of his work were used as a reference in the literature review of this chapter. Macgregor’s global study (1993) offers the following guidelines for evaluating seeps:

1. Seepage patterns are strongly controlled by regional and local structures. Seeps are most common in young overpressured diapir-rich basins and in active thrust belts. They are rare in tectonically inactive basins.

2. Most large deep accumulations do not seep directly to the surface.

3. Intracratonic and foreland basins show a small number of seeps relative to reserves, and thrust belts show an anomalously large number of seeps and, consequently, depleted reservoirs.

4. The presence of seeps over basins or prospects considerably reduces the exploration risk. The absence of seeps over tectonically active basins or shallow-faulted prospects increases the risk.

Macgregor (1993) compared the global occurrences of seeps with tectonics and subsurface petroleum reserves. In the north and south Sumatra Basins, he found that most of the visible seeps are derived from the smaller shallower traps and from those most strongly affected by diapirism or faulting. The larger deeper fields not connected to the surface by faulting rarely showed visible seeps.

Well-populated areas of the world generally report many petroleum seeps. Selley (1992) documented 173 seepages and impregnations in Great Britain. The seeps were
found primarily around the margins of basins where permeable carrier beds unconformably overlie impermeable "basement" rocks. The main sources of the petroleum seeps were believed to be Devonian oil shales and Carboniferous shales and coals. Seepages were also found associated with faults, particularly in the Wessex and Wealden Basins of Great Britain where the Liassic is the probable source (Selley, 1992).

There are three classes of seeps, depending on rates of seepage:

1. Slow seepage creates microseeps, forming low concentrations of hydrocarbons in the shallow sediments. These can only be measured by sensitive instruments such as fluorimeters, chromatographs or mass spectrometers. The seep signal reflects a slow and episodic accumulation of oil and gas over thousands or tens of thousands of years.

2. Macroseeps, where hydrocarbons migrate more rapidly, are sufficiently large to avoid biodegradation in the shallow subsurface.

3. Flowing macroseeps occur where hydrocarbon migrates at a sufficient rate to overcome biological barriers.

Seeps are particularly important in exploring new basins or areas. Only about one explored basin in three is sufficiently petrolierous to contain even one very large oil field (North, 1985). Nevertheless, nearly all the important oil-producing regions of the world were first discovered by surface oil and gas seeps. The first oil wells of Canada, Pennsylvania, Oklahoma, California and Texas were drilled near oil seeps. The giant Masjid-I-Suliman field in Iran was the first big oil discovery in the entire Middle East. The discovery well was drilled near an oil and gas seep that had leaked through the cap rock. Another example of seeps along the edges of a basin or where structural uplifts have exposed the oil-bearing stratigraphical sequence is in the Lake Maracaibo area of Venezuela (Hunt, 1996). There are more than 200 oil and gas seepage locations in western Venezuela, many of which occur along the flanks of the Venezuelan Andes and the Perija Mountains. Seepage ranges from a few barrels of oil to asphalt lakes that cover several kilometres. Along the northwest edge of the Venezuelan Andes, small seeps issue from fractured igneous rocks that have been thrust basinwards over Tertiary or Cretaceous sediments. Seeps are associated with Cretaceous, Miocene and Eocene
Chapter 6: Hydrocarbon seeps near Al Qarqaf Arch

sediments. The Mene Grande field, El Mene, La Paza and the Boliver coastal fields were all drilled because of seeps.

The most common observation over the years has been the close association of surface hydrocarbon anomalies with faults and lineaments. Many faults periodically open and close because of the episodic release of high-pressure gas. Jones and Drozed (1983) found a clear association between surface hydrocarbon anomalies and fault zones in the Utah-Wyoming overthrust belt. The thrust fault in the Ryckman Creek Anticline area of Wyoming reaches the base of the Tertiary, which is approximately 1000 m thick. Anomalous seepage of methane, propane and butanes is associated with the position of the thrust faults at the base of the Tertiary. They indicate that gases from deep reservoirs have migrated updip along the thrust plane and then vertically through the Tertiary section. A similar close association of subsurface faults and high surface hydrocarbon concentrations was observed at Pine View field, Utah, along the thrust belt.

Seeps are common at the outcrops of unconformities and permeable homoclinal beds such as in the Western Canada and Eastern Venezuelan Basins. They occur along normal faults, as at Gebel Zeit in Egypt, and thrust faults, as at the Infants field in Colombia (Link, 1952). Seeps are also commonly associated with sedimentary intrusions, such as the mud volcanoes in the Caspian Sea off Baku and the piercement salt domes in the U.S. Gulf Coast. The asphalt lake of western Trinidad is a giant seep, as are the sabre-toothed-tiger-bearing La Brea Tar Pits near Los Angeles, California.

In Libya several hydrocarbon seeps were discovered in 1957 but apparently never reported in publications (Massa et al., 1994). They are located south of Quttah village, some 90 km to the northwest of Sabha (Figure 6.01). They consist of bituminous sandstones, poorly consolidated. An analysis of bitumen samples gave the following results:

Asphaltenes 19.65%

Oil constituents 45.70%

Petroleum resins 34.65%

Sulphur 9.7%.
6.2 Hydrocarbon seepage along Al Qarqaf Arch

6.2.1 Introduction

As we have seen in Chapter 2, the vicinity of arches constitutes focal areas for hydrocarbon migration and accumulation in different places around the world. The present study was undertaken to highlight the migration of hydrocarbons to areas of arch structures from adjacent sedimentary basins. The objective of this part of the study is to map the spatial distribution of hydrocarbon seeps along Al Qarqaf Arch. Soil samples of some hydrocarbon seeps were collected and geochemically analyzed (Figure 6.01). Nine sites were selected where high vertical hydrocarbon seepage from underlying hydrocarbon reservoirs could cause surface and near surface geochemical change in the soils. Numerous hydrocarbon indications can be observed in Wadi El Shatti along an E-W trend some 10 km long. During the fieldwork, it became clear that water from several irrigation wells contaminated by hydrocarbons was regarded as non-drinkable by the inhabitants of the area. It seems to be common practice to spill contaminated water until the quality is good enough for irrigation. The approach used in this study was an empirical analysis of known areas of historical hydrocarbon seeps, which were assumed to have the potential for present seep activity. The Landsat TM and Spot XS images of the area were used for lineament analysis and lithological mapping of the areas of hydrocarbon seeps. Neither Landsat TM nor Spot XS can spectrally discriminate seeps. However, hyperspectral data have the capability for this kind of mapping.

The area of study is located 90 km north of the city of Sabha (Figure 6.01), in the areas of Quttah, Bir Shirhan and Brak. Geologically, the area belongs to the southern part of Al Qarqaf Arch and to the adjoining northern part of the Murzuq Basin. The area is located between 27° 00’ and 27° 40’ N and 13° 00’ and 14° 35’ E. Wadi El Shatti is a generally E-W trending depression (Figure 6.01), between 10 and 15 km wide.

The lowermost substage is built of Cambrian strata belonging to the Hassawanah Formation. The strata generally dip very gently, forming the southern rim of the dome of Jabal Al Hassawanah. In the western part of the area, Ordovician sandstones of the Memouniat Formation (the upper Caledonian substage) unconformably overlie the Cambrian sediments. Devonian formations dip southwards at angles only locally greater than 1°. The valley floor is principally composed of surficial deposits of Quaternary age,
Chapter 6: Hydrocarbon seeps near Al Qarqaf Arch

in the form of alluvium, gravel and sand accumulations. Tournaisian rocks crop out of the surficial cover in some places. In the area of study, important faults of ENE-WSW direction locally form the tectonic boundary separating the Hassawanah, Memouniat and the Devonian Formations. The strike of the fault largely coincides with Al Qarqaf Arch direction (about 70°).

Direct natural evidence for the existence of oil and gas in the area of Al Qarqaf Arch has been provided in different areas by surface occurrences of oil and gas seeps, and bituminous calcareous sediments. However, no asphalt or tar sands were observed in the areas that were checked during the fieldwork. Two types of seep were observed in the area. The first type is the primary seep, where the hydrocarbon has migrated directly to the surface. This type is presented by some seeps of the Quttah area (Figures 6.02 and 6.05). The second type can be regarded as secondary seeps. This type resulted from the contamination of groundwater by hydrocarbons and is evidenced by the residue of contaminated groundwater near water wells (Figures 6.03 and 6.04).

The example presented in Figure 6.01 concerns two wells at a distance of 170 km. It is a good example in as much as it links well A1-NC58 to well A1-NC115, which is situated in the far north of the Murzuq Basin. Other significant discoveries are being appraised in the area at the present time. One may add that the Silurian sediments directly beneath the fields of concessions NC-115 are insufficiently mature and, therefore, could not have supplied hydrocarbons to overlying reservoirs. A short-distance migration is thus excluded. It does not seem possible, with the data in hand, to refute the by now well-documented hypothesis of a long-distance migration of the Silurian oil. The distance would be at least 150 or 200 km and, consequently, the Silurian oil is considered as allochthonous.
Figure 6.01 Location map of the study area, and hydrocarbon migration and surface-cap relationship (after Meister et al., 1981).

During the fieldwork, about eight soil samples were taken from the area of Quttah (Figure 6.06), and it is expected that the seeps cover a much larger area. Therefore, we took an additional sample at Brak (about 60 km east of the Quttah area (Figure 6.06), which confirms our idea. More work needs to be done to delineate the total area of seep.
6.2.2 Objective

The primary objective of this study was to verify the presence and the geochemical analysis of the hydrocarbon seeps in the area of Al Qarqaf Arch, using remote sensing and geochemical analysis methods.

6.2.3 Methodology

6.2.3.1 Fieldwork

Reconnaissance soil sampling was undertaken in areas considered to be affected by hydrocarbon seeps.

6.2.3.2 Remote sensing

Remote sensing of hydrocarbon-induced alterations holds great promise as a rapid cost-effective means of detecting alterations in surface soils and rocks. The Spot XS data of 20 m resolution and multispectral Landsat TM data of 30 m resolution were registered and analyzed for discrimination between different rock types and to map surface structures in the area. Ground control points were then established in a few days’ fieldwork, using a hand-held Global Positioning System (GPS) device that allowed the image to be accurately tied to known points on the ground. The main observation that can be made from the interpretation of remote sensing images of the area of hydrocarbon seepage is that the distance between the two areas of hydrocarbon seepage in Quttah (known seepage) and Brak (verification of larger areal extent) is about 60 km (E-W). The presence of hydrocarbon seepage in both areas this distance apart indicates that the hydrocarbon migration to the surface occurs over a large area.

6.2.3.3 Geochemical analysis

6.2.3.3.1 Pyrolysis and TOC analysis

Rock-eval analysis was performed in duplicate samples, using standard techniques (Espitalie and Bordenave, 1993). Total organic carbon (TOC) was determined for decarbonated samples and total carbon was determined for whole rock samples.
6.2.3.3.2 Extraction and gas chromatography

Crushed sediments (typically 15 gm) were exhaustively extracted by soxhlet apparatus (DCM/methanol; 93/7 ml v/v). The entire extracts were injected using Carlo Erba mega series 5300 gas chromatography. The gas chromatography was fitted with an on-column injector and an OV-1 (cross-linked methysilicone) fused silica capillary column (25 x 0.32 mm i.d.). The temperature was programmed from 50° to 100°C at 8°C min and from 100° to 300°C at 4°C min, with helium employed as the carrier gas. Compounds were identified using a combination of relative GC retention times.

6.2.3.3.3 UV and IR spectroscopy

Selected extract samples were dissolved in n-hexane solvent and scanned in the UV region from 190 nm to 400 nm, using a PU8800 UV/VIS spectrophotometer. Selected extract samples were also dissolved in carbon tetrachloride solvent and scanned using a Unicam PU9512 IR spectrophotometer.

6.2.4 Data interpretation

The following analysis procedure (Espitalie and Bordenave, 1993) is used for the final interpretation of these data. It has proved very valuable in analyzing and comparing petroleum prospects in other areas.

6.2.4.1 Bulk geochemical analysis

The total organic carbon content versus extracts, as shown in Figure 6.08, indicates that all the samples consist of migrated hydrocarbon. The fractionation data shown in Table 6.01 indicate a high proportion of resin plus asphaltenes (64% to 91%), depleted in saturates (1.9% to 18%) and aromatics (4% to 18%). These data refer to heavy asphaltic crude resulting from severe biodegradation that was reinforced by water washing, oxidation and loss of volatiles.
Table 6.01 Location, bulk parameters and composition of oil seep samples from the area of study (S1: free hydrocarbons, S2: present potential of the source rock, TOC: total organic carbon, BS: Bir Shirhan, Q: Quttah and B: Brak).

6.2.4.2 Gas chromatography

The fingerprints of gas chromatograms of selected extracts of sand soil samples (Figure 6.08) suggest the loss of n-alkanes and the presence of a significant unresolved branched and cyclic component. These results are consistent with the fractionation data, which points to extensive biodegradation in these sand samples.
Figure 6.07 TOC versus total extracts of the hydrocarbon soil samples.
Chapter 6: Hydrocarbon seeps near Al Qarqaf Arch

Figure 6.08 Gas chromatograms of selected extracts of hydrocarbon seeps and samples 1, 2, 3 and 4. Numbered peaks are n-alkane carbon numbers.

6.2.4.3 Infrared and ultraviolet spectra

The infrared (IR) absorption spectra of three selected extracted samples are shown in Figure 6.09. The IR spectra indicate the presence of several types of functional groups containing C, H and O. No evidence of nitrogen-containing functional groups was found. Aliphatic CH2 and CH3 groups are indicated by absorption in the range 2920 to
2850 cm⁻¹ and may be due to a type of aromatic substitution. The band at approximately 1700 cm⁻¹ is due to C=O stretching vibration in carboxyl groups. The presence of OH groups is indicated by a broad absorption band at 3400 to 3430 cm⁻¹. The ultraviolet fluorescence (UV) absorption spectra of three selected samples are shown in Figure 6.10. All the samples show absorbencies that reflect aromatic compounds; absorption in the range 229 nm may be due to a type of biodegraded mercaptans. The IR and UV spectra indicate that all the extracted sand soil samples contain hydrocarbon.

Figure 6.09 Infrared spectra (IR) of selected extracts of sand soil samples.
Figure 6.10 Ultraviolet fluorescence (UVF) of selected extracts of hydrocarbon soil samples.

6.2.5 Conclusions

Extensive evidence in two areas of hydrocarbon seepage (Quttah and Brak) has been studied. Various combinations of (1) regional geological studies, (2) interpretation
of Landsat TM and Spot remote sensing images, and (3) geochemical analysis of soil samples were used to locate and analyze the hydrocarbon seeps in the area. Hydrocarbon seeps in both Quttah and Brak were found near the unconformable contact between the Devonian Quttah and Debdab Formations (Figure 6.06).

According to the literature (Massa et al., 1994), the hydrocarbon seeps are found only in the Quttah area, but this study indicates that the hydrocarbon is spread over a large area (Figure 6.01). Additional, more systematic sampling is needed to determine the total area of seepage more accurately. Alternatively, modern hyperspectral remote sensing (e.g. the ASTER sensor) could be successful in eliminating this laborious task, by detecting the total seepage area by remote sensing (with limited ground truth).

The presence of seeps along a well-defined NE-SW trending normal fault almost parallel to the orientation of Al Qarqaf Arch indicates that probably the oil has migrated from the northern flank of the Murzuq Basin. The orientation and nature of the fault points to a deep penetration of the Murzuq Basin sediments. Looking at the distribution of the oil fields in the Murzuq Basin, one may conclude, from the presence of seeps, that other hydrocarbon fields may exist in the intervening area (Figure 6.01). Therefore, these hydrocarbon seeps on the surface should provide the ability to carefully focus seismic exploration for structural and stratigraphical accumulations.

6.2.6 Implications for hydrocarbon exploration

In this study, several seeps were analyzed primarily around the margins of the Murzuq Basin, where permeable carrier beds unconformably overlie impermeable "basement" rocks. The main sources of the petroleum seeps were believed to be Silurian Tanezzuft Formation shales. Seepages were also found associated with faults, particularly in the area of Quttah.

Surface hydrocarbon seeps are of great interest and importance to hydrocarbon exploration. With proper geological interpretation, they may be a direct lead to commercial reservoirs. Residual petroliferous material often indicates that hydrocarbons have at times passed through particular rock types, formations or structures. Studying the nature of hydrocarbon seeps can help to provide a better understanding of the hydrocarbon trapping potential of an area.
Chapter 6: Hydrocarbon seeps near Al Qarqaf Arch

The two areas of hydrocarbon seepage near Quttah and Brak could be selected as sites for detailed investigation in respect to the following:

1. Surface geochemistry in hydrocarbon exploration relies on the process of vertical migration. One of the key elements in the theory of vertical migration of hydrocarbons is the rate at which hydrocarbon migrates from the reservoir to the surface. The rate of hydrocarbon migration has been a subject of debate for a number of years.

2. Detailed seep-oil correlation between the samples of the hydrocarbon seeps and crude oil from different reservoirs in the Murzuq Basin in order to determine or define the migration distance.

3. Hyperspectral remote sensing and analysis of the area of hydrocarbon seeps in order to study the capability of this technology to map hydrocarbon seeps in arid environments.
Chapter 7: Conclusions and recommendations

7.1 Introduction and conclusions

In this thesis, different data sources were used to study the structural, paleogeographical and hydrocarbon systems of the Ghadamis and Murzuq Basins, west Libya, with emphasis on their relation to the intervening Al Qarqaf Arch.

1. The global study of arch structures has indicated the types of hydrocarbon traps to be expected because of the similarity between the structural and sedimentary configuration of arches in different basins.

Arches are either surface or near surface structures formed by the uplifting of the basement due to tectonic activity. In many continents the records indicate that arching has been the dominant structural style during the Early Paleozoic. The similarity of the geological environment around arches worldwide, from the structural and stratigraphical point of view permits the prediction of hydrocarbon traps that may be expected around arches. They include types such as pinchouts especially in areas of clastic sedimentary cover, as in the area of Hassi Maessoud (Algeria), and reef structures in areas of carbonate build ups, as in the case of the Peace River (western Canada), as well as onlap, truncation and unconformities. The burial depth of arches usually has an influence on the type of traps. The model extracted from the study (see Chapter 2, Section 2.6; Figures 2.05 and 2.06) indicates that in buried arches traps are broad anticlines, pinchouts, lateral porosity unconformities, local fault truncations and reefs. In the case of near surface arches, the traps expected range from structural (simple anticlines, faulted anticlines and faults) and stratigraphical (pinchout, onlap, unconformity, erosion and non-deposition) to combination traps. Relative to the buried arch type, the hydrocarbon accumulations in areas of near surface arches are smaller in size and reserves. This can be explained as the result of the smaller structures associated with near surface arches, the smaller size of the traps and the increased chance of leaking reservoirs.

2. The simultaneous use of satellite image data interpretation and aeromagnetic, seismic and well data analysis has proved to be effective in delineating the surface and subsurface configuration of the Ghadamis and Murzuq Basins (Table 7.1).
Chapter 7: Conclusions and recommendations

The geometry of the Ghadamis and Murzuq Basins is asymmetrically curved in shape. The shape of the two basins is clearly visible on the remote sensing images; the Murzuq Basin is triangular in shape with its tip oriented to the south (towards the Djadu Basin, which is the continuation of the Murzuq Basin in the Republic of Niger). Both basins have more than one depocenter. This may have influenced hydrocarbon paths and the development of reservoir conditions and trapping systems. The Murzuq Basin is divided into two subbasins: the main Murzuq Basin in the west and the Dor El Qussah subbasin in the east. The boundary between the two subbasins (Ben Ghenemah Arch) is clearly visible in remote sensing images and aeromagnetic maps.

The correlation between the structural contour map of the basement and the present topography map (Figure 3.01) shows that the basement structures and topography are well expressed at the surface, as shown by the elevation map. The shape, geometry and boundaries of the two basins can be easily traced; major faults such as the Dor El Qussah fault zone are clearly visible on the map.

A hitherto unknown structure in the northern part of the Ghadamis Basin (Figure 3.04) has been described. The presence of a low magnetic anomaly about 130 km wide and 300 km long should be considered interesting for hydrocarbon exploration, especially with the presence of some known oil fields in the area.

Digital merging of the aeromagnetic map with a Landsat TM mosaic of the area indicates that many magnetic basement structures are well expressed at the surface, especially in the margins of the basins. Most of the faults in the area are basement faults. These faults extend to the surface in the western and eastern parts of the Murzuq Basin. The modelled topography of Al Qarqaf Arch (Figure 3.13), constructed from well log data, indicates that Al Qarqaf Arch was formed during the period extending from Late Cambrian-Early Ordovician to Late Devonian and that both adjoining basins have more than one depocentre, which may influence hydrocarbon trapping systems. The geometry of Al Qarqaf Arch is most likely a combination of small basement highs not completely separating the Ghadamis Basin from the Murzuq Basin, as they are partly connected in the area of the Atchan Saddle.
<table>
<thead>
<tr>
<th>Basin</th>
<th>Geometry</th>
<th>Fault trends and lineaments</th>
<th>Surface characteristics (remote sensing analysis)</th>
<th>Overall type of faults</th>
<th>Surface characteristics (remote sensing analysis)</th>
<th>Fault trends and lineaments</th>
<th>Overall type of faults</th>
<th>Surface characteristics (remote sensing analysis)</th>
<th>Fault trends and lineaments</th>
<th>Overall type of faults</th>
<th>Surface characteristics (remote sensing analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghadamis</td>
<td>Asymmetrical and curved in shape</td>
<td>More than one depocentre</td>
<td>Small NE-SW trending magnetic basement flows are observed clearly</td>
<td>NE-SW</td>
<td>Most likely a combination of small arches and depression are observed</td>
<td>NE-SW trending high on the eastern side of the basin and NW-SE trending in the western side.</td>
<td>NE-SW</td>
<td>NW-SE trending in the eastern side of the basin and NW-SE trending in the western side.</td>
<td>NE-SW trending</td>
<td>More than one depocentre</td>
<td></td>
</tr>
<tr>
<td>Al Qarnat Arch</td>
<td>SW-NE trending arch</td>
<td>More than one depocentre</td>
<td>Not separating the two basins are completely very clearly</td>
<td>NE-SW</td>
<td>Most likely a combination of small arches and depression are observed</td>
<td>NE-SW trending high on the eastern side of the basin and NW-SE trending in the western side.</td>
<td>NE-SW</td>
<td>NW-SE trending in the eastern side of the basin and NW-SE trending in the western side.</td>
<td>NE-SW trending</td>
<td>More than one depocentre</td>
<td></td>
</tr>
<tr>
<td>Murzuq Basin</td>
<td>Asymmetrical and curved in shape</td>
<td>More than one depocentre</td>
<td>Small NE-SW trending magnetic basement flows are observed clearly</td>
<td>NE-SW</td>
<td>Most likely a combination of small arches and depression are observed</td>
<td>NE-SW trending high on the eastern side of the basin and NW-SE trending in the western side.</td>
<td>NE-SW</td>
<td>NW-SE trending in the eastern side of the basin and NW-SE trending in the western side.</td>
<td>NE-SW trending</td>
<td>More than one depocentre</td>
<td></td>
</tr>
</tbody>
</table>

**General Conclusions:**
1. The Ghadamis and Murzuq Basins are not completely separated from each other. They are partly connected in the area of Alqarnat Saddle.
2. Most of the discovered hydrocarbons in the area are located in areas of high magnetic anomalies.
3. Al Qarnat Arch is most likely a combination of small arches or high basement magnetic anomalies.

Table 7.1 Surface and subsurface characteristics summary of Al Qarnat Arch and the Ghadamis and Murzuq Basins.
3. A comparison of the Ghadamis and Murzuq Basins reveals several important differences in structural and stratigraphical styles, which have a major bearing on the distribution and type of the hydrocarbon traps (Tables 7.02 and 7.03).

In some ways, both the Ghadamis and Murzuq Basins could be viewed as part of a single western Libyan structural unit: a N-S oriented super-basin. On the other hand, the study indicates that the two basins are different in structural evolution, which was influenced by their relative positions with respect to the Hoggar and Tibisti Massifs and to the influence of Al Qarqaf Arch.

In many aspects both basins proved to be similar. They are typical intracratonic basins, characterized by extensional basement-controlled faulting, doming and vertical movements along the reactivated basement faults during the Caledonian and Hercynian Orogenies. This resulted in two major unconformities, the Caledonian and Hercynian Unconformities. Other major structures are to a large extent inherited from reactivated Pre-Cambrian structural alignments. However, the Murzuq Basin is structurally more complex and is characterized by NW-SE and NE-SW trending wrench faults (see Chapter 3, Section 3.4.4.3 and Figure 3.11), resulting in the formation of flower structures (Chapter 3, Figure 3.11), which are absent or less developed in the Ghadamis Basin. These wrench faults most probably control the hydrocarbon migration and accumulation in some parts of the Murzuq Basin.

The aeromagnetic image of the area shows several important structural differences (Figure 3.02). The Murzuq Basin is characterized by NW-SE trending highs in the western part and NE-SW trending high and low magnetic anomalies in the eastern part. These areas could be prospective areas for hydrocarbon exploration. The regional cross sections, sand percentage maps and sand/shale ratio maps indicate that most Silurian and Devonian units are missing over large parts of the Murzuq Basin (Figures 4.03 and 4.04). The absence of these units has great influence on the hydrocarbon systems in the Murzuq Basin. However, these units are well represented in the Ghadamis Basin. Absence of Lower Silurian Tanezzuft shales in the eastern part of the Murzuq Basin (Dor El Qussah subbasin) may have precluded hydrocarbon generation and accumulation and, consequently, exploration activities have focused on the central and western parts of the Murzuq Basin.
<table>
<thead>
<tr>
<th>Formation</th>
<th>Rock type</th>
<th>Source of sediments</th>
<th>Relation to Al Qarqaf Arch</th>
<th>Depositional environment</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carb.</td>
<td>Mrar</td>
<td>Mainly sandstone, shales</td>
<td>S-SW</td>
<td>Partly influenced by the arch</td>
<td>Marine/lagoonal and deltaic</td>
</tr>
<tr>
<td></td>
<td>Tahara</td>
<td>Mainly sandstone</td>
<td>S-SW</td>
<td>Partly influenced by the arch</td>
<td>Continental/ marine</td>
</tr>
<tr>
<td></td>
<td>Aouinet Ouenine</td>
<td>Sandstone, shales and siltstone</td>
<td>S-SW</td>
<td>Thinning of FM in area of the arch</td>
<td>Continental/ marine</td>
</tr>
<tr>
<td></td>
<td>Ouan Kasa</td>
<td>Mainly sandstone</td>
<td>S-SW</td>
<td>Thinning of FM in area of the arch</td>
<td>Deltaic/ marine</td>
</tr>
<tr>
<td></td>
<td>Tadrart</td>
<td>Dark massive, cross bedded sandstone</td>
<td>S-SW</td>
<td>Thinning of FM in area of the arch</td>
<td>Continental/deltaic to marine</td>
</tr>
<tr>
<td>Silurian</td>
<td>Acacus</td>
<td>Fine to medium, cross bedded sandstone</td>
<td>SW</td>
<td>Thinning of FM in area of the arch</td>
<td>Fluvial/deltaic to marine</td>
</tr>
<tr>
<td></td>
<td>Tanezzuf</td>
<td>Shale</td>
<td>S-SW</td>
<td>Thinning of FM in area of the arch</td>
<td>Deltaic/ marine</td>
</tr>
<tr>
<td>Ordv.</td>
<td>Memouniat</td>
<td>Massive, cross bedded sandstone</td>
<td>S-SW</td>
<td>Thinning of FM in area of the arch</td>
<td>Marine</td>
</tr>
</tbody>
</table>

General Conclusions:

1. Depositional thinning of the Silurian sediments over Al Qarqaf Arch suggests that it was an intermittently active structure throughout the Silurian period.
2. Isopach and Sand % maps of Cambro-Ordovician, Silurian, Devonian and Carboniferous periods clearly illustrate the tectonic influence on the sedimentary fill of the Ghadamis and Murzuq Basins.
3. Al Qarqaf Arch was an intermittently active structural feature during most of the Paleozoic Era. Most of the formations of Ordovician, Silurian, Devonian and Carboniferous have a decreased thickness in the area of the arch.
4. The sand%, sand ratio maps and paleocurrents of the Silurian, Devonian and Carboniferous formations indicate that the main source of these rocks is from SE and SW (Tibisti and Hoggar Massifs).

Table 7.2 Summary of paleogeography of hydrocarbon systems of the Ghadamis and Murzuq Basins.

Chapter 7: Conclusions and recommendations
<table>
<thead>
<tr>
<th>Basin</th>
<th>Area</th>
<th>main source rock</th>
<th>Main reservoir</th>
<th>Field size</th>
<th>Trap Age</th>
<th>Trap Type</th>
<th>Migration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghadamis Basin</td>
<td>Basin margin (North)</td>
<td>Tanezzuft Formation</td>
<td>Mainly Silurian reservoirs: (Acacus Formation)</td>
<td>&lt;50 MMB</td>
<td>Herc/Ast</td>
<td>* Structural * Combination</td>
<td>Lateral + vertical</td>
</tr>
<tr>
<td></td>
<td>Basin centre</td>
<td>Tanezzuft Formation</td>
<td>Mixed Silurian (Acacus FM) Devonian (Tadart FM, Aouinet Qunine FM, Tahara FM) Carboniferous (Mrar FM) Triassic (Ras Hamia FM).</td>
<td>50-100 MMB</td>
<td>Herc</td>
<td>* Structural * Combination</td>
<td>Lateral</td>
</tr>
<tr>
<td></td>
<td>Basin margin (South-adjacent to Al Qarqaf Arch)</td>
<td>Tanezzuft Formation</td>
<td>Mainly Devonian reservoirs: (Tadart Formation). Minor reservoirs: Ordovician Memoniat FM.</td>
<td>&gt;150 MMB</td>
<td>Herc</td>
<td>mainly Combination traps</td>
<td>Lateral + vertical</td>
</tr>
<tr>
<td>Murzuq Basin</td>
<td>Basin margin (North-adjacent to Al Qarqaf Arch)</td>
<td>Tanezzuft Formation</td>
<td>Mainly Ordovician reservoirs: (Memoniat Formation) Minor reservoirs: Devonian Tahara FM.</td>
<td>&lt;150 MMB some of recently discovered fields (NC174) reach Ultimate Recovery (MMB) of 500 MMB</td>
<td>Herc</td>
<td>* structural</td>
<td>Lateral + vertical</td>
</tr>
<tr>
<td></td>
<td>Basin centre</td>
<td>Tanezzuft Formation</td>
<td>Mainly Ordovician reservoirs: (Memoniat Formation) Minor reservoirs: Devonian Aouinet Qunine FM, and Tahara FM</td>
<td>&lt;50 MMB</td>
<td>Herc</td>
<td>* structural</td>
<td>Lateral</td>
</tr>
</tbody>
</table>

Table 7.3 Names, locations and reservoir characteristics of hydrocarbon accumulations in the Ghadamis and Murzuq Basins.
4. A comparison between the known oil field distribution in the study area and other arch-influenced basins indicates additional areas for further exploration near the arch.

Study of the distribution and hydrocarbon characteristics of near surface arches, as in the case of El Baul Arch (Venezuela) and Barrow Arch (USA), indicates that areas adjacent to near surface arches are characterized by the presence of several types of traps (Figures 5.07 and 5.08). These are (A): structural (simple anticline, faulted anticlines, faults) and (B): stratigraphical traps (pinchout, onlap, unconformity). Applying this model in the case of Al Qarqaf Arch suggests that areas of the Ghadamis and Murzuq Basins adjacent to Al Qarqaf Arch are prospective areas for hydrocarbon exploration (Figure 7.01). Most of the to date discovered hydrocarbon accumulations in the Ghadamis and Murzuq Basins are trapped in structural and combination traps, whereas most of the hydrocarbon discovered adjacent to Al Qarqaf Arch is trapped in combination traps. The areas of the two basins adjacent to the arch are prospective areas.

The hydrocarbon systems of the Ghadamis and Murzuq Basins are partly influenced by Al Qarqaf Arch.

Expected traps to be present in both basins close to the arch area are:

1. Onlap of transgressive Tanezzuft shales sealing and sourcing the Cambro-Ordovician sandstones.

2. Pinchout of the Upper Silurian Middle Devonian sequence.

3. Onlap of transgressive marine shale onto the Silurian Middle Devonian sequence.

Hydrocarbon occurrence varies across the Ghadamis and Murzuq Basins. It appears to follow transgressive/regressive facies patterns and is stratigraphically and structurally controlled. The most important set of reservoirs are the sandstones of the Ouan Kasa, Tadrart and Acacus Formations. The base of Aouinnet Ouenine overlies this set of reservoir formations and is underlain by the top of Tanezzuft shale.
Chapter 7: Conclusions and recommendations

In the case of the Murzuq Basin, especially in the western part of the basin, a different hydrocarbon trapping system is a result of a major strike-slip fault system along 10° E. The traps range from flower structures to reverse faults (Figure 7.01).

LEGEND:
- Trap types
- Stratigraphic Trap.
- Structural Trap.
- Combination trap.
- Hydrocarbon seeps area
- Prospective areas:
  - Near-surface trap types.
  - Wrench related trap types.

Figure 7.01 Map showing regional distribution of traps in the Ghadamis and Murzuq Basins and proposed areas of hydrocarbon exploration interest.
Chapter 7: Conclusions and recommendations

5. The recognition of the strike-slip nature of a series of faults in the Murzuq Basin may indicate the possible presence of oil fields in flower structures along these faults.

Wrench faulting played an important role in the deformation of the western part of the Murzuq Basin. It is characterized by the presence of a regional strike-slip fault along the 10° E. Strike-slip tectonics are generally driven by basement-involved faulting. When basement faults are reactivated, a zone of rotational bulk strain develops in the sedimentary overburden. Figure 3.11A shows the image-interpretation of a Landsat TM mosaic of the western Murzuq Basin, showing lineaments and folded structures resulting from the strike-slip fault zone of 10° E. The figure shows flower structures associated with this major fault. These flower structures are interesting for hydrocarbon exploration. The main trap type of the Elephant oil field, discovered in the western Murzuq basin in 1997, is reverse faults resulting from strike-slip faulting. This may indicate the possible presence of oil fields in flower structures along these faults (see Chapter 5, Section 5.4.2.4 and Figure 5.11).

6. The seeps identified along and on Al Qarqaf Arch prove the lateral and vertical migration of oil. On the one hand, this shows the presence of mature source rock in the vicinity but, on the other hand, it could indicate major loss of oil through migration along faults that reach the surface.

Several hydrocarbon seeps located along the southern edge of Al Qarqaf Arch were observed and studied (Chapter 6). The presence of the seeps along a well-defined NE-SW trending normal fault almost parallel to the orientation of Al Qarqaf Arch reinforces the probability that the oil migrated from the northern flank of the Murzuq Basin (Figure 6.06). Looking at the distance to the nearest oil field in the Murzuq Basin (Figure 6.01), one may conclude that other fields may exist in the intervening area. The main source of the petroleum seeps was believed to be Silurian Tanezzuft Formation shales. It may be added that the Silurian sediments that are directly underneath the fields in the northern parts of the Murzuq Basin are insufficiently mature and, therefore, they could not have supplied hydrocarbons to overlying reservoirs. A short-distance migration is thus excluded. Long-distance migration of the Silurian oil most probably occurred. The distance would be at least 150 to 200 km and consequently the Silurian oil is allochthonous.

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The existence of strike-slip faults in the area suggests that the hydrocarbon is leaking from the flower structures associated with wrench faulting close to the area of the hydrocarbon seeps.

As we have seen in Chapter 5, fresh-water flushing is a key factor in the hydrocarbon accumulations in the Murzuq Basin. The high topographical elevation of the Cambro-Ordovician sequence makes the outcrops and rising highlands to the south around the Hoggar Massif (see Figure 4.02) a prime candidate for being a recharge area for the Cambro-Ordovician aquifers in the subsurface. The hydrocarbon seeps encountered along Al Qarqaf Arch (see Chapter 6) confirm the evidence of dysmigration. In this study (Chapter 6), the interpretation placed on these observations is that meteoric water has flushed Cambro-Ordovician and Devonian sandstones and that Al Qarqaf Arch acted as a barrier to these meteoric waters (see Chapter 6).

7. The study indicates that Al Qarqaf Arch has an influence on the structural and paleogeographical setting and hydrocarbon distribution of the adjacent parts of the Ghadamis and Murzuq Basins.

The modelled topography of Al Qarqaf Arch, constructed from well log data, (Figure 3.13) indicates that Al Qarqaf Arch was formed during the period extending from Late Cambrian-Early Ordovician to Late Devonian.

The lineament analysis of satellite images of the area (Figure 3.06) and the rose diagrams (Figure 3.07) show that lineaments of Al Qarqaf Arch and adjacent parts of the Ghadamis and Murzuq Basins are strongly influenced by the NE-SW trending arch. This has conditioned the trapping system in the southern parts of Ghadamis Basin, where the faults and folds axes are trending in the same direction as Al Qarqaf Arch (Figure 5.10). The influence of the arch is less in the case of the Murzuq Basin, where the influence of wrench faults along the flanks of the basin is marked and most of the structural traps are NW-SE in direction.

The arch has influenced the sedimentation pattern (Chapter 4). Paleocurrent data on Cambro-Ordovician and Devonian rocks, and isopach and percentage maps of the Ordovician, Silurian, Devonian and Carboniferous rocks indicate that the first influence
of Al Qarqaf Arch on the sedimentary facies started with the Devonian Tadrart Formation.

Combinations of structural and stratigraphical traps are expected to be the dominating mode of entrapments in areas close to the arch.

The analysis of hydrocarbon systems in the Ghadamis and Murzuq Basins clearly illustrates that the influence of the arch on the trapping system in the Ghadamis Basin is stronger than in the Murzuq Basin. In general, the oil fields close to the arch are characterized by small reserves (Chapter 5). That most of the Silurian and Devonian Formations are missing over large parts of the Murzuq Basin explains the absence of these reservoirs in the area.

As we have seen in Chapter 5, it is interesting to compare the actual traps encountered in the Ghadamis and Murzuq Basins (Figure 5.07) with the general model of trap types associated with near surface arches (Chapter 2, Section 2.6 and Figure 2.05). In the Ghadamis Basin, we indeed find structural traps in the centre of the basin and combination to stratigraphical traps towards the flanks.

The distribution of oil fields in the area appears to be confined to a regional trend, which reflects a close relationship between tectonism, sedimentation, oil migration and accumulation.

7.2 Recommendations

To improve understanding of the surface and subsurface characteristics of the arch and adjacent sedimentary basins for the purpose of oil exploration, the following additional studies are considered useful:

1. Full understanding of the regional geological and geographical framework of the sedimentary facies distributions in relation to their reservoir quality. This is of practical importance where the regional structural framework is complex and a substantial variation of sedimentary facies occurs over a short distances. Moreover, in the considered areas, stratigraphical traps linked to onlap and pinchout of reservoir rocks around regional arches and domes could exist.
2. Detailed gravity and aeromagnetic survey and analysis are strongly recommended in order to verify in detail the magnetic expressions of the deeply buried basement surface and to map structural styles of the overlaying sediments.

3. Regional seismic analysis and correlation in different parts of the Ghadamis and Murzuq Basins in order to study the types of fault and fold patterns in both basins and the influence of Al Qarqaf Arch, particularly the structures associated with the strike-slip faults in the Murzuq Basin and detailed analysis preferably with 3D seismic surveys.

4. Investigation of the formation water salinity, which may give some clues to the nature and age relationships between oil emplacement, erosional stripping and fresh-water flushing. In some areas, oil may be emplaced after the erosional stripping and fresh-water flushing of the reservoir rocks. In such cases, anomalous salinity values can be expected.

5. Study of the regional pressure distribution in the aquifers, especially in the Murzuq Basin based on well data. This will help in understanding the migration trends in the two basins.

For the spatial distribution and geochemical analysis of hydrocarbon seeps in Al Qarqaf Arch, the following suggestions might be a subject for detailed study:

1. Detailed seep-oil correlation of samples of the hydrocarbon seeps with the crude oil from different reservoirs in the Murzuq Basin to determine the likely source of the seeps.

2. Additional, more systematic sampling is needed to delineate the total area of seepage more accurately. Alternatively, modern hyperspectral remote sensing (e.g. the ASTER sensor) could be helpful in guiding this laborious task.
SUMMARY

The Ghadamsis and Murzuq Basins in Western Libya have been explored for oil and gas since 1956. In comparison with the large discoveries in the Sirt Basin of central Libya, success was rather limited and in consequence activities were somewhat low key. Much of the area is fairly remote desert, making operations difficult and expensive. Nevertheless, quite a number of wells were drilled by many different companies and some small fields were found in the Ghadamsis Basin. Recently several larger oil fields were discovered in the Atchan Saddle area which forms the SW extension of Al Qarqaf Arch which separates the two basins. This combined with the observation of oil seeps along the southern flank of Al Qarqaf Arch provided the incentive to make a comprehensive study of the petroleum geology of the two basins and the separating arch.

So far the available data was scattered over many company reports pertaining to separate concession areas. Thus a major effort was required to collect relevant information into a practical database. Also remote sensing data from satellite observations was obtained and processed into the right format to provide broad scale information into which the local seismic and well data could be integrated. Of particular importance was the use of analogue models from other hydrocarbon basins overlying or adjacent to arches in order to understand the type and distribution of oil types in Western Libya. The significance of the oil seeps was given much attention because of the indications of the presence of mature source rock and the possible migration routes. Through the integration of these data of different type and origin much light could be thrown on the geological systems and the hydrocarbon migration and trapping history in the two basins.

This study has academic and an economic aspects. The academic aspects include:

(1) literature survey and the analysis of arches worldwide, with special emphasis on Paleozoic arches and their influence on hydrocarbon migration and accumulation in the adjacent sedimentary basins;

(2) the investigation, mapping and analysis of the tectonic basement structures and their surface expressions in the area of Al Qarqaf Arch and the Ghadamsis and Murzuq Basins, using remote sensing, acromagnetic, seismic and well log data; and
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(3) the analysis of the influence of Al Qarqaf Arch on the distribution of facies in particular the depositional history and tectonic evolution of the Silurian and Devonian units, which are the main source and reservoir rocks in area.

The economic value includes:

(1) the analysis of hydrocarbon systems (e.g. play maps) in the Ghadamis and Murzuq Basins in relation to Al Qarqaf Arch;

(2) the mapping and analysis of hydrocarbon seeps along Al Qarqaf Arch, and its significance for hydrocarbon exploration in the area; and

(3) the creation of a digital database containing a wealth of data pertaining to the architecture of the two sedimentary basins and their hydrocarbon occurrences. This information was collected and integrated for the present study. The economical benefit consists of the availability and compatibility of data that was scattered until now. This concerns both the different nature of the data (geology, Remote Sensing, geophysics, well data) as well as the limited scope, mostly not beyond the boundaries of concessions of oil companies, prohibiting the correlation of data over the entire area.

Analysis of arches from different places around the world shows that arches are either surface or buried structures formed by uplift of the basement due to tectonic activity. In many continents, records indicate that arching was the dominant structural style during the Early Paleozoic. The similarity of the geological environment around arches worldwide, from the structural and stratigraphical point of view, enables the establishing of a model for the prediction of hydrocarbon traps likely to be found around arches. The burial depth of arches usually has an influence on the type of traps. The model extracted from the study indicates that traps in buried arches are broad anticlines, pinchouts, lateral porosity changes, unconformities, local fault truncations and reefs. In the case of near surface arches, the traps expected range from structural (simple anticlines, faulted anticlines and faults) to stratigraphical (pinchout, onlap, unconformity erosion and non-deposition) and combinations. Relative to the buried arch type, the hydrocarbon accumulations in areas of near surface arches are smaller in size and reserves. This can be explained as the result of the smaller structures associated with near surface arches, consequently the smaller size of the traps and the increased chance of leaking reservoirs.
Spot XS images, Landsat TM images and Radar ERS-1 images were digitally enhanced and merged, and used for mapping structural and lithological features and lineament analysis of the area. Aeromagnetic data were digitally acquired and enhanced and subsequently used for mapping the structural framework of the area. Seismic sections were used along the western part of the Murzuq Basin for mapping the fault and fold patterns.

Correlation of the structure contour map of the basement with the topography shows that the basement structures are well expressed at the surface. Correlation of the aeromagnetic coverage with a Landsat TM mosaic of the area confirms that many magnetic basement structures are well expressed at the surface, especially in the margins of the basins. Most of the faults in the area are basement faults; these faults extend to the surface in western and eastern parts of the Murzuq Basin.

A comparison of the Ghadamis and Murzuq Basins reveals several important differences in structural and stratigraphical styles, which have a major bearing on the types and distribution of hydrocarbon traps. In some ways, both the Ghadamis and Murzuq Basins could be viewed as part of a single western Libyan structural unit, a N-S oriented super-basin. On the other hand, the study indicates that the two basins are different in structural evolution, which was influenced by the relative positions of the two basins with respect to the Hoggar and Tibisti Massifs and by Al Qarqaf Arch. Al Qarqaf Arch was formed in Late Paleozoic-Early Mesozoic times, during the Hercynian Orogeny, as NE-SW striking uplifts dividing the Pelagian-Ghadamis-Murzuq-Djadu super-basin. The arch has remained as a (discontinuous) positive feature ever since. Due to the location of the Murzuq Basin between the Hoggar Massif in the west and the Tibisti Massif and the Dor El Qussah fault system in the east, the structural style of the Murzuq Basin is more complicated than that of the Ghadamis Basin. The geometry of Al Qarqaf Arch is most likely a combination of small basement highs not completely separating the Ghadamis Basin from the Murzuq Basin; for example, they are partly connected in the area of the Atchan Saddle.

The Murzuq Basin is structurally characterized by NW-SE and NE-SW trending wrench faults, resulting in the formation of flower structures. There are absent or less developed in the Ghadamis Basin. These wrench faults most probably control the hydrocarbon migration and accumulation in the Murzuq Basin to a large extent. The aeromagnetic image of the area confirms this, and is characterized by NW-SE and NE-SW trending magnetic anomalies in the western and eastern margins, respectively. Therefore, these areas could be prospective areas for hydrocarbon exploration. In the
northern part of the Ghadamis Basin, a low magnetic anomaly about 130 km wide and 300 km long was observed. Also this area could be an interesting target for hydrocarbon exploration, especially because some oil fields have been discovered there already.

About 120 well logs distributed over the entire area of study were used for constructing structural, isopach, sand percentage and sand/shale ratio maps of the Cambro-Ordovician, Silurian and Devonian units. They indicate that most of the Silurian and Devonian units are missing over large parts of the Murzuq Basin. This has great influence on the hydrocarbon systems in the Murzuq Basin. Absence of the Early Silurian Tanezzuft shales in the eastern part of the Murzuq Basin (Dor El Qussah subbasin) has negatively affected the hydrocarbon potential in the area. This has led to exploration activities being focused on the central and western parts of the Murzuq Basin. Paleocurrent data on Cambro-Ordovician and Devonian rocks, as well as isopach and sand percentage maps of the Ordovician, Silurian, Devonian and Carboniferous units indicate that the first influence of Al Qarqaf Arch on the sedimentary facies started from the Devonian Tadrart Formation.

From the database of 120 wells, data from 70 producing wells were used to analyze the patterns of hydrocarbons in the area. This includes reservoir characteristics, such as reservoir types, age, traps, thickness, lithology, source rocks, etc.

Al Qarqaf arch is a surface arch, and therefore the before mentioned model is applicable. The oil and gas fields that are discovered so far in the zone adjacent to the arch are predominantly so-called combination traps, where both structural as well as stratigraphical elements play a role in the trapping.

Hydrocarbon occurrence varies across the Ghadamis and Murzuq Basins. The most important reservoirs are the sandstones of the Ouan Kasa, Tadrart and Acacus Formations. This set of reservoirs is overlain by the base of the Aouinat Ouenine Formation and underlain by the top of Tanezzuft shale. In the case of the Murzuq Basin, particularly in the eastern part, the system is different. The trapping system of the hydrocarbon over there is a result of a major strike-slip fault system along 10° E. The trapping system includes flower structures and reverse faults.

Fresh-water flushing is a key factor in the hydrocarbon accumulations in the Murzuq Basin. The high topographical elevation of the Cambro-Ordovician sequence (about 3000 m above sea level) makes the outcrops and rising highlands to the south
around the Hoggar Massif a prime candidate for being a recharge area for the Cambro-Ordovician aquifers in the subsurface (about 1700 m below sea level in the central part of the Murzuq Basin). The hydrocarbon seeps encountered along the southern side of Al Qarqaf Arch confirm the evidence of dysmigration. In this study, the interpretation placed on these observations is that meteoric water has flushed Cambro-Ordovician and Devonian sandstones from the Hoggar Massif toward north/northeast and that Al Qarqaf Arch acted as a barrier to these meteoric waters. The seeps identified along the southern side of Al Qarqaf Arch prove the lateral and vertical migration of oil. On the one hand, this shows the presence of mature source rock in the area; but it also indicates (major) leaks of oil through migration along faults that reach the surface.

Several hydrocarbon seeps located along the southern edge of Al Qarqaf Arch were observed and studied. The presence of the seeps along a well-defined NE-SW trending normal fault, almost parallel to the orientation of Al Qarqaf Arch, reinforces the assumption that the oil has migrated from the northern flank of the Murzuq Basin. Looking at the distance to the nearest oil field in the Murzuq Basin (about 170 km), one can conclude that other fields may exist in the intervening area. The main source of the petroleum seeps is believed to be Silurian Tanezzuft Formation shales. However, the Silurian sediments that are directly beneath the fields of the northern parts of the Murzuq Basin are insufficiently mature and, therefore, they could not supply hydrocarbon to overlying reservoirs. A short-distance migration is thus excluded. Long-distance migration of the Silurian oil most probably occurred. The distance would be at least 150 to 200 km and, consequently, the Silurian oil in the northern Murzuq Basin is allochthonous.

To improve understanding of the surface and subsurface characteristics of Al Qarqaf Arch and adjacent sedimentary basins for the purpose of oil exploration, additional studies are considered useful. For example, detailed gravity and aeromagnetic survey and analysis are strongly recommended in order to verify the described magnetic expressions of deeply buried basement surfaces. More comprehensive analysis of regional seismic data is suggested, as well as correlation over different parts of the basins, to study the types of fault and fold patterns in both basins and the influence of Al Qarqaf Arch. Also study of the structures associated with the strike-slip faults in the Murzuq Basin and detailed analysis, preferably with 3D seismic surveys, are particularly recommended.

Distribution and maturity studies of all possible source rocks are recommended, as well as studies of source rock-cap rock relationships, in particular around Al Qarqaf
Summary

Arch. Investigation of the formation water salinity may give some clues to the nature and age relationships between oil generation and migration, erosional stripping and fresh-water flushing. In some areas, oil may be emplaced after the erosional stripping and fresh-water flushing of the reservoir rocks. In such cases, anomalous salinity values can be expected.

From the spatial distribution and geochemical analysis of hydrocarbon seeps south of Al Qarqaf Arch, the following might be a subject for detailed study: detailed seep-oil correlation of samples of the hydrocarbon seeps with crude oil from different reservoirs in the Murzuq Basin in order to determine the origin and the migration distance. The study suggests that additional, more systematic sampling is needed to delineate the total area of seepage more accurately. Additionally hyperspectral remote sensing (e.g. the new Aster and/or Hyperion sensors) could be successful in guiding this laborious task detecting the total seepage area by remote sensing.
SAMENVATTING
(Summary in Dutch)

De Ghadamis en Murzuq bekens in west Libië zijn het onderwerp geweest van olie en gas exploratie sinds 1956. In vergelijking met de grote voorraden die zijn ontdekt in het Sirte bekken van centraal Libië was het succes nogal beperkt, en daarmee ook de activiteiten. Een groot deel van het gebied is nogal ontoegankelijke woestijn, wat de exploratie activiteiten moeilijk en kostbaar maakt. Desondanks werden toch tamelijk veel boringen verricht door de vele maatschappijen, en enkele kleine velden werden in het Ghadamis bekken gevonden. In de laatste tijd zijn enkele grote olievelden ontdekt in het gebied van de Atchan Saddle, welke de zuidwestelijke voortzetting vormt van Al Qarqaf Arch, een opwelling die de beide bekens scheidt. In combinatie met de waarneming van oliesijpelingen langs de zuidelijke flank van Al Qarqaf Arch geeft dit genoeg aanleiding om een veelomvattende studie te maken van de petroleum geologie van de twee bekens en de tussenliggende opwelling.

Tot dusverre zijn de beschikbare gegevens verspreid geweest in vele bedrijfsrapporten die afzonderlijke concessie gebieden beslaan. Derhalve was een grote inspanning nodig om alle relevante informatie samen te brengen in een praktisch gegevensbestand. Ook satelliet remote sensing data is voor deze studie verkregen. Optimale beeldverwerking heeft bijgedragen aan het grootschalig overzicht, waarin de lokale boorgegevens en seismische secties geïntegreerd konden worden. Het gebruik van analoge modellen, ontwikkeld vanuit andere oliehoudende bekens met of grenzend aan opwellingen, was van groot belang om de types en verdeling van oliehoudende structuren in westelijk Libië te verduidelijken. Aan de betekenis van de oliesijpelingen is veel aandacht besteed vanwege de aanwijzingen voor het voorkomen van rijk oliemoer disteente en mogelijke migratie paden. Door de integratie van deze gegevens van verschillende soort en oorsprong is het mogelijk gebleken om nieuw licht te werpen op de geologische opbouw en de koolwaterstof migratie en accumulatie geschiedenis in de twee bekens.

Deze studie heeft wetenschappelijke en economische aspecten. De academische onderwerpen behelzen:

(1) Een literatuur studie en analyse van tektonische opwellingen over de gehele wereld, met nadruk op Paleozoïsche opwellingen en hun invloed op de migratie en accumulatie van koolwaterstoffen in de aangrenzende sedimentaire bekens;

(2) Het onderzoeken, karteren en analyseren van de tektonische ondergrond structuren en hun expressie aan de oppervlakte in het gebied van Al Qarqaf Arch en de
aangrenzende Ghadamis en Murzuq bekkens, met behulp van remote sensing, aeromagnetische en seismische data en boorgegevens;

(3) Analyse van de invloed van Al Qarqaf Arch op de verspreiding van facies, in het bijzonder de afzettingsgeschiedenis en tektonische ontwikkeling van de Silurische en Devonische formaties, welke de belangrijkste oliemoedergesteenten en reservoir gesteenten in het gebied vormen.

De economische aspecten omvatten:

(1) De analyse van petroleum systemen (bijv. scenario kaarten) in de Ghadamis en Murzuq bekkens in relatie tot Al Qarqaf Arch;

(2) Het karteren en analyseren van olie sijpelingen aan de zuidzijde van Al Qarqaf Arch, en de betekenis hiervan voor olie exploratie in het gebied;

(3) Het aanleggen van een digitaal gegevensbestand van de vele gegevens die betrekking hebben op de architectuur van de twee sedimentaire bekkens en de olie/gas voorkomens, welke in verband met deze studie verzameld en geïntegreerd zijn. Het economische belang hiervan bestaat uit het beschikbaar hebben van veel data die vooralsnog versnipped werd. Dit slaat zowel op de verschillende aard van de data (geologie, remote sensing, geofysica, boorgegevens) alsook op de beperkte reikwijdte, die meestal niet verder uitstreek dan de concessiegrenzen van een exploratie maatschappij, en derhalve veelal niet over het gehele gebied gecorreleerd is.

Een vergelijkende studie van opwelvingen in verschillende delen van de wereld laat zien dat het structuren aan de oppervlakte of bedekte structuren zijn, gevormd door opheffing van de ondergrond als gevolg van tektonische activiteit. De inventarisatie laat zien dat dit in veel continenten de overheersende deformatie stijl was tijdens het Vroeg Paleozoïcum. De overeenkomst van geologische condities in de omgeving van opwelvingen over de gehele wereld, bezien vanuit een structureel en stratigrafisch oogpunt, maakt het mogelijk een model te ontwikkelen dat de voorspelling van olie- en gasvoorkomens kan verbeteren. In het algemeen heeft de diepte van opwelvingen (= de dikte van de bedekking) een invloed op het type van olievoorkomens. Het model dat in deze studie ontwikkeld is laat zien dat oliereservoirs in opwelvingen die bedekt zijn veelal bestaan uit: brede anticlinalen, uitwигgingen, laterale porositeitveranderingen, discordanties, lokale breuk afsnijdingen en riffen. In het geval van opwelvingen die zich aan de oppervlakte bevinden, variëren de verwachte reservoirs van structureel
Summary

(enkelvoudige anticlinalen, doorbroken anticlinalen en breuken) tot stratigrafisch (uitwijingen, onlap, erosieve en non-depositie discordanties) en combinaties daarvan. In vergelijking tot de bedekte opwelvingen, zijn de olie en gasvoorkomens rond opwelvingen aan de oppervlakte kleiner in omvang. Dit kan verklaard worden als gevolg van de kleinere structuren die met opwelvingen aan de oppervlakte gepaard gaan, en de toenemende kans op het lekken van deze reservoirs.


Correlatie van de structurele contourdkaart van het basement met de topografie laat zien dat de basementstructuren duidelijk weerspiegeld zijn aan de oppervlakte. Correlatie van de aeromagnetische bedekking met een Landsat-TM mozaïek van het gebied bevestigd dat vele magnetische structuren in de ondergrond duidelijk waarneembaar zijn aan de oppervlakte, speciaal in de marges van de bekken. De meeste breuken in het gebied zijn basement breuken; deze breuken komen aan de oppervlakte aan de westelijke en oostelijke zijde van het Murzuq bekken.

Een vergelijking van de Ghadamis en Murzuq bekken laat enkele belangrijke verschillen in structurele en stratigrafische stijl zien, welke belangrijke gevolgen hebben voor de types en de verspreiding van potentiële olie/gas velden. In sommige opzichten kunnen de Ghadamis en Murzuq bekken gezien worden als één enkele west-Libische structurele eenheid, een noord-zuid georiënteerd super bekken. Aan de andere kant laat de studie zien dat de twee bekken juist verschillend zijn in hun structurele ontwikkeling, als gevolg van hun relatieve positie ten opzichte van de Hoggar en Tibisti massieven en Al Qarqaf Arch. Al Qarqaf Arch werd gevormd in het Laat-Paleozoïsche/Vroege-Mezozoïsche tijdvak, tijdens de Hercynische orogenese, als NO-ZW georiënteerde opheffingen die het Pelagian-Ghadamis-Murzuq-Djada superbekken verdeelden. Al Qarqaf Arch is sinds die tijd altijd een (discontinue) positief fenomeen geweest. Wegens de locatie van het Murzuq bekken tussen het Hoggar Massief in het westen en het Tibisti Massief en het Dor El Qussah breuksysteem in het oosten is de structurele configuratie van het Murzuq bekken gecompliceerder dan die van het Ghadamis bekken. De geometrie van Al Qarqaf Arch is waarschijnlijk een combinatie van kleinere basement opheffingen die het Ghadamis bekken niet volledig scheiden van het Murzuq bekken; beide bekken zijn bijvoorbeeld gedeeltelijk verbonden in het gebied van het Atchan zadel.
Het Murzuq bekken wordt structureel gekarakteriseerd door NW-ZO en NO-ZW georiënteerde horizontaalverschuivingen, die de vorming van tulppstructuren veroorzaakten. Deze zijn afwezig of eventueel minder goed ontwikkeld in het Ghadamis bekken. Deze transversale breuken beïnvloenden zeer waarschijnlijk de koolwaterstof migratie en accumulatie in het Murzuq bekken in hoge mate. Het aeromagnetische beeld bevestigd dit, en wordt gekenmerkt door NW-ZO en NO-ZW georiënteerde magnetische anomalieën, respectievelijk aan de westelijke en oostelijke zijde van het bekken. Deze delen zouden derhalve prospectieve gebieden voor olie/gas exploratie kunnen zijn. In het noordelijke deel van het Ghadamis bekken is een magnetisch lage anomalie van ongeveer 130 km breed en 300 km lang opgemerkt. Ook dit gebied zou een interessant doel voor olie/gas exploratie kunnen zijn, te meer daar er al enkele velden ter plaatse ontdekt zijn.

Ongeveer 120 boorlocaties verspreid over het gehele studiegebied en enkele regionale dwarsdoorsneden zijn gebruikt om structurele-, isopach-, zand percentage- en zand/schalie ratio kaarten te maken van de Cambro-Ordovicische, Silurische en Devonische formaties. Deze geven aan dat de meeste Silurische en Devonische eenheden ontbreken over grote delen van het Murzuq bekken. Dit heeft belangrijke consequenties voor het voorkomen van koolwaterstof in het Murzuq bekken. De afwezigheid van de Vroeg-Siluur Tanezzauf schalies in het oostelijk deel van het Murzuq bekken (het Dor El Qussah subbekken) heeft een negatieve invloed op het koolwaterstof potentieel in dat gebied. Dit heeft ertoe geleid dat de exploratie activiteit zich geconcentreerd heeft in de centrale en westelijke delen van het Murzuq bekken. Paleo-stroomrichting data van Cambro-Ordovicische en Devonische gesteenten, evenals isopach en zand percentage kaarten van de Ordovicische, Silurische, Devonische en Karbonische formaties, laten zien dat de eerst invloed van Al Qarqaf Arch op de sedimentaire facies begon met de Devonische Tadrart Formatie.

Een gegevensbestand van reservoir karakteristieken, zoals reservoir type, ouderdom, structuur, dikte, lithologie, moedergesteente, etc. is opgezet voor ongeveer 70 olie en gas producerende boorlocaties. Dit is gebruikt om de patronen van olie/gas voorkomens in het gebied te analyseren.

Al Qarqaf Arch is een opwelling die aan de oppervlakte komt en dus is het eerder genoemde model voor dit soort opwelling van toepassing. De tot nu toe ontdekte olie en gas voorkomens in de zones grenzend aan de Arch zijn voornamelijk combinaties, waarbij zowel structurele als stratigrafische elementen een rol spelen bij het gevangen houden van de koolwaterstoffen.
Het voorkomen van koolwaterstoffen varieert echter ook over de Ghadamis en Murzuq bakkens. Het blijkt samen te gaan met transgressieve/regressieve facies patronen en is stratigrafisch en structureel bepaald. De meest belangrijke reservoirs zijn de zandstenen van de Ouan Kasa, Tadrart en Acacus Formaties. Deze serie reservoirs wordt naar boven toe begrenst door de basis van de Aouinet Oueninc Formatie en naar onder door de top van de Tanezzuft schalies, en wordt tevens doorsneden door discordanties. In het geval van het Murzuq bekken, in het bijzonder het oostelijk gedeelte, is het systeem anders. Het olie/gas-vangende systeem aldaar is het gevolg van een belangrijk transversaal breukysystem parallel aan 10° O. Dit systeem bevat tulipstructuren met daaraan gerelateerde opschuivingen.

Zoetwater influx speelt een sleutelrol in de olie en gas voorkomens in het Murzuq bekken. De grote topografische hoogte van de Cambro-Ordoviscische sequentie (ongeveer 3000 m boven zeeniveau) maakt de ontsluitingen en oprijzende hooglanden naar het zuiden rond het Hoggare massief tot een ideaal gebied voor infiltratie voor de Cambro-Ordoviscische aquifers in de ondergrond (tot ongeveer 1700 m beneden zeeniveau in het centrale deel van het Murzuq bekken). De olie sijpelingen aan de zuidzijde van Al Qarqaf Arch zijn het bewijs voor dismigratie. De interpretatie die hier aan deze observaties gegeven wordt is dat meteorisch water de Cambro-Ordoviscische en Devonische zandstenen vanaf het Hoggare massief in noord/noordoostelijke richting doorspoeld heeft, en dat Al Qarqaf Arch als een barrière voor dit meteorisch water gediend heeft. De olie sijpelingen die langs de zuidkant van Al Qarqaf Arch aangetroffen zijn bevestigen de laterale en verticale migratie van olie. Aan de ene kant bevestigt dit de aanwezigheid van rijp oliemoedergesteente in dit gebied, terwijl het aan de andere kant een aanwijzing is voor lekkende reservoirs en het verlies van olie langs breuken naar de oppervlakte.

Verschillende olie sijpelingen die zich langs de zuidelijke rand van Al Qarqaf Arch bevinden zijn waargenomen en bestudeerd. De aanwezigheid van de sijpelingen langs een geprononceerde NO-ZW lopende breuk, bijna parallel aan de oriëntatie van Al Qarqaf Arch, bevestigd de veronderstelling dat de olie afkomstig is uit de noordelijke flank van het Murzuq bekken. Als men de afstand tot het dichtstbijzijnde bekende olieveld in het Murzuq bekken beziet (ongeveer 170 km), kan men concluderen dat er zich waarschijnlijk nog andere onontdekte velden in het tussengelegen gebied bevinden. Als belangrijkste oliemoedergesteente van de olie sijpelingen worden de schalies van de Silurische Tanezzuft Formatie beschouwd. Echter, de Silurische sedimenten die zich direct onder de olievelden van het noordelijke Murzuq bekken bevinden zijn niet rijp genoeg, en kunnen derhalve de olie voor de bovenliggende reservoirs niet gegenereerd hebben. Daarom is migratie over korte afstand uitgesloten, en is lange afstand migratie
van de Silurische olie het meest waarschijnlijk. De afstand bedraagt ten minste 150-200 km, en derhalve is de Silurische olie in het noordelijke Murzuq bekken allochtoon.

Om het begrip van de oppervlakte en ondergrond karakteristieken van Al Qarqaf Arch en de aangrenzende sedimentaire bekkens te vergroten met het oog op olie exploratie, worden additionele studies nuttig geacht. Gedetailleerde aeromagnetische en zwaartekracht onderzoeken worden bijvoorbeeld sterk aanbevolen om de beschreven magnetische expressie van de diepe ondergrond structuur nader te bepalen. Een meer samenhangend onderzoek van regionale seismische data wordt gesuggereerd, evenals correlatie studies over verschillende delen van de bekkens, om de types van breuk en plooi patronen in de bekkens en de invloed van Al Qarqaf Arch te karakteriseren. Ook wordt een studie naar de structuren die samenhangen met de transversale breuken in het Murzuq bekken, met behulp van gedetailleerde analyse, bij voorkeur van 3-D seismiek, sterk aanbevolen.

Studies naar de verspreiding en de rijpheid van alle mogelijke oliemoedergedestenten worden ook aanbevolen, evenals het bepalen van de relatie oliemoedergedestente met afsluitingslagen, in het bijzonder rond Al Qarqaf Arch. Onderzoek naar de saliniteit van de formatiewaters kan enige aanknopingspunten geven betreffende de aard en ouderdomsrelaties van olie generatie en migratie, opheffing en erosie, en zoetwater spoeling. In sommige gebieden zou de olie pas na de opheffing, erosie en zoetwater spoeling van de reservoir gesteenten op haar plaats gekomen kunnen zijn. In deze gevallen zullen anomale saliniteits gehaltes verwacht moeten worden.

Betreffende de ruimtelijke verdeling en geochemische analyse van de olie sijpelingen ten zuiden van Al Qarqaf Arch, zouden de volgende onderwerpen nader bestudeerd kunnen worden: gedetailleerde correlatie van olie monsters uit de sijpelingen met ruwe olie van de verschillende reservoirs in het Murzuq bekken, om de oorsprong en migratieafstand te bepalen. De huidige studie laat zien dat waarschijnlijk een meer systematische monstersname nodig is om het totale gebied waarin oliesijpelingen voorkomen beter te beschrijven. Aanvullend onderzoek met hyperspectrale remote sensing methoden (bijv. met de nieuwe Aster en/of Hyperion sensoren) zou nuttig kunnen zijn om bij deze omvangrijke taak behulpzaam te zijn, namelijk om het totale gebied met olie sijpelingen in kaart te brengen.
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* The name of the first author is spelled different from the title page of this thesis due to variation in transliteration of the Arabic script into Latin script on official documents.


CURRICULUM VITAE

Yahia Ahmed Al Festawi was born in Tripoli, Libya on August 17th, 1959. He completed secondary and high school in Tripoli in 1978. Later in the same year, he started his study in the Department of Geological Engineering, Faculty of Petroleum and Mining Engineering, Al Fateh University, Tripoli, where he obtained his B.Sc. in 1983, with specialization in hydrocarbon exploration. In 1983 he started to work at the Petroleum Research Centre, Tripoli, Libya as exploration researcher in the exploration research department. He did his M.Sc research on application of remote sensing and data integration for hydrocarbon exploration in Sirt Basin, Libya at the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, the Netherlands, and obtained his M.Sc. degree in 1989. In 1991 he started his work with Biruni Remote Sensing Centre, Tripoli, Libya as a technical general Manager. In mid 1996 he started his Ph.D. research at ITC, Enschede, in conjunction with the research school “Centre for Technical Geosciences” of the Faculty of Applied Earth Sciences, Delft University of Technology, the Netherlands.
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Figure 6.04 Field photo of hydrocarbon seep S2
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