CRETACEOUS SOURCE ROCKS - AL-RUB AL-KHALI BASIN, SAUDI ARABIA - A GEOLOGICAL AND GEOCHEMICAL STUDY

By

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ABSTRACT

A total of 108 samples from ten boreholes covering the Cretaceous formations in ALRub ALKhali basin, south-east Saudi Arabia, have been used for organic geochemical analyses. The construction of facies layer maps and thickness maps for each interval of the Cretaceous section in the study area revealed the Cretaceous depositional history. This is combined with a geological modelling of the area to interpret the configuration and the stratigraphic evolution of the basin.

ALRub ALKhali basin was undefined and it remained as part of the Arabian Platform sedimentation pattern up to the Middle Cretaceous. A major change in the depositional system occurred during the deposition of Safaniya Member, Middle to Late Albian time. The area became more differentiated with an intrashelf basin breaking up the shallow carbonate platform in the north-east of the study area. This marked the start of ALRub ALKhali basin development. Another intrashelf basin formed in the east of the study area during the deposition of Mishrif Member, Late Cenomanian to Late Turonian Time.

Regional geochemical sampling indicates the Lower Safaniya and Lower Mishrif to be potential petroleum source rock units. These organic rich intervals are composed mostly of lime mudstones deposited in relatively quiet anoxic waters of regional intraplatform embayments. Both sequences are dominated by oil prone, sapropelic amorphous, and chemical type II organic matter. Maturity assessments indicate these two intervals to be

immature over the study area.

By contrast, the remainder of the sampled Cretaceous units are too poor in organic matter to qualify as potential source rocks in the study area. The chemical type of their dispersed organic matter varies considerably, from mixed type II/III and type III to type IV kerogens, depending on the extent of oxidation of their depositional environments and the distance from the paleoshore line. The terrestrial fraction of their organic matter decreases basinward to a minimal while fine-grained amorphous is abundant.

The study points to a strong relationship between the occurrence of the Lower Safaniya and Lower Mishrif organic facies and the development of intrashelf basins in ALRub ALKhali. From this association, it is possible to establish the geographical extent of this organic facies by simply mapping these regional depressions.

Intrashelf basins of shallow carbonate platforms can be deduced using seismic stratigraphy. Thus, the most likely occurrence of potential source rock intervals can be inferred. This makes it feasible to predict and locate the geographical and stratigraphical distribution of these source intervals in the subsurface of the area under exploration.

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TABLE OF CONTENTS

Page

ABSTRACT 2

ACKNOWLEDGEMENT 4

TABLE OF CONTENTS 5

LIST OF TABLES 11

LIST OF FIGURES 12

LIST OF PLATES 16

ERRATA & CORRIGENDA 16A

CHAPTER ONE

INTRODUCTION 17

1.1 AREA OF STUDY 18

1.2 HISTORY OF HYDROCARBON EXPLORATION IN SAUDI ARABIA 18

1.3 HYDROCARBON OCCURRENCES IN ALRUB ALKHALI 23

1.4 PREVIOUS WORK ON THE GEOLOGY AND HYDROCARBON SOURCE-ROCK INVESTIGATIONS OF ALRUB ALKHALI 24

1.5 THE PRESENT WORK 24

1.5.1 Objectives 25

1.5.2 Sample Collection 26

1.5.3 Sample Identification 28

CHAPTER TWO

GEOLOGICAL REVIEW AND HYDROCARBON HABITAT OF SAUDI ARABIA 29

2.1 INTRODUCTION 30

2.2 GEOLOGICAL SETTING 30

2.3 PLATE TECTONICS 33

2.4 REGIONAL GEOLOGY 37

2.5 STRUCTURE 40

2.6 STRATIGRAPHY 44

CHAPTER THREE

ALRUB ALKHALI BASIN : STRATIGRAPHIC EVOLUTION AND HYDROCARBON SOURCE HABITAT 53

3.1 GENERAL PRINCIPLES 54

3.1.1 Stratigraphic Framework 54

3.1.2 Stratigraphic Nomenclature 56

3.1.3 Hydrocarbon habitat and depositional environment 57

3.2 BASIN EVOLUTION 57

3.2.1 Neocomian (Sulaiy, Yamama, and Buwaib Formations) 57

3.2.2 Barremian (Biyadh Formation) 60

3.2.3 Aptian (Shuaiba Formation) 63

3.2.4 Early Albian (Khafji Member) 66

3.2.5 Middle to Late Albian (Safaniya Member) 66
3.2.6 Early Cenomanian (Mauddud Member) 71
3.2.7 Middle Ceno (Rumaila, Ahmadi, and Wara Members) 75
3.2.8 Late Cenomanian and Turonian (Mishrif Member) 75
3.2.9 Campanian and Maestrichtian (Aruma Formation) 78
3.3 GEOLOGICAL MODELLING OF THE BASIN 85

CHAPTER FOUR

ANALYTICAL TECHNIQUES 88

4.1 INITIAL SAMPLE PREPARATION 90
4.2 MACERATION 90
4.3 DENSITY SEPARATION 92
4.4 TOTAL ORGANIC CARBON DETERMINATION 95
4.4.1 Sample Preparation 95
4.4.2 Instrument Description 95
4.4.3 Operating Procedure and Sample Analysis 100
4.4.4 Presentation of Results 101
4.4.5 Sample Reproduceability 101
4.5 CHN ANALYSIS OF KEROGEN 101
4.5.1 Sample Preparation 101
4.5.2 Instrument Description 103
4.5.3 Operating Procedure and Sample Analysis 103
4.5.4 Presentation of Results 103
4.5.5 Sample Reproduceability 104

5.6 OXYGEN ANALYSIS OF KEROGEN 104
4.6.1 Sample preparation 104
4.6.2 Instrument Description 104
4.6.3 Operating Procedure and Sample Analysis 107
4.6.4 Presentation of Results 109
4.6.5 Sample Reproduceability 110
4.7 PROGRAMMED TEMPERATURE PYROLYSIS OF WHOLE ROCK SAMPLE 110
4.7.1 Principles of the Method 110
4.7.2 Sample Preparation 110
4.7.3 Instrument Description 112
4.7.4 Operating Procedure and Sample Analysis 114
4.7.5 Presentation of Results 115
4.7.6 Sample Reproduceability 117

CHAPTER FIVE

ORGANIC RICHNESS OF THE CRETACEOUS INTERVALS 119

5.1 INTRODUCTION 120
5.2 TOTAL ORGANIC CARBON (TOC) CONTENT OF SAMPLES 121
5.3 FACTORS INFLUENCING ORGANIC RICHNESS OF THE SAFANIYA AND MISHRIF 126
5.3.1 Bottom Water Oxygenation 128

5.3.2 Primary Biologic Productivity 131
5.3.3 Rate of Sediment Accumulation 132
5.3.4 Sediment - particle size 135
5.3.5 Palaeobathymetry (Water Depth) 138
5.3.6 Oceanic Anoxic Events 139

CHAPTER SIX

QUALITY AND MATURITY OF KEROGEN IN THE CRETACEOUS INTERVALS 141

6.1 INTRODUCTION 143
6.2 ELEMENTAL ANALYSES 145
6.2.1 Introduction 145
6.2.2 Results and Interpretation of the Elemental Analyses of the Cretaceous Kerogens 153
6.3 CHARACTERIZATION OF KEROGENS BY DENSITY FRACTIONATION 169
6.3.1 Introduction 169
6.3.2 Density Fractionation of the Cretaceous Kerogens 171
6.4 CHARACTERIZATION OF KEROGENS BY TRANSMITTED LIGHT MICROSCOPY 176
6.4.1 Introduction 176
6.4.2 Assessment of Cretaceous kerogens by Transmitted Light Miscroscopy 186
6.5 PROGRAMMED PYROLYSIS OF WHOLE-ROCK SAMPLES ..219

6.5.1 Introduction 219
6.5.2 Results and Interpretation 222
6.6 RELATIONSHIP BETWEEN ORGANIC RICHNESS, KEROGEN TYPE, LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE CRETACEOUS SECTION 225

CHAPTER SEVEN

INTRASHELF BASINS AND ORGANIC FACIES PREDICTION 232

7.1 INTRODUCTION 233
7.2 ORGANIC FACIES CONCEPT 237
7.3 INTRASHELF BASINS AND ORGANIC FACIES PREDICTION 246

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS 248
8.1 CONCLUSIONS 249
8.2 RECOMMENDATIONS FOR FURTHER STUDY 253

REFERENCES AND BIBLIOGRAPHY 254

LIST OF TABLES

TABLE *TITLE* *PAGE*

4.1 Total organic carbon, sample reproduceability 102

4.2 Carbon determinations, sample reprodueability 105

4.3 Hydrogen determinations, sample reproduceability 106

4.4 Oxygen determinations, sample reproduceability 111

4.5 The standard rock sample reproduceability 118

5.1 Results of the total organic carbon analysis of the rock samples 122

5.2 $CaCO_3$ contents of representative samples form the Safaniya and Mishrif 137

6.1 Percent Carbonizations and atomic H/C ratio for Kerogen Catagenesis stage 152

6.2 Elemental composition and typing of the Cretaceous Kerogen sample 154

6.3 Estimated volume percentage of Kerogen fractions 172

6.4 Transmitted-light microscopic assessment of the Cretaceous Kerogens 187

6.5 Results of programmed temperature pyrolysis of selected whole rock sample 223

LIST OF FIGURES

Figure	*Title*	*Page*
Figure 1.1	Index map showing the study area	19
Figure 1.2	Location of the boreholes used in the study	27
Figure 2.1	Location of major basins and tectonic units in the Arabian Peninsula	32
Figure 2.2	Reconstruction of the continents as at the late Jurassic	34
Figure 2.3	Reconstruction of the continents as at the end of the Cretaceous	36
Figure 2.4	Surface distribution of the six main sedimentary cycles	38
Figure 2.5	Scematic cross-section from the basement to the Arabian Gulf	41
Figure 2.6	Structural sketch map of the Middle East sedimentary basin	42
Figure 2.7	Generalized Cretaceous and Jurassic stratigraphic section	45
Figure 2.8	Schematic regional stratigraphic development of the Mid-Jurassic to Albian	48
Figure 2.9	Habitat parameters and distribution of oil and gas accumulations in the Mid-Jurassic to Albian	49

Figure 3.1 Structure contour map for the top of the Cretaceous of ALRub AlKhali Basin 55

Figure 3.2 Key to layer maps, Figures 3.3 through 3.12 58

Figure 3.3 Neocomian Environments of Deposition 59

Figure 3.3A Isopach map of Biyadh, Buwaib, Yamama & Sulaiy Formations 61

Figure 3.4 Barremain Environments of Deposition 62

Figure 3.5 Middle Aptian Depositional Environments 64

Figure 3.5A Isopach map of Shuaiba Formation 65

Figure 3.6 Early Albian Depositional Environments 67

Figure 3.6A Isopach map of Khafji Member 68

Figure 3.7 Middle to late Albian Depositional Environments 72

Figure 3.7A Isopach Map of Safaniya Member 69

Figure 3.8 Early Cenomanian Depositional Environments 73

Figure 3.8A Isopach map of Mauddud Member 74

Figure 3.9 Middle Cenomanian Depositional Environments 76

Figure 3.9A Isopach map of Rumaila, Ahmadi and Wara Members ..77

Figure 3.10 Late Cenomanian to late Turonian Depositional Environments 80

Figure 3.10A Isopach map of Mishrif Member 79

Figure 3.11 Campanian Depositional Environments 82

Figure 3.11A Isopach map of Aruma Formation 84

Figure 3.12 Maestrichtian Depositional Environments 83

Figure 3.13 Geological modelling of ALRub ALKhali 85A

Figure 4.1 Method used for fractionating acid insoluble organic matter 93

Figure 4.2 Simplified diagram of combustion and analytical system 97

Figure 4.3 Combustion Train 98

Figure 4.4 Detector Flow Diagram 99

Figure 4.5 Combustion Train, Oxygen Analysis.....108

Figure 4.6 Schematic Diagram of Whole-Rock Programmed-Temperature 113

Figure 4.7 A diagramatical illustration of analytical steps and an example of a recorded detector response 116

Figure 5.1 Variations of the organic carbon richness of the Lower Safaniya and Lower Mishrif throughout all the sampled boreholes 127

Figure 5.2 Schematic diagram showing depositional setting in an intrashelf basinal environment 133

Figure 5.3 Sedimentation rates for the Safaniya and Mishrif plotted with their TOC values 136

Figure 6.1 Van Kervelen diagram showing types of kerogen, and principal products generated during thermal evolution 146

Figure 6.2(a) Van Krevelen diagram: Well. 3 156

Figure 6.2(b) Van Krevelen diagram: Well. 4 157

Figure 6.2(c) Van Krevelen diagram: Well. 5 158

Figure 6.2(d) Van Krevelen diagram: Well. 9 159

Figure 6.2(e) Van Krevelen diagram: Well. 10 160

Figure 6.2(f) Van Krevelen diagram: Well. 11 161

Figure 6.2(g) Van Krevelen diagram: Well. 4 162

Figure 6.2(h) Van Krevelen diagram: Well. 12 163

Figure 6.3 Variations of specific gravity of kerogen with maturation 170

Figure 6.4 Comparison of kerogen classification 179

Figure 6.5 Comparison of various maturation indicators based on kerogen analysis 182

Figure 6.6 Colour designation of Ridgway (1912) and Peters et al (1977) 185

Figure 6.7 Lower Safaniya and Lower Mishrif source bed depositional model in AlRub AlKhali 231

Figure 7.1 Isopach map of Mishrif Member, with TOC distribution across the study area 241

Figure 7.2 Isopach map of Safaniya Member, with TOC distribution across the study area 242

Figure 7.3 Distribution and Isopach of a Jurassic source rock section 244

Figure 7.4 Schematic cross-section showing the development of an intrashelf basin in Abu Dhabi 246

LIST OF PLATES

PLATE	*TITLE*	*PAGE*
6.1	Kerogen type III "with terrestrial influence"	193
6.2	Kerogen type III "without terrestrial influence"	197
6.3	Mixed type II/III Kerogen "with terrestrial influence"	201
6.4	Mixed type II/III Kerogen "without terrestrial influence"	205
6.5	Kerogen type IV	209
6.6	Kerogen type II	213
6.7	Maturation assessment using sapropelic amorphous colour	217
6.8	Indicators of open marine environments	227

ERRATA & CORRIGENDA

CHAPTER ONE

In describing sample collection - Sec. 1.5.2 (page 26), it can be added that sample cuttings used in this study were dry and clean from drilling mud contamination.

Sample descriptions were based on the lithological composite logs, the wireline logs, and the study of cuttings aided by binocular microscope.

CHAPTER THREE

It should be stated that, the formation tops used in the construction of the thickness maps used in this chapter were mostly based on ARAMCO's interpretations.

The lithological data used to establish Figure 3.2 which is a legend to the facies maps (Figure 3.3. to 3.12) came from lithological composite logs provided by ARAMCO.

The isopach contour maps were computer generated using CPS PC by Radian Corporation (U.S.A.), in conjunction with autocad.

CHAPTER FOUR

All experimental work was done, on instruments and techniques used and developed by Imperial college, under appropriate instructions and supervision, according to standard techniques. Critical points are:

1. Maceration (p.90):

   A - Weight of rock samples taken were between 5-60 grams (dependent on lithology and TOC - higher weights were taken for low TOC and limestone)

   B - In HCL acid treatment, each sample was stirred hourly and left overnight.

   C - In HF acid treatment, each sample was stirred at intervals of two hours and left overnight. Then a second final portion of HF was added.

   D - Neutrality was determined using litmus paper

2. The TOC and elemental analysis equipment was used according to the manufacturer's instructions under which conditions, the manufacturer claims an accuracy of ± 0.3% absolute of the element concerned, with a 95% confidence level and a precision of 0.2% (C, S, O) or 0.1% (N, H). This combined with reproduceability demonstrated in Tables 4.1, 4.2, 4.3, 4.4 and 4.5 gives a high level of confidence in the validity of the results obtained.

CHAPTER EIGHT

The following can be added to Sec. 8.2 page 253:

1. Differentiation between sapropelic amorphous (hydrogen rich) and fine-grained amorphous (hydrogen poor) has been achieved in this study using combination of density separation, transmitted-light microscopy, and elemental analysis techniques. However, for further study, additional tests such as UV excitation/fluorescence microscopy could be useful in organic matter type determination and maturation assessment.

2. Extract/G.C. determinations of pristane/phytane ratios to further look into the proposed differences between oxydizing and reducing depositional environments could be applied to further studies of the area. The lack of sufficient sample quantity for such analysis (as indicated in p. 26) prevented the application of this technique.

3. In hindsight, because organic petrography is subjective, GC MS techniques for maturity examinations or a molecular level studies to aid source rock correlation studies would have been a good confirmation method.

4. Use of either commercially available equipment or more modern versions rather than conversion used at Imperial College would bave been an improvement because:

   a - speedier and therefore more samples can be processed
   b - more compatable with other data from other laboratories
   c - more information can be obtained (e.g. Rock Eval P_3).

REFERENCES AND BIBLIOGRAPHY

Additional list of references for chapter 7 is added at the end of the references and bibliography list (p. 276).

CHAPTER ONE

INTRODUCTION

1.1 AREA OF STUDY 18

1.2 HISTORY OF HYDROCARBON EXPLORATION IN SAUDI ARABIA 18

1.3 HYDROCARBON OCCURRENCES IN ALRUB ALKHALI 23

1.4 PREVIOUS WORK ON THE GEOLOGY AND HYDROCARBON SOURCE-ROCK INVESTIGATIONS OF ALRUB ALKHALI 24

1.5 THE PRESENT WORK 24

1.5.1 Objectives 25

1.5.2 Sample Collection 26

1.5.3 Sample Identification 28

1.1 *AREA OF STUDY*

ALRub ALKhali basin is the most significant feature in a large geographic province called ALRub ALKhali or The Empty Quarter. This province is situated in the southern part of Saudi Arabia. It is bordered by the Oman Mountains on the east, the Hadramaut Plateau on the south, the Yemen Highlands on the west, and the Arabian Shield on the northwest. The basin is an elongate trench about 800 Km by 300 Km trending north-east and plunging gently into the Arabian Gulf. The majority of ALRub ALKhali is sand dunes of many shapes except for some patches of outcrops in the west and sabkhas in the extreme eastern parts (Powers et al, 1966). It is considered the largest continuous body of sand in the world. The area is classified as an arid region with temperatures during the warmest months generally exceeding 50 degrees centigrade.

This project deals with the Cretaceous sedimentary section of ALRub ALKhali basin in Saudi Arabia. The area of study is shown in Figure 1.1.

1.2 *HISTORY OF HYDROCARBON EXPLORATION IN SAUDI ARABIA*

Almost all the exploration work in Saudi Arabia has been done by Arabian American Oil Company (ARAMCO). Prior to the start of oil search in 1933, references to the geology of the country were scarce. In May 1933, the Saudi Arabian Government granted an oil concession to Standard Oil Co. of California. The first geological field party arrived in September

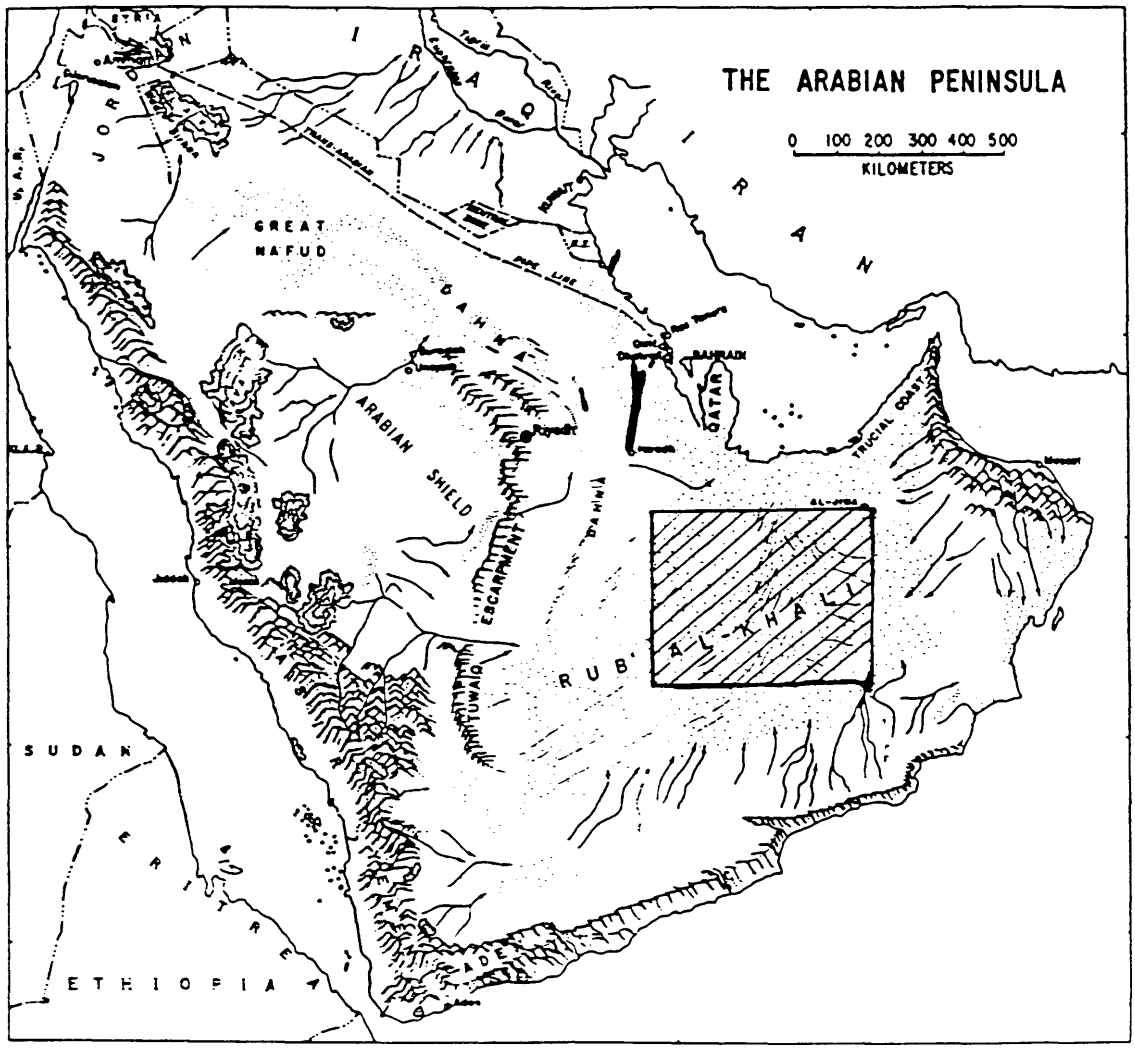


Figure 1.1 Index map showing the study area.

1933 (ARAMCO, 1962). Within a short time Dammam Dome was mapped, on outcrops, and subsequently recommended for drilling.

Dammam Dome, a salt dome, was the first prospect to be tested by deep drilling. Dammam well-1 was spudded in April 1935. Results were disappointing and the well was abandoned after reaching the Middle Cretaceous. Nine more wells were later drilled at Dammam without promising results. Thus, the Middle Cretaceous zones, productive at nearby Bahrain Island, had proved a disappointment in ten wells. Dammam well 7 was the first well programmed to test deeper strata. Drilling of well 7, suspended while the Middle Cretaceous was tested, was resumed in late 1937. This well encountered first gas and then large quantities of oil in the Arab Formation (Late Upper Jurassic). It was completed in the C Member of the Arab Formation in March 1938. From that time onward, exploration, drilling and development have continued without interruption, except for a short period during the war when exploration was at a very low level, but drilling continued.

The exploration methods used have been surface geologic mapping aided by aerial photographs, structure drill core hole profiles, deep stratigraphic drilling, seismic mapping, gravity meter and surface magnetometer surveys.

Most of the sedimentary area has been covered by geologic mapping at 1:1,000,000 scale. Complete coverage has been made by aerial photography at 1:60,000 scale. Under a cooperation project between the

Saudi Government, ARAMCO, and the United States Geological Survey, these data were used to prepare a geologic map of the Arabian Peninsula at 1:2,000,000 scale plus 21 quadrangle maps, both geologic and geographic, at 1:50,000 scale. The maps were published by the U.S.G.S.

By 1977, about 1200 structure core holes have been drilled by ARAMCO. The primary objective was investigation of the structural pattern on a regional scale plus the outlining of areas for wildcat drilling. Six oil fields were discovered by this method. Except for about 20 holes in the southwestern ALRub ALKhali, horizons no deeper than the top of the Aruma Formation (Upper Cretaceous) were used (ARAMCO, 1978).

Stratigraphic drilling has been done on a large scale. The objective of this programme was to investigate the sedimentary section as deeply as possible in widely scattered spots. These wells were not knowingly placed on structural highs as oil-search was not the objective. A total of 38 wells have been drilled, all penetrating the Upper Jurassic with 12 going into the Paleozoic. These wells ranged in depth from 1200 m to over 4300 m.

Seismic surveys were started in 1937 and, except for interruption during the war years, have continued to the present with as many as seven operating at a time. This has resulted in almost complete coverage of the present main producing areas and ALRub ALKhali basin. One of the most successful methods used is the long-range refraction profile using the Hith Anhydrite as the refractor. Owing to the consistent and uniform character of this anhydrite layer over most of the sedimentary area and its position at

the top of the Arab producing zone, it presents the most accurate structural interpretation short of actual drilling. Virtually all the area from the 27th meridian in the northwest down to and including most of ALRub ALKhali has been covered by this method. The offshore area has been covered by a marine seismic survey.

A gravity meter survey has been made covering all the area from the 45th meridian in the northwest to the 20th parallel in ALRub ALKhali. South of this latitude about 50 percent of the area has been covered by reconnaissance profiles. Magnetometer observations were taken at most of the gravity stations (ARAMCO, 1980).

As a result of this thorough exploration coverage, the structural pattern of the area has been well defined and all the major structures have been drilled which has accounted for most of the present reserve. Stratigraphic trap possibilities do exist but the present state of knowledge does not provide means for evaluating such a potential. The Paleozoic section below the Khuff Formation (Upper Permian) offers good possibilities and recent oil discoveries have confirmed that but no data exists on the character of these sediments.

At the end of 1963, ARAMCO had discovered productive oil in eleven widely scattered fields and sixteen different reservoirs. Total estimated remaining proved reserves of crude oil were about 55 billion barrels at the close of 1963 (ARAMCO, 1962).

Today, Saudi Arabia is the world's largest exporter of oil and possesses the biggest reserves, conservatively estimated at 250 billion barrels. Recent discoveries in the Paleozoic near the capital Riyadh, which are still being assessed, may add 20 to 30 billion barrels to those reserves.

1.3 *HYDROCARBON OCCURRENCES IN ALRUB ALKHALI*

Oil exploration work started in this vast area in the 1950's. However, results are disappointing compared to the main hydrocarbon producing areas, north of ALRub ALKhali basin.

To date, only two oil fields have been discovered (ARAMCO, 1980). These are Shaybah and Ramlah, adjacent to the border with AbuDhabi, east of the study area. The estimated original recoverable oil reserves of the Shaybah field which was discovered in 1968 are 1828 million barrels. The reservoir for both fields is in the Shuaiba Formation, Lower Cretaceous.

In addition to the discovery of those two oil fields, Kidan gas field was discovered in the same area in 1967 (ARAMCO, 1980). Gas accumulations were found in the Arab C, D, and Jubaila Formations of the Jurassic. The estimated recoverable gas reserves of this field are 3.3 billion cubic metres.

1.4 *PREVIOUS WORK ON THE GEOLOGY AND HYDROCARBON SOURCE-ROCK INVESTIGATIONS OF ALRUB ALKHALI*

Apart from the unpublished work carried by the Arabian American Oil Company (ARAMCO), references to the geology and hydrocarbon source rocks of the basin in Saudi Arabia are scarce. Virtually all the subsurface geology and in particular the evolution of ALRub ALKhali basin are unknown. Based on unpublished well-reports, Soliman and ALShamlan (1982) attempted a brief review of the geology of the Cretaceous sediments of ALRub ALKhali. Newell and Hennington (1983) provided a discussion on the potential petroleum source rock deposition in the Middle Cretaceous. Apart from these, there has been little published material directly concerning the geology and hydrocarbon source rocks of ALRub ALKhali basin in Saudi Arabia.

1.5 *THE PRESENT WORK*

As an actively explored area, ALRub ALKhali has undergone significant scrutiny in terms of its hydrocarbon potential, however, results are disappointing compared to the adjacent productive area of the Trucial Coast. Hydrocarbon source rock studies might help to understand and explain the situation and provide a better assessment to the problem. In order to achieve this goal, an interpretation of the depositional environments and the basin evolution were necessary for understanding such an evaluation. This work is a combination of geological and geochemical studies.

1.5.1 *OBJECTIVES*

The main objectives of this study are:

1. To study the stratigraphy of ALRub ALKhali basin using the available data in order to interpret the facies and depositional environments of the study area.

2. To establish and study the burial history of the study area in order to understand, as much as possible, the evolution and development of the basin.

3. To identify the stratigraphical and geographical distribution of the Cretaceous source-rock units in the basin.

4. Characterize each unit in terms of organic richness and organic matter type.

5. To investigate the relationships between the organic matter richness of these units and their depositional environments.

6. Establish the degree of thermal maturation of the source units.

7. Estimate, if possible, the timing of hydrocarbon generation and migration.

8. To establish, if possible, oil to source rock correlation.

1.5.2 *SAMPLE COLLECTION*

After studying the lithological composite logs, the wireline logs, and the cuttings, aided by binocular microscope, samples of shales and carbonates were selected from ten boreholes at the interested zones. The location of these boreholes is shown in Figure 1.2. Well H2 is outside the basinal area and has been used in the geological modelling of the basin. Great patience had to be taken in collecting the samples since most of the wells drilled experienced caving in of formations especially while drilling shale sections. Hence the samples are contaminated by cavings of the shale from above while drilling the deeper horizons. Every effort is taken to cover all units of the Cretaceous section in the study area.

Concentrations of sample collection are more closely spaced in shale, argillaceous limestone, and limemudstone sections especially of those which are considered to be possible source rocks.

Sparse collections of samples from the limestone and shale of secondary interests are also made for the source rock evaluation. To provide large enough sample size for analysis, three to four ditch samples covering a 9 to 12 metre interval were grouped together.

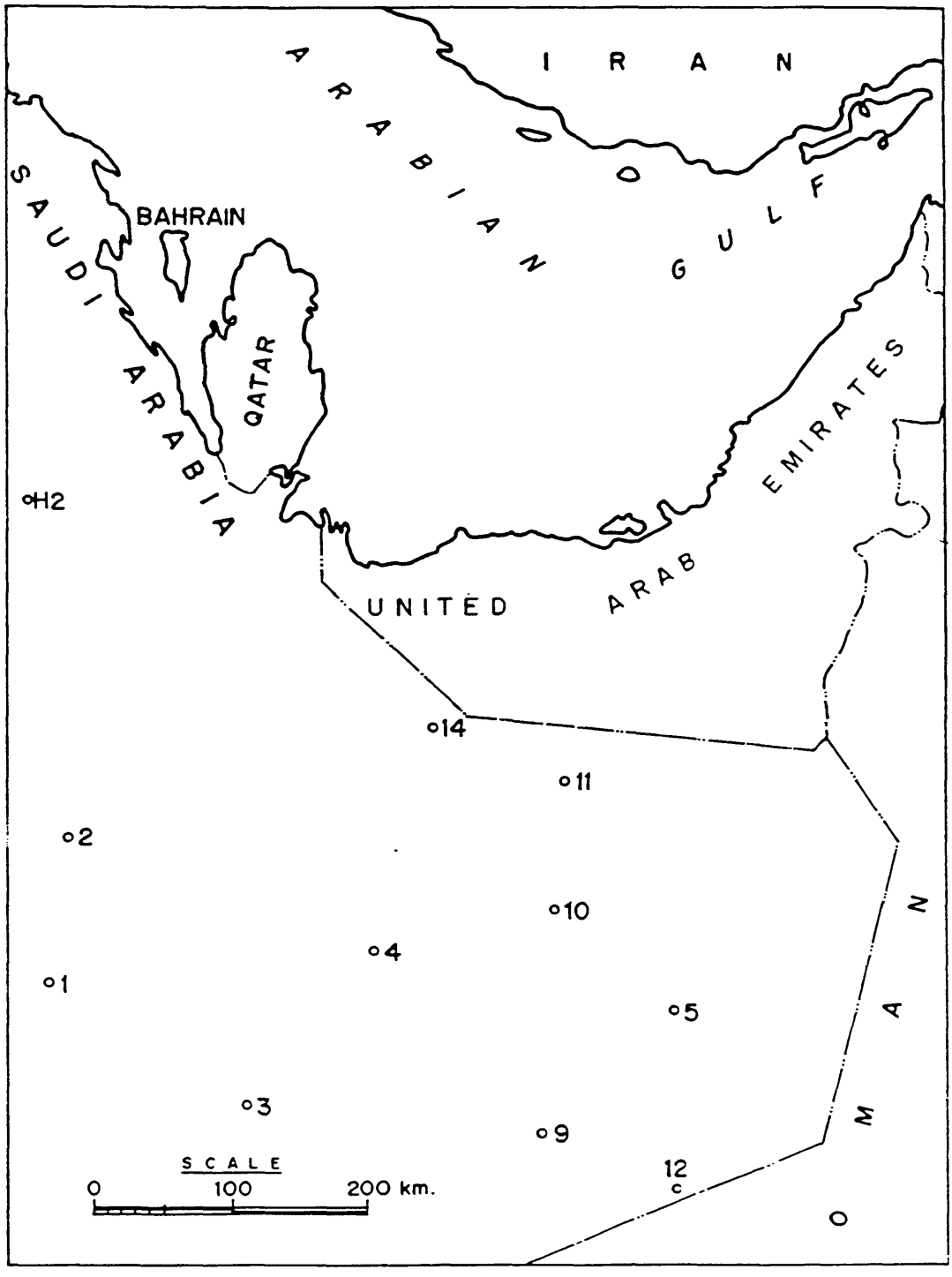


Figure 1.2 Location of the boreholes used in the study.

1.5.3 *SAMPLE IDENTIFICATION*

The location and the formation of a rock sample may be identified from its combined letters and number code. The first group of letters before a stroke indicates the name of sample formation: Ar = Aruma Formation; Mi = Mishrif Member; R-A-W = Rumaila, Ahmadi and Wara Members; Ma= Mauddud Member; Sa = Safaniya Member; Kh = Khafji Member; Sh = Shuaiba Formation; Bi = Biyadh Formation, Bu = Buwaib Formation; Ya = Yamama Formation; Su = Sulaiy Formation. The next number immediately after the stroke indicates the sample location or number of borehole. The number at the end of a sample code indicates the stratigraphic position of the sample in terms of age and for each formation or member, samples are numbered in order of increasing depth/age.

An example of a sample code is Ar/1-2. This implies the second Aruma sample (in order of depth/age) from well number one.

CHAPTER TWO

GEOLOGICAL REVIEW AND HYDROCARBON HABITAT OF SAUDI ARABIA

2.1 INTRODUCTION 30

2.2 GEOLOGICAL SETTING 30

2.3 PLATE TECTONICS 33

2.4 REGIONAL GEOLOGY 37

2.5 STRUCTURE 40

2.6 STRATIGRAPHY 44

2.1 *INTRODUCTION*

The oil deposits in Saudi Arabia can be divided into two large, uniform hydrocarbon areas separated by the Central Arabian arch. This arch is well expressed in the outcrop pattern of Precambrian rocks and its younger sedimentary cover. The structure appears to have originated during the Precambrian and has influenced the geologic history of these two areas at various times during the Phanerozoic (Powers et al, 1966; Glintzboeckel, 1981;Ayres et al, 1982; Garfield, 1985). The area to the north of the arch contains the major part of hydrocarbons discovered to date in the country. All but about two per cent of these hydrocarbon reserves lie on the Interior Platform with the two per cent lying on the lower edge of the Interior Homocline bordering the platform. The area to the south of Central Arabian arch has had a different geologic history from the area to the north. The major part of this area lies in the large ALRub AlKhali geographic province. The most significant feature in this province is ALRub ALKhali basin. Its stratigraphic evolution and hydrocarbon source habitat are discussed in detail in the next chapters of this project. Nearly all major oil discoveries in Saudi Arabia are from Jurassic and Cretaceous rocks. For this reason, only those elements bearing on oil in these rocks will be treated in this chapter in considering Saudi Arabian geology.

2.2 *GEOLOGICAL SETTING*

Saudi Arabia occupies most of the Arabian Peninsula. This peninsula, a southern projection of Asia Minor, is set off from Africa by the Red Sea,

from Iran by the Arabian Gulf and the Gulf of Oman, and is bounded on the south by the Arabian Sea and the Gulf of Aden as shown in Figure 2.1. To the west is the Arabian Shield, a vast complex of largely Precambrian igneous and metamorphic rocks that occupies about one-third of the peninsula. To the east is the Arabian Shelf which has conveniently been subdivided into an almost flat "interior homocline" and an "interior platform".

Bordering the shield is the Interior Homocline. This is a belt of sedimentary rocks that dip towards the basin slightly and uniformly, reflecting the attitude of the basement. The width of the Homocline is about 400 Km. The dip of older rocks of the Homocline average slightly over one degree, while younger rocks have a gentler dip of about half a degree. The Homocline follows the eastern margin of the Arabian Shield from the northwest border to the east of ALRub ALKhali. It is dominated by a series of west facing strike escarpments extending for a distance of 500 to 1400 Km without significant interruption. The older rocks of the Homocline are of Paleozoic age and occur in the west. Successively younger rocks of Mesozoic and early Tertiary ages occur to the east.

East of the Homocline is the Interior Platform. This is a broad area of relatively low relief terrain in which older rocks are buried by Tertiary and younger deposits. On the Platform, systematic dip of the shield area no longer predominates. There are several basinal sags in the Platform which have from time to time received thicker deposits relative to the surrounding areas. These are Sirhan/Turayf, Dibdibba, North Arabian

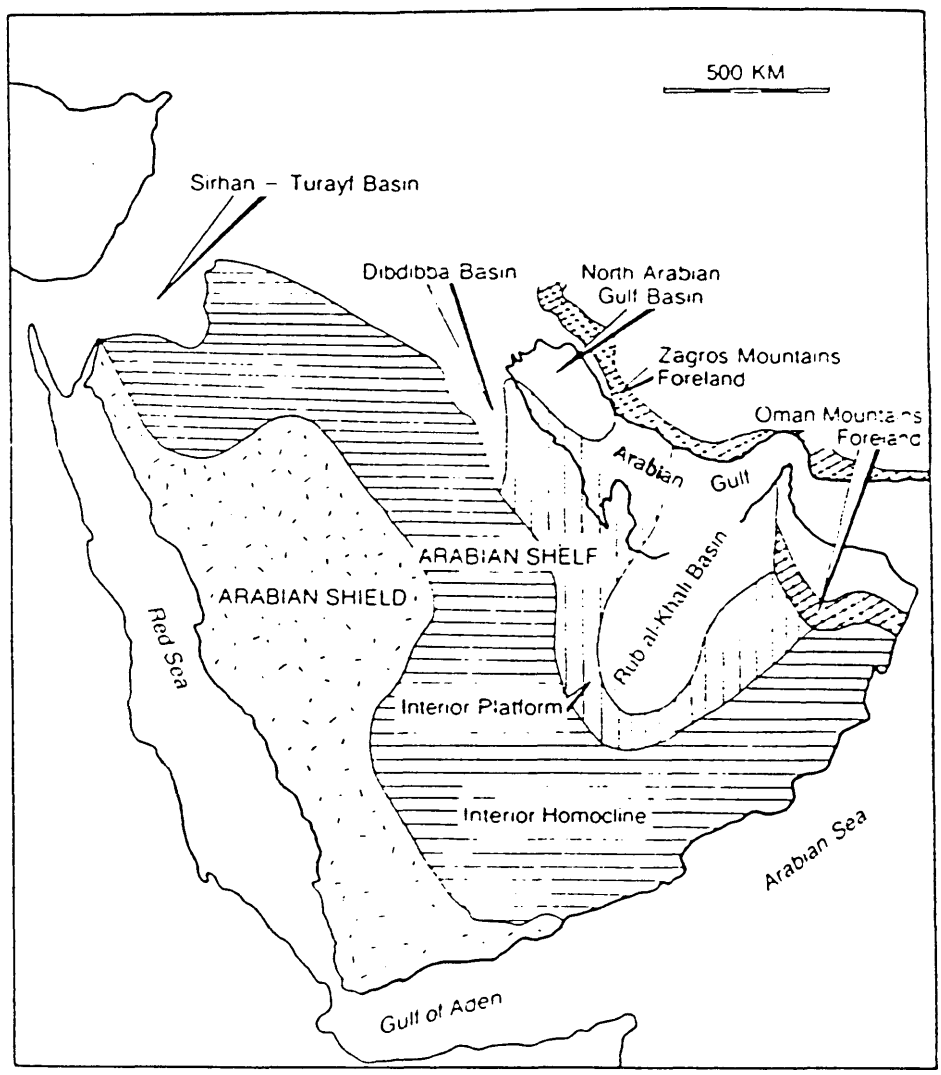


Figure 2.1 Location of major basins and tectonic units in the Arabian Peninsula.
(After Powers et al, 1966)

Gulf and ALRub ALKhali basins.

2.3 *PLATE TECTONICS*

The examination of a geologic province in terms of its plate tectonic evolution can aid in understanding the cause of geologic patterns associated with its oil and gas accumulations. At the beginning of the Cambrian, the areas north and east of Saudi Arabia, i.e., Turkey, Northern Iraq and Southwestern Iran, were covered by the Tethys Sea. Between the Tethys and the Arabian Peninsula, there were great epicontinental seas that spread widely in the eastern parts of the peninsula. In these seas a succession of almost flat lying strata were deposited during the Paleozoic, Mesozoic, and Cenozoic ages.

Figure 2.2 shows the Late Jurassic worldwide distribution of land masses and areas of ocean water. Saudi Arabia at this time was the site of a broad, stable platform at least 1350 Km wide in a northeast to southwest direction. Shallow-water carbonate deposition was the dominant regional sedimentational type until latest Paleocene time. Only limited pulses of clastic and evaporite deposition interrupted this pattern. The relative stability of the broad Jurassic platform is clearly shown by the extensive, near parallelism of bedding planes. This shallow water platform was on the north-east corner of the African Plate, the Saudi Arabian Peninsula still being an integral part of it. The seaway was an arm of Tethys, near the equator, indicating a warm climate domination.

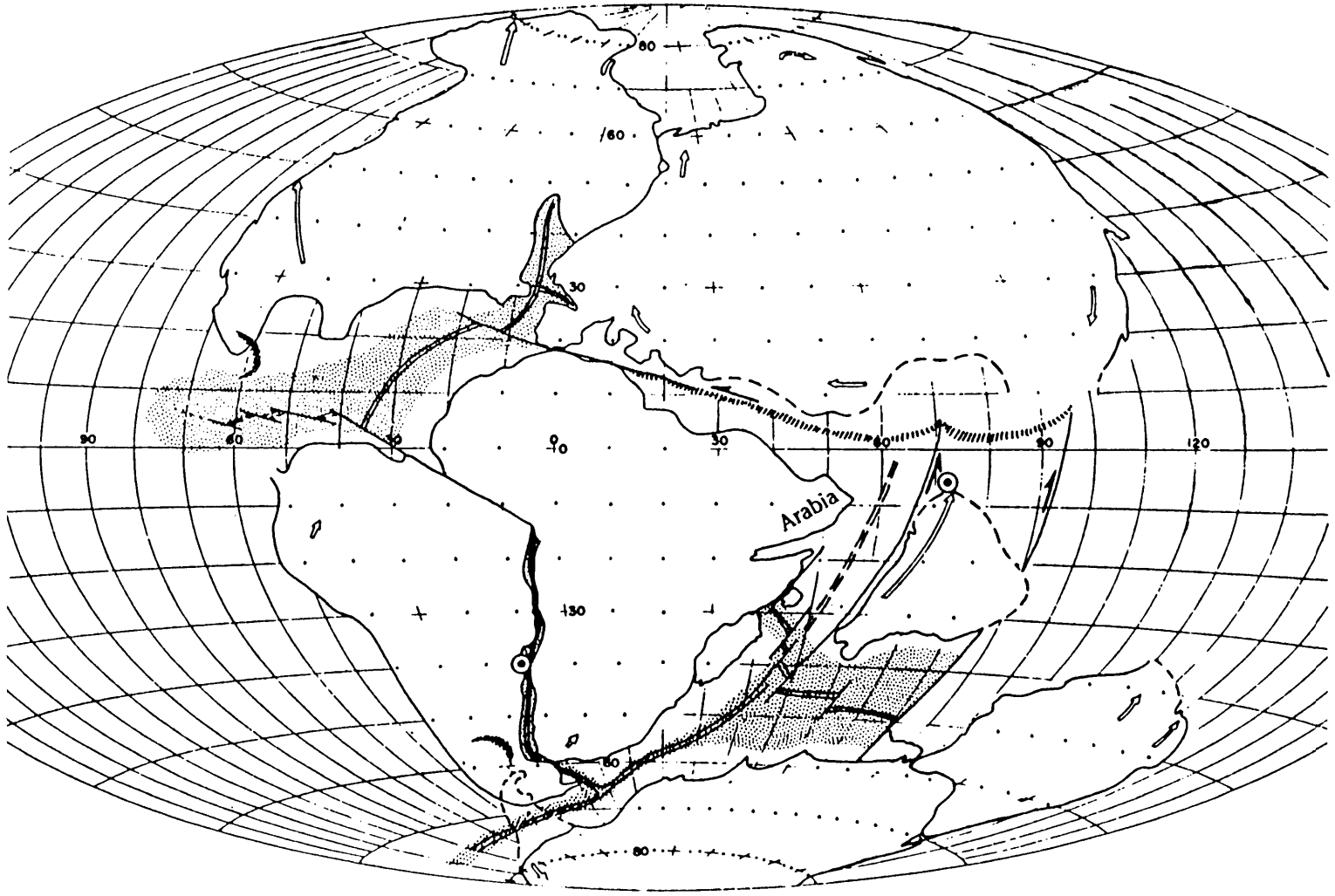


Figure 2.2 Reconstruction of the continents as at the late Jurassic. (After Dietz and Holden, 1970)

Figure 2.3 shows a setting for Saudi Arabia at the end of the Cretaceous. It was very similar to that shown for it in Late Jurassic time (Figure 2.2). This setting reflects continued stability for the northeastern corner of the greater African plate throughout the 70 million years separating these two times. Though Iran was the site of orogenic and magmatic activity, Arabia was protected by its crustal rigidity, suffering only gentle regional tilting and growth (a few degrees or less) over basement-controlled structures, or others believed to have formed over mobile basal Paleozoic salt (Murris, 1984; Husseini and Husseini, 1990). This gentle growth took place in pulses, with a major pulse occurring in the Upper Cretaceous at the base of the Aruma Formation. By then, a gentle tilting toward the northeast was also taking place. A vast area in eastern Saudi Arabia underwent only minor flexing with regional and local dips being only a few degrees or less.

From the Mesozoic to present, Saudi Arabia has changed only slightly. It was modified only gently during the Cenozoic in two ways. First, the west-central part of the country was broadly and gently uplifted in a domal sense, while the eastern part of the country was concurrently depressed. Thus, a 970 Km wide, nearly planar segment of a local craton tilted eastward and flexed slightly in a north to south direction. Resulting regional dips are a degree or less (Brown, 1972). Second, existing structures continued to grow, increasing their flank dips by a few degrees and in some cases, less than a degree.

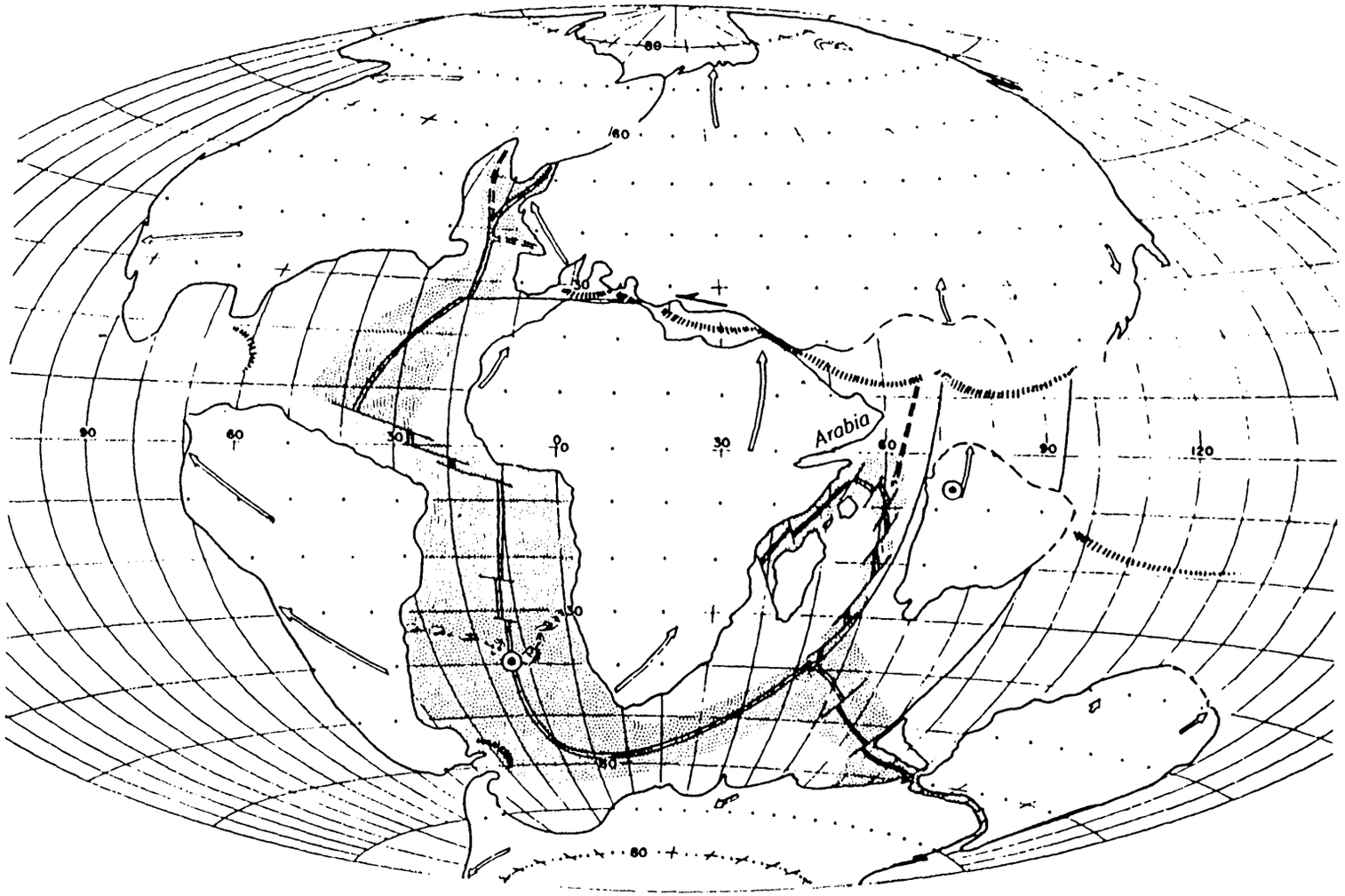


Figure 2.3 Reconstruction of the continents as at the end of the Cretaceous. (After Dietz and Holden, 1970)

It should be pointed out that the area of the large Saudi Arabian oil fields was insulated from any significant structural modifications resulting from dynamic crustal action along the borders of the Arabian plate. It was during the Tertiary that the opening of the Red Sea took place (Garfield, 1985). The Arabian Plate thus moved north-northeast, away from Africa. Its convergence and subduction under the Iranian terrain caused the Arabian Plate to tilt slightly to the northeast and to form the anticlines and thrusts of the Iranian Zagros Mountains on the northeast side of the Arabian Gulf. The central part of the Arabian Craton was rigid and remained essentially unchanged from the start of the Cenozoic.

2.4 *REGIONAL GEOLOGY*

The surface geology of the Arabian Peninsula is shown in Figure 2.4. Four important characteristics of this area can be recognized. The first is the presence of an extensive and broad western shield area of Precambrian rocks, over 1100 Km long, and up to 540 Km wide, with some Cenozoic extrusive volcanics present in its western part. This shield area occupies about one-third of the peninsula.

The second characteristic is the long, simple, and arcuate flanking outcrops to the east of the shield, involving successive bands of Paleozoic, Mesozoic, and then Cenozoic rocks. Up to 5.5 Km of sedimentary rocks are present in this cover rock sequence in the east-central part of Saudi Arabia. Six major sedimentary cycles are recognized in the sequence as shown in Figure 2.4. Each cycle is preceded by a relatively major but very low

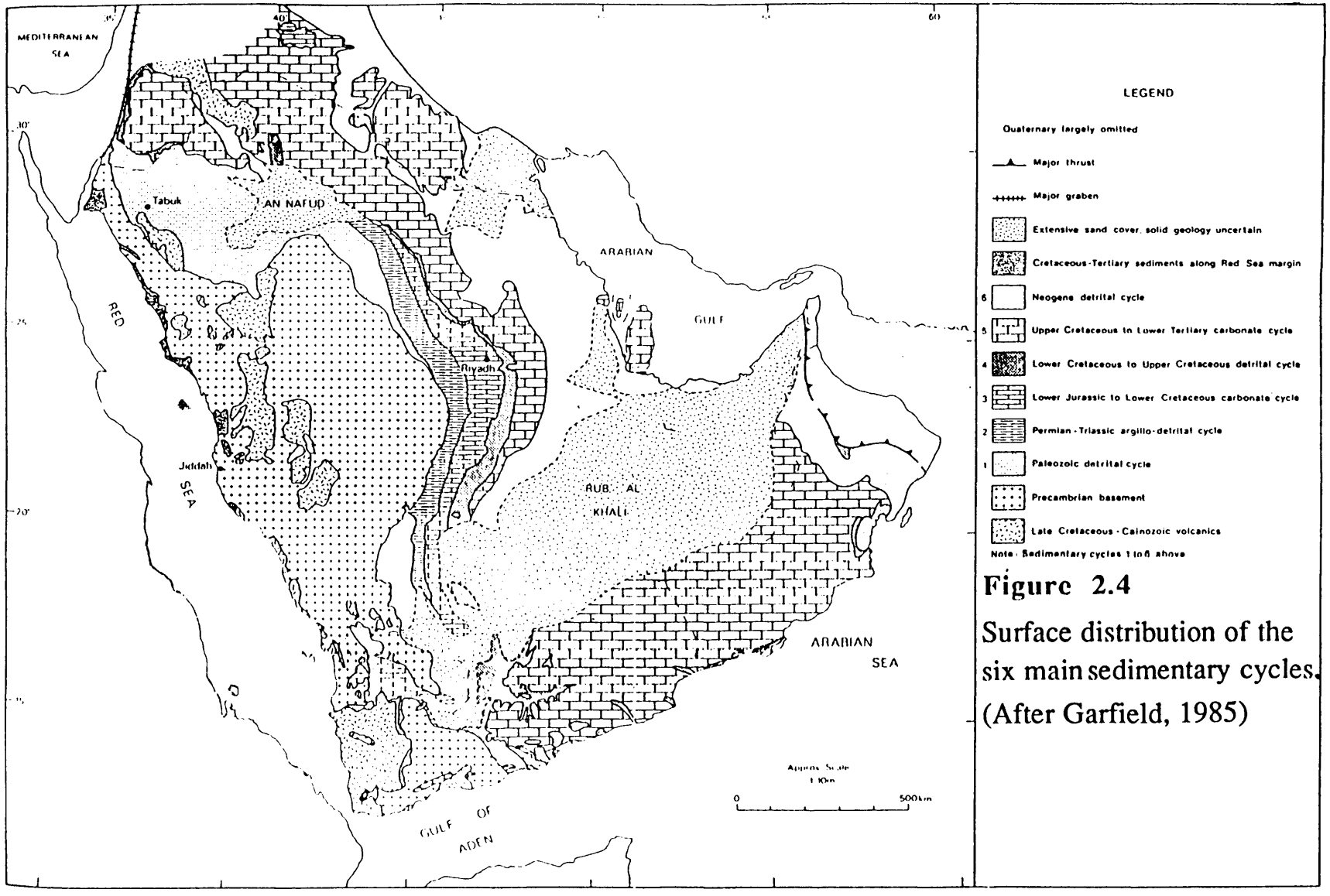


Figure 2.4

Surface distribution of the six main sedimentary cycles. (After Garfield, 1985)

angle unconformity that reflects a major regression. Within each cycle further unconformities, disconformities, regressions and transgressions can be identified (Garfield, 1985). The relative simplicity of this outcrop pattern is the result of the erosion of the gently warped sedimentary rocks of these ages from the higher western portion of a slightly domed cratonic plate. The central belt of north-trending and east-dipping Paleozoic and Mesozoic rocks extends continuously for nearly 1400 Km, and the basal Tertiary strata do so for over 800 Km. These outcrops are generally at elevations of 450 to 900 m above sea level. The majority of the Precambrian terrain is between 900 and 1800 m above sea level.

The third characteristic of the area is the broad extent of Cenozoic sediments and Quaternary surficial deposits (including much drifting sand) that exist for hundreds of kilometers to the east of the Mesozoic outcrops. The vast majority of this young terrain is less than 600 m above sea level. The long, northeast-trending ALRub ALKhali, floored with Quaternary, is the site of sand dunes hundreds of meters high separating level and flat sabkha interdune surfaces.

The fourth characteristic of the area is the rarity of faults cutting the exposed sedimentary rocks. The cover rocks in Saudi Arabia have been affected by few faults, these being a limited throw, apart from the Central Arabian graben and a few other block-faulted areas (see Dixon, 1982). Faulting within the Precambrian affects the exposed sedimentary rocks only rarely.

In total then, the geologic map of Saudi Arabia documents the presence of the simplest surface geology imaginable, with very broad and unbroken extents of low-dipping, unfaulted Cenozoic rocks, underlain in the west by continuous Mesozoic, and rarely faulted. This pattern overlies nearly parallel but varying thicknesses of Paleozoic. It is noteworthy that the bulk of the Saudi Arabian oil fields are concentrated in a relatively limited area. Here, the Mesozoic base does not exhibit only east-homoclinal dip off the exposed shield to the west, but, is characterized by some generally north-plunging domes (Tleel, 1973; ARAMCO, 1975).

2.5 *STRUCTURE*

The true-scale regional structure of eastern Saudi Arabia is difficult to present graphically because of the extent, flatness, and relative thinness of the sedimentary rock prisms. Figure 2.5 shows a schematic cross-section from the basement (Arabian Shield) to the Arabian Gulf. This section best documents the regional stability and rigidity of the continental crust underlying this area in Cenozoic and Mesozoic times and to a more questionable degree in Paleozoic time. Powers et al (1966) were among the first geologists to emphasize this stability. The Interior Homocline dips basinward at about a degree from the younger components. The Interior Platform, bordering the homocline, is a remarkable flat area in which systematic dip off the crystalline core no longer prevails. Several major north-south anticlinal trends rise above the general level of the platform and include the great oil fields of Saudi Arabia (Figure 2.6).

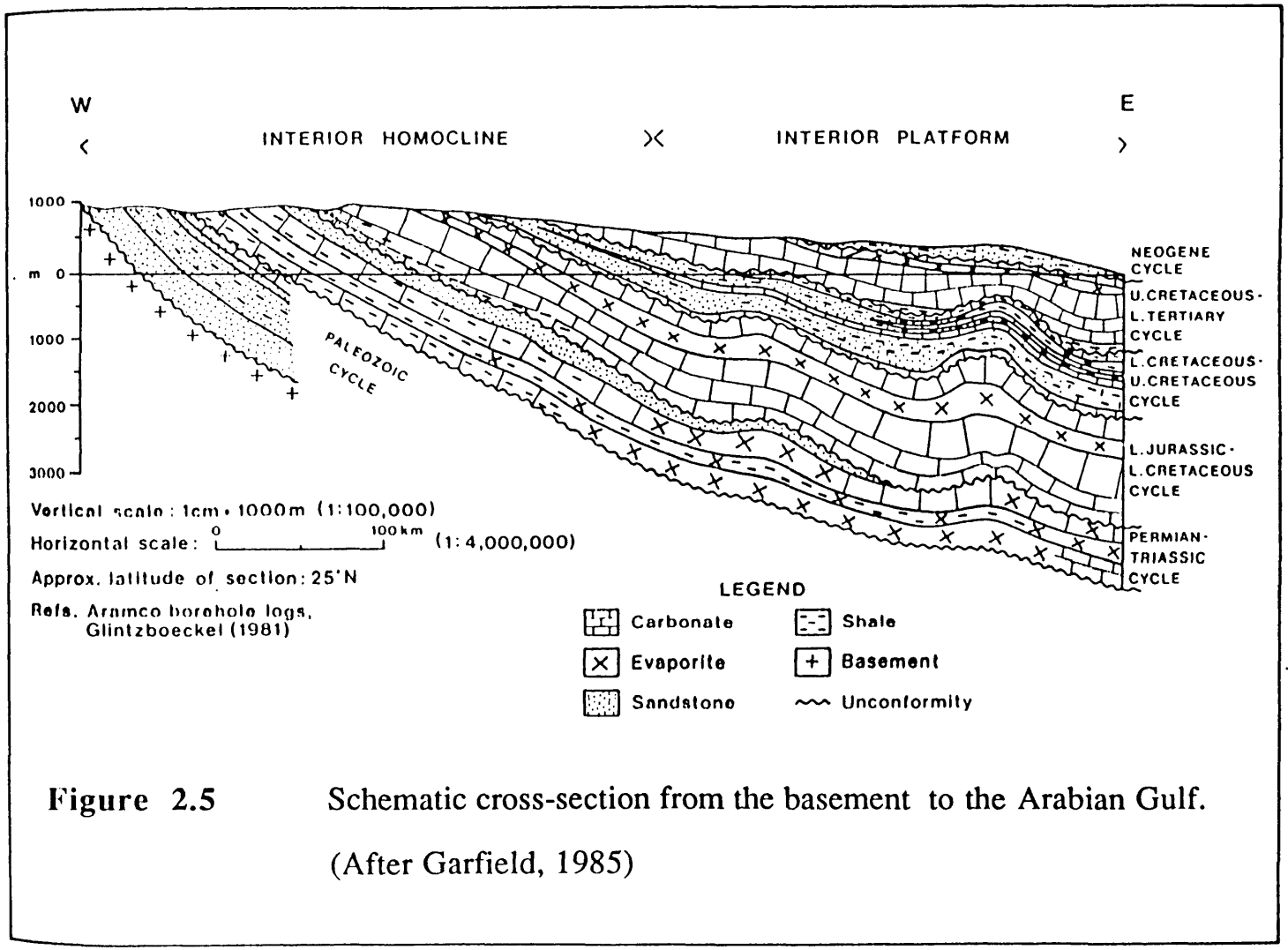


Figure 2.5 Schematic cross-section from the basement to the Arabian Gulf. (After Garfield, 1985)

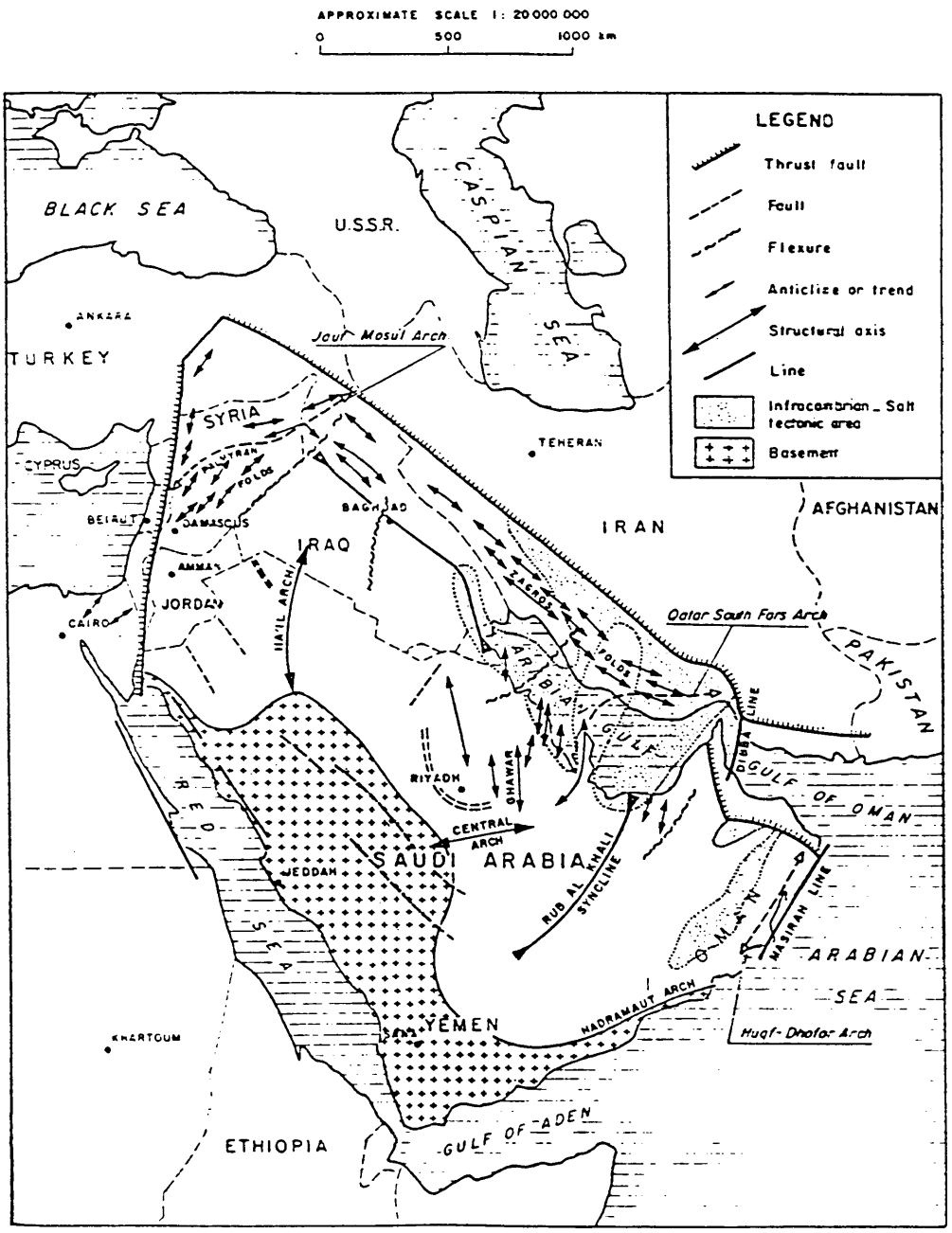


Figure 2.6 Structural sketch map of the Middle East sedimentary basin showing the north-south anticlinal trends of the Arabian Platform. (After Glintzboeckel, 1981)

Maximum local flank dips near the top of the Jurassic are 5 to 10 degrees for Ghawar, which is the largest oil field in Saudi Arabia (ARAMCO, 1959); 4 degrees for Abqaiq, immediately to the north (El-Aguar, 1960); and 2 1/2 degrees for Harmaliya, immediately to the east of Ghawar (Ibrahim et al, 1981). Mesozoic rocks in the area have been flexed only slightly since their time of deposition.

The area southeast of Ghawar oil field received lesser thicknesses of Mesozoic sediments and greater thicknesses of Paleozoic sediments than has the area to the northwest of Ghawar. As the Arabian craton slowly subsided during the Mesozoic, it was very subtlely segmented into blocks involving lesser or greater subsidence. The recognition of local thickening or thinning of stratigraphic units usually requires very careful data gathering and analysis because bounding bedding planes are so parallel.

A published map of Ghawar oil field (ARAMCO, 1959) shows variously steepened local flanks (up to 10 degrees and documents a close similarity in form between a Bouguer gravity anomaly over the Ghawar structure and the form of known subsurface structure near the top of the Jurassic. ARAMCO staff (1959) suggest that this anticline is basement controlled. The hydrocarbon productive structures of eastern Saudi Arabia are primarily anticlines of depression. Total downward movement of strata through time, from an original site of deposition near sea level, far exceeded any short-term uplifts and truncation. During Mesozoic time when the entire area was sinking, sedimentation equalled subsidence. However, anticlinal areas did not sink as far as synclinal areas. Highs

developed over basement in southwesterly fields of Saudi Arabia and over probable mobile salt (Precambrian to Cambrian) in the more northeasterly fields.

Minor faulting does occur in Saudi Arabian fields. In one part of Ghawar there are possible normal faults of small displacement which do not alter the fundamental characteristics of the structure, (ARAMCO, 1959). A published map at Harmaliyah, east of Ghawar, shows faults affecting the Jurassic, with throws up to 55m (Ibrahim et al, 1981). Although minor bending occurred, relatively small crestal and flank faults of small displacement would be expected in the carbonates and sandstones dominating the Mesozoic column. Such faulting probably exists in the Hout oil field, in the Divided Zone offshore (Divided Zone is an area between Saudi Arabia and Kuwait). This field is immediately north of the Saudi Arabian border and involves crestal normal faulting in Middle Cretaceous beds, where faults with up to 180m of throw die out downward within 900m. (Hosoi and Murakami, 1971). Flank dips here are 8 1/2 and 5 1/2 degrees.

2.6 *STRATIGRAPHY*

Figure 2.7 is a generalized Cretaceous and Jurassic stratigraphic section showing lithology, reservoir units, and source rocks found in the area of the Saudi Arabian oil fields. The Mesozoic section varies from zero at its western outcrop edge to an estimated thickness of 4900m or more near the coastline, 520 Km to the east (Brown, 1972). The degree to which the

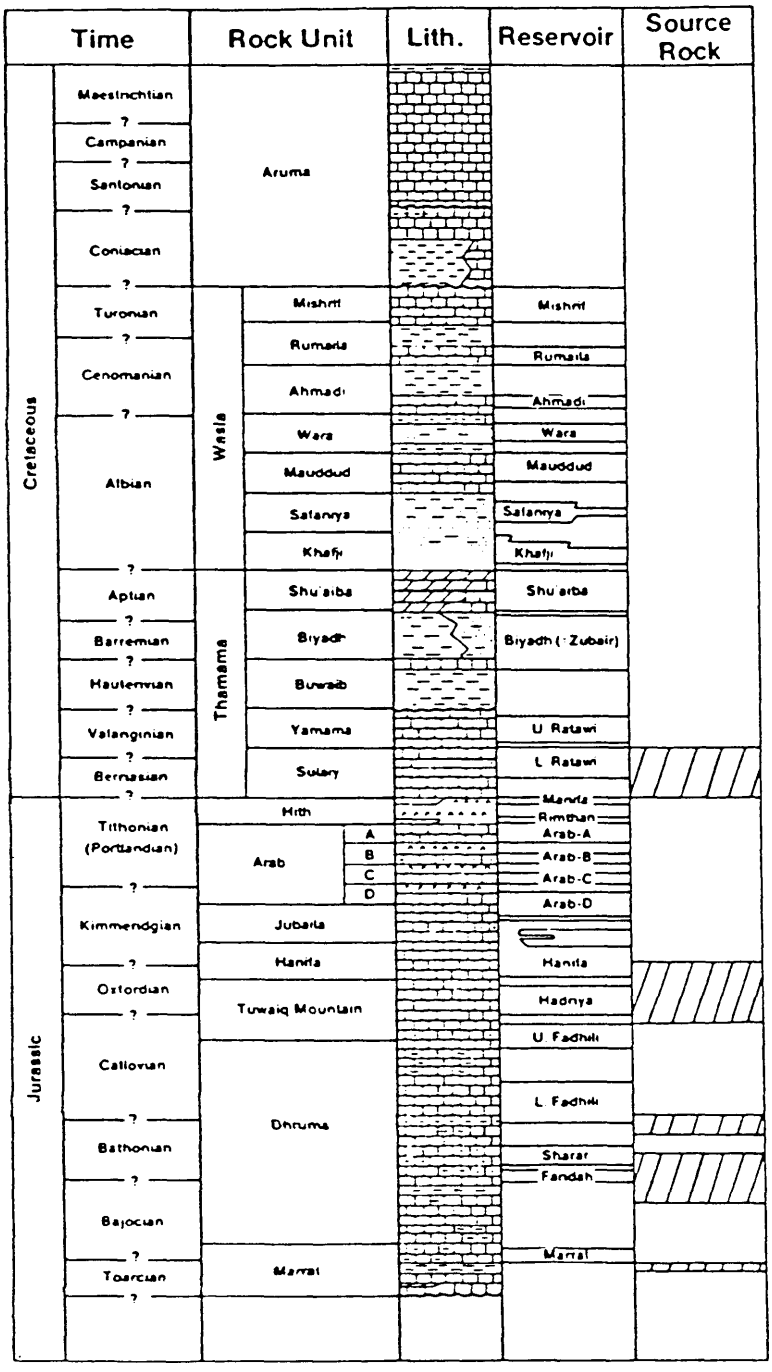


Figure 2.7 Generalized Cretaceous and Jurassic stratigraphic section showing lithology, reservoir units, and source rocks of the main producing areas in Saudi Arabia. (After Ayres et al, 1982)

total sequence may vary in thickness is shown in the cross section on Figure 2.5. As shown by the lithologic symbols in Figure 2.7, the Mesozoic is dominated by carbonate, but it also has a significant sequence of evaporites and some prominent and important sandstones. In this figure are shown the level at which some 24 reservoir zones occur in the various oil fields (Ayers et al, 1982). Dunnington (1967) graphically showed that oil in the northeasterly offshore corner of the main producing area in Saudi Arabia occurs in Cretaceous reservoirs, whereas oil farther south and southwest tends to occur in Jurassic rocks. This information was later confirmed by Halbouty et al (1970) and Ayers et al (1982).

A remarkable aspect of Saudi Arabian Mesozoic stratigraphy is the existence of many geographically widespread porous zones overlain by effective cap rocks. The petrology of these rocks (calcarenites, calcarenitic limestones, dolomites, micrites, and evaporites) which developed over an expansive shelf that existed over thousands of square kilometres has been discussed in detail by many workers (e.g. Steineke et al, 1958; Bramkamp and Powers, 1958; Powers, 1962; Murris, 1984). Capping can occur by micritic limestone, shaly beds, dolomitic beds, and evaporites. The famous Upper Jurassic Hith anhydrites, in a section 150m thick at Ghawar, extends over most of eastern Saudi Arabia. The lowermost Hith anhydrite is the effective cap for many tens of billions of barrels of oil in the Arab-D reservoir throughout the 260 Km long Ghawar anticline, as well as in other fields.

The sandstone shown in the Cretaceous in Figure 2.7 is the main rock body, having lesser lateral extent than most others. This unit pinches out easterly and undergoes a facies change to marine shales and limestones along a generally north to south line about 160 Km east of Ghawar (Glintzboeckel, 1981). It is still sheet-like and widespread enough to form excellent reservoirs in offshore Saudi Arabia.

Eastern Arabian Mesozoic rocks extend over many thousands of square kilometres, with individual stratigraphic units often being correlated for hundreds of kilometres. Murris (1984) has comprehensively described and illustrated this relationship. Of particular value are the two cross sections he published, extending east from the Ghawar oil field for a distance of nearly 720 Km. In these cross-sections (Figure 2.8 and Figure 2.9), he shows the amazing continuity of rock units in the interval Middle-Jurassic to Albian. He documents alternating porous and non-porous rocks, as well as two prominent source rocks.

The late Jurassic transgression which started during the late Callovian is very evident in Figure 2.8. In the east is the inbuilding carbonate margin, separated from the deep open-marine marls and cherty limestones by lithoclinal surfaces. West of the margin is the intrashelf depression, where in late Oxfordian to early Kimmeridgian time euxinic conditions prevailed. The Jurassic source rocks are thinly laminated organically rich intrashelf basinal carbonates (Ayers et al, 1982; Murris, 1984). These are occasionally interbedded with anhydrite - rich layers suggestive of deposition in a warm environment. High salinities in the sediments may

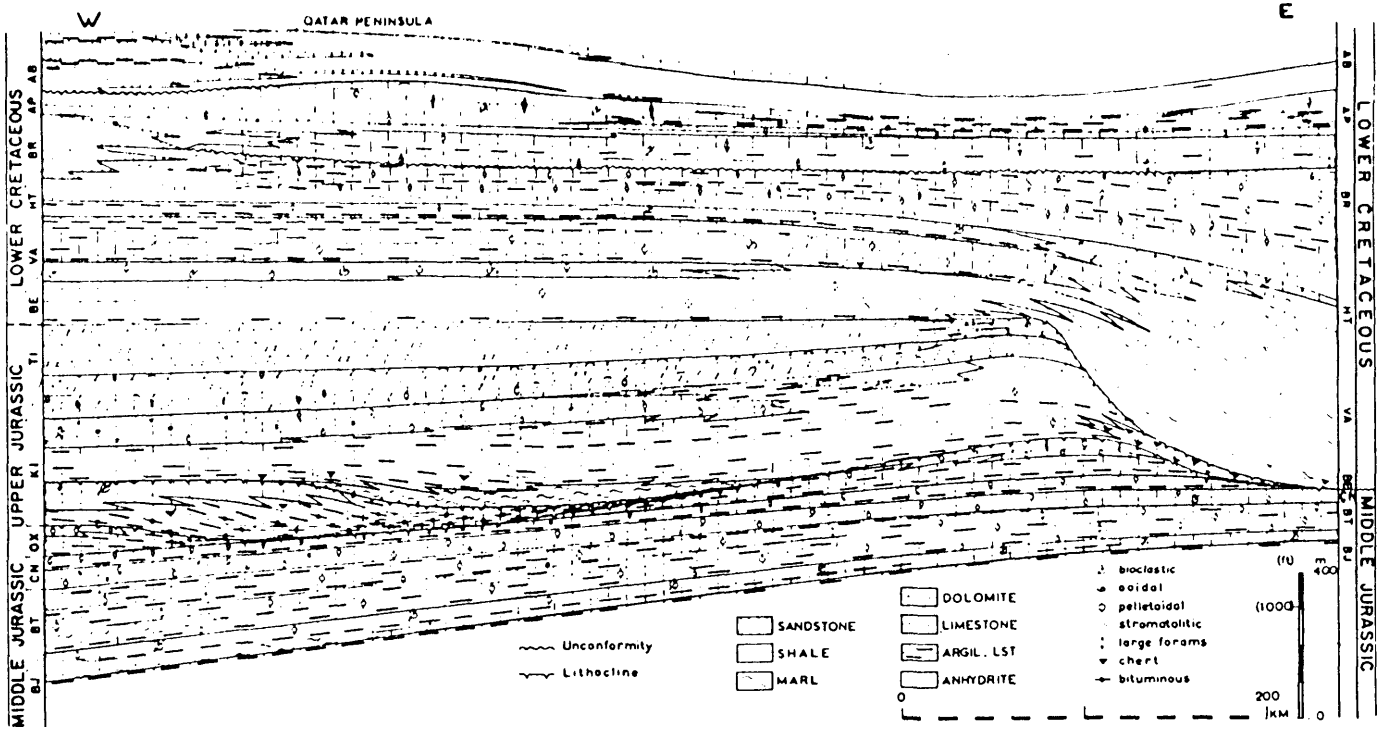


Figure 2.8 Schematic regional stratigraphic development of the Mid-Jurassic to Albian, Central Arabian Gulf area. (After Murris, 1984)

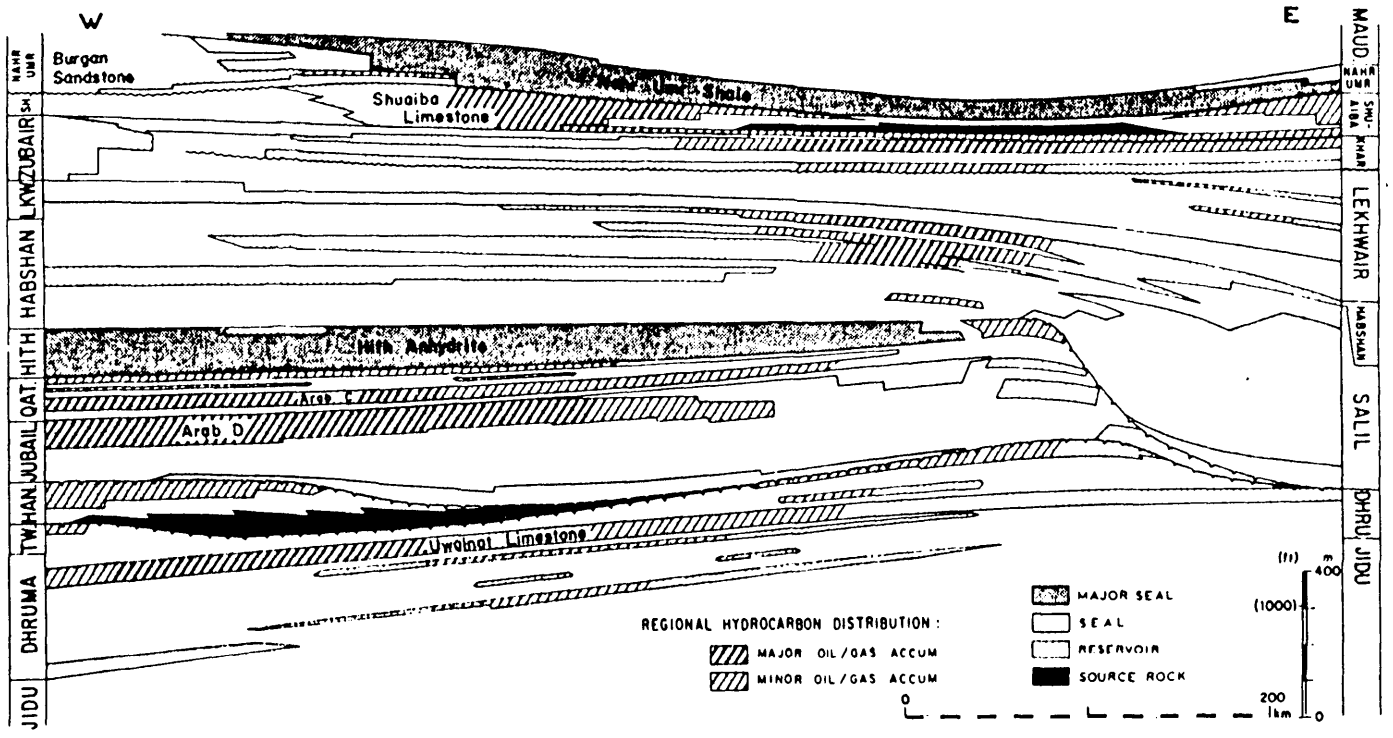


Figure 2.9 Habitat parameters and distribution of oil and gas accumulations in the Mid-Jurassic to Albian, Central Arabian Gulf area. (After Murris, 1984)

indicate stratification of the water column followed by cyclical flux inducing algal blooms and then returning to further stratified columns. The organic-rich Callovian and Oxfordian in the Arabian Platform reach considerable thickness, with more than 100m of source rock in excess of 1% Total Organic Carbon (TOC) recorded in an area of prolific oilfields (Ayres et al, 1982). The Callovian to Oxfordian are regarded as the only Jurassic source rocks capable of generating the vast Saudi Arabian reserves. TOC values average 3-5%, the rocks being so organically rich that they have distinct wireline log characteristics. They show high resistivities and low sonic responses comparable to oil-bearing reservoirs. However, gamma responses are generally high and conventional core analyses indicate that they are quite tight. The log characteristics, cuttings and core data allow correlation of this source facies over long distances and log responses have been used in areas of uniform lithology to estimate and map source richness. A number of basins (the Arabian and Gotnia) have been mapped within the Arabian Platform, with more than 100m of strata where TOC values exceed 1%. However, the differential subsidence rates in the basins was only slightly greater than the surrounding shelf area and the area was probably composed of a series of shallow intrashelf basins. The source facies have characteristics of both deep and shallow water sedimentation. Ammonites, coccoliths, spicules and the fine peloidal character, together with the laminated, and laterally continuous nature of the sediments suggest deep water. However, miliolid and agglutinated foraminifera and accessory anhydrite are indicative of shallower water. The presence of a wide variety of life-forms indicates that bottom conditions were not always toxic. The high salinities probably restricted

the number of species present and assisted with the preservation of the organic matter without developing extreme toxic conditions. Most of the organic matter is amorphous, suggesting algal or simple life-forms which may have formed as a film of algal or fungal material at the sediment-water interface. Ayres et al (1982) indicated that geochemical evidence confirms that the oil comes from an algal and/or bacterial source deposited in a reducing environment.

The Lower Cretaceous also contains source potential, but is not as thick or as rich as the Upper Jurassic. In Saudi Arabia, the Berriasian-Valaginian has adequate organic richness in the northeast of the main producing area, with oil accumulation in reservoirs of this age being confined to this region. The large accumulations of oil in Middle Cretaceous reservoirs in northern Saudi Arabia are geochemically and physically similar to Jurassic oils. The loss of continuity of Jurassic seals along the margins of the Gotnia source rock basin may have allowed vertical migration along salt solution collapse or fold-related fractures along the edge of the basin. Another possible source for oil is the Albian or northern and eastern Saudi Arabia, where an intrashelf basin developed (Ayres et al, 1982).

In summary, two major levels of Mesozoic production occur throughout the Arabian Platform. The most prolific is the Upper Jurassic, with the Cretaceous being important but less prolific. In both types there is a fortuitous juxtaposition of source, reservoir, and seal. The facies are laterally extensive and the structures are broad and simple. Source beds for the oil are the Upper Jurassic and Lower Cretaceous intrashelf basinal

carbonates. These are interbedded with and overlain by porous reservoirs, generally limestone, and are capped by the Hith Anhydrite in the Jurassic and the Nahr Umr Shales in the Cretaceous. In general, the Lower Cretaceous overlying the Hith Anhydrite is devoid of hydrocarbons. However, at the edge of the evaporites and occasionally where these are breached by faulting, leakage from the Arab A-D reservoirs allowed charging of overlying Cretaceous reservoirs. In general, however, loss of seal efficiency through faulting is minimal, due to the broad unfaulted nature of the structures.

CHAPTER THREE

ALRUB ALKHALI BASIN : STRATIGRAPHIC EVOLUTION AND HYDROCARBON SOURCE HABITAT

3.1 GENERAL PRINCIPLES 54

3.1.1 Stratigraphic Framework 54

3.1.2 Stratigraphic Nomenclature 56

3.1.3 Hydrocarbon Habitat and Depositional Environment 57

3.2 BASIN EVOLUTION 57

3.2.1 Neocomian (Sulaiy, Yamama, and Buwaib Formations) 57

3.2.2 Barremian (Biyadh Formation) 60

3.2.3 Aptian (Shuaiba Formation) 63

3.2.4 Early Albian (Khafji Member) 66

3.2.5 Middle to Late Albian (Safaniya Member) 66

3.2.6 Early Cenomanian (Mauddud Member) 71

3.2.7 Middle Cenomanian (Rumaila, Ahmadi, and Wara Members) 75

3.2.8 Late Cenomanian and Turonian (Mishrif Member) 75

3.2.9 Campanian and Maestrichtian (Aruma Formation) 78

3.3 GEOLOGICAL MODELLING OF THE BASIN 85

3. 1. *GENERAL PRINCIPLES*

3.1.1. **Stratigraphic Framework**

ALRub ALKhali area was part of the Arabian Platform sedimentation pattern up to Middle Cretaceous. The depositional history is dominated by carbonate sedimentation on a broad, stable platform flanked on the east by the open Tethys ocean. To the west, the carbonates were replaced by clastics.The source for the clastics was the uplifted highlands of the Arabo-African continent.

A major change in the depositional system occurred in ALRub ALKhali area during Middle to Late Albian (deposition of Safaniya Member). The area became more differentiated, with an intrashelf basin breaking up the shallow carbonate platform in the norh-east of the study area. This marked the start of ALRub ALKhali basin evolution during which the basin geometry changed throughout the Middle Cretaceous. Another intrashelf basin formed in the east of the study area during the Late Cenomanian to Late Turonian.

Near the end of the Turonian a major change in the depositional system occurred related to the Alpine orogeny affecting the Tethyan realm. A shale-filled foredeep was formed along the rising orogeny, east and north-east of the study area (Oman Mountain complex). Stable conditions returned, with the carbonate realm covering the study area (Maestrichtian) at the end of the Cretaceous. Figure 3.1 is a structure contour map for the

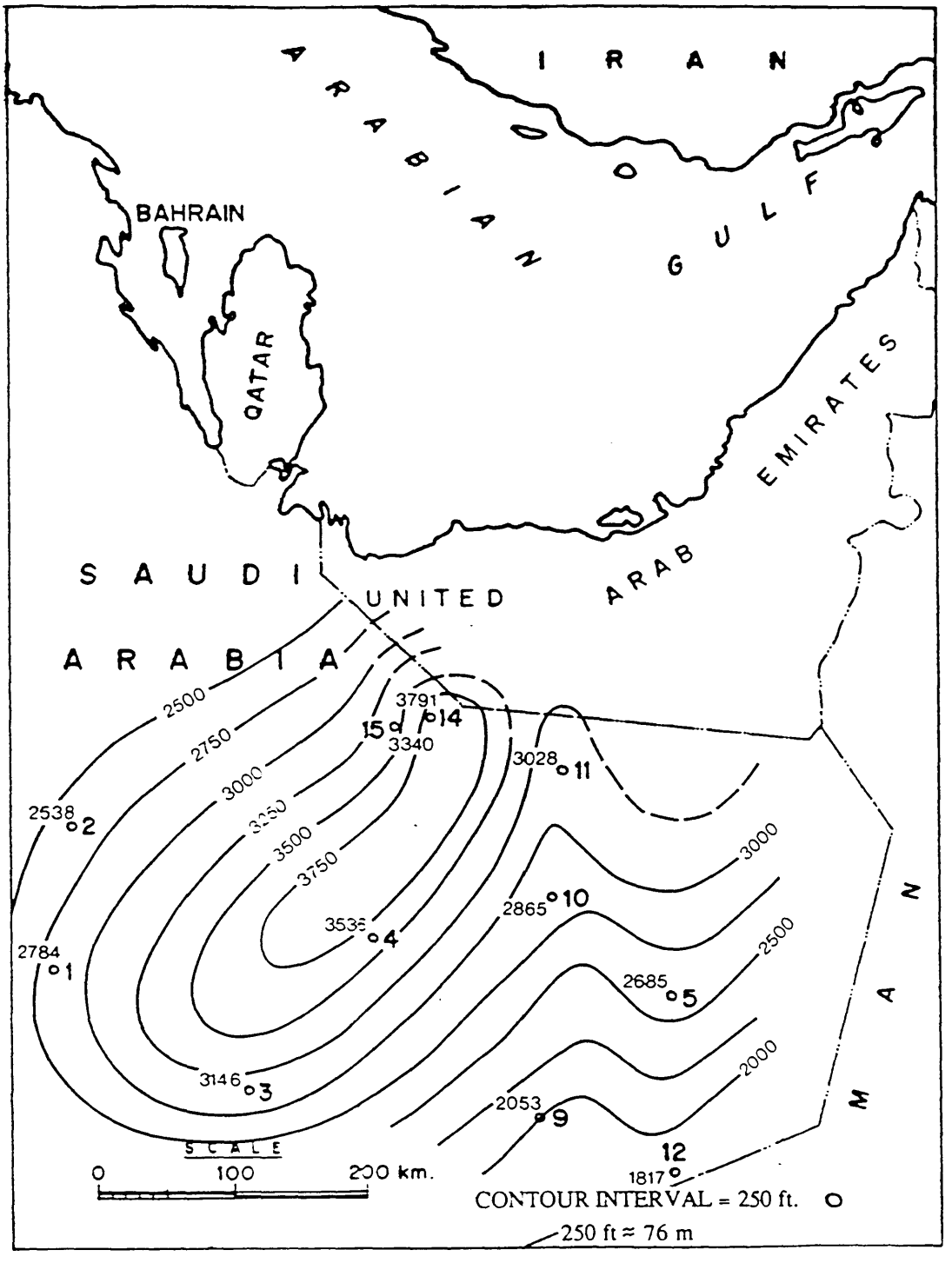


Figure 3.1 Structure contour map for the top of the Cretaceous of ALRub AlKhali Basin.

top of the Cretaceous.

3.1.2. **Stratigraphic Nomenclature**

It should be noted that in the Middle East, three and not two major sub-divisions of the Cretaceous are recognised : the Lower (Berriasian to Aptian) ; the Middle (Albian to Turonian) ; and the Upper (Coniacian to Maestsrichtian).

Intensive subsurface investigations by many oil companies in the area led to inconsistency in the usage of the various lithostratigraphic terms as well as in the placement of stratigraphic boundaries. The late recognition of facies transitions has also led to conflicting terminologies. In some cases, a unit may have formational status in one terminology and member status in another (example, Mishrif Formation in U.A.E. and Mishrif Member in S.A.). In other cases, formational names are used for rock units with different lithologies (example, Biyadh and Wasia Formations).

In this study, member and formation names used are based on an informal ARAMCO stratigraphic nomenclature system used for the Cretaceous section of ALRub ALKhali basin. In this system the members and formations are used more in time-stratigraphic sense than the customary lithostratigraphic sense due to the absence of a defined regional stratigraphic framework in ALRub ALKhali basin.

3.1.3. **Hydrocarbon Habitat and Depositional Environment**

The regional distribution of hydrocarbon habitat-controlling parameters, such as source rock, reservoir, and seal is directly affected by the interplay of changes in sea level, climatic variations, epeirogenetic crustal movements, and synsedimentary structural growth or subsidence. These factors controlled to a large extent the depositional patterns on the shallow carbonate shelf area which characterize ALRub ALKhali area.

In this study, an attempt is made to adapt a model for potential source rock identification based on a work developed by Murris (1984) for source rock-reservoir rock association in the central part of the main Middle East basin. The Cretaceous depositional history of the study area is revealed by constructing interval facies layer maps and interval thickness maps for each interval of the Cretaceous section in the study area. Figure 3.2 serves as a legend to the layer maps of Figures 3.3 through 3.12. It lists the depositional environments present in ALRub ALKhali basin with the lithologies typical of the various environments. Also indicated is the possible translation of these lithologic units into potential hydrocarbon source habitats.

3.2. *BASIN EVOLUTION*

3.2.1 **Neocomian (Sulaiy, Yamama, and Buwaib Formations)**

Sedimentation in the study area was continuous between the Jurassic and the Cretaceous (Glintzboeckel, 1981 ; Harris *et al.*, 1984). Figure 3.3 shows

Depositional Environment		Lithology		Hydrocarbon Source
		Main	Other	
Humid Climate: Alluival - U. Coastal Plain		Sandstone	Silt/Claystone Lignite	G
Lower Coastal Plain		Sandstone Siltst./Claystone	Lignite Carbonate	G
Clastic	Shallow Shelf	Shale	Silt/Sandstone Limestone	
Mixed	Shallow Shelf	Shale/Marl Limestone	Silt/Limestone	
Carbonate	Shallow Shelf	Limestone	Shale/Marl Dolomitic L.S.	
Clastic	Intrashelf Basin	Shale/Marl	Siltstone Bituminous Sh.	(X)
Mixed	Intrashelf Basin	Shale/Marl Arg.Limestone	Bituminous L.S. Siltsone	X
Carbonate	Intrashelf Basin	Arg.Limestone Bituminous L.S.	Marl/Shale	((X))

G = gas source only

X = well developed source

((X)) = high quality source

(X) = doubtful source

Figure 3.2 Key to layer maps, Figures 3.3 through 3.12 (Adapted from Murris, 1984)

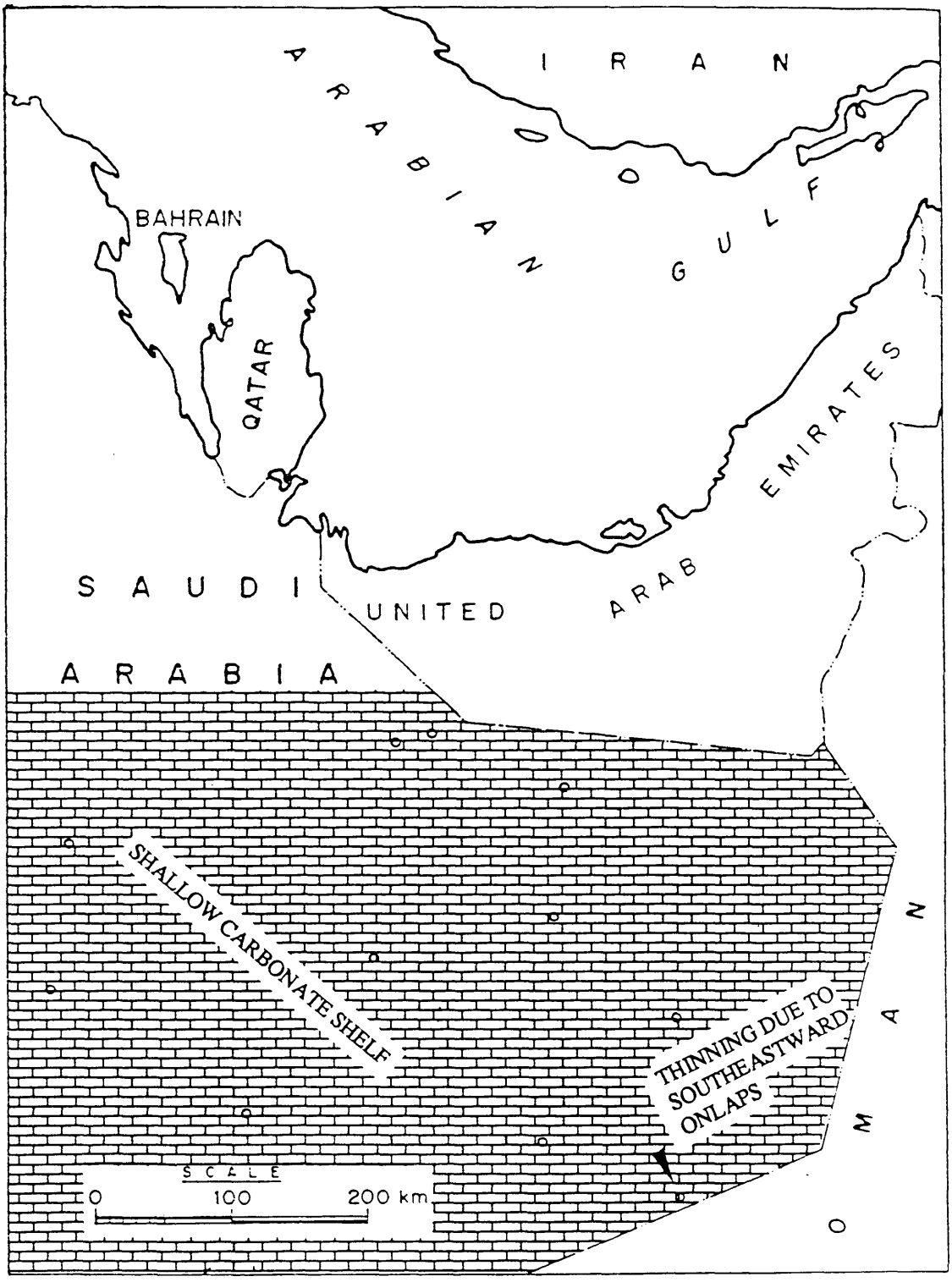


Figure 3.3 Neocomian Environments of Deposition

(Sulaiy, Yamama, and Buwaib Formations)

the depositional pattern during the Neocomian. A wide shallow carbonate shelf (mainly limestone) resulting from marine transgressions dominated ALRub ALKhali in early Cretaceous (Soliman and Al Shamlan, 1982 ; Harris *et al.*, 1984).

ALRub ALKhali area was uplifted and suffered erosion at the end of the Valanginian, followed by a widespread transgression and deposition of the Buwaib Formation (Hauterivian). The unconformity is between two carbonate units (Alsharhan and Naim, 1986).

The Neocomian and Barremian regional isopach pattern in ALRub ALKhali basin shows similar patterns to the late Jurassic (Figure 3.3A). The section thins southeastward due to a basement high observed in the area of well 12 (Gorin et al, 1982). There is a regular increase in thickness (widely spaced contours) northwards.

3.2.2 **Barremian (Biyadh Formation)**

It appears that the sea-level dropped during Barremian time and the study area was affected by a marine regression dominating the Arabian Platform (Murris, 1984 ; Alsharhan and Naim, 1986). Figure 3.4 depicts the depositional environments in ALRub ALKhali during that time (deposition of Biyadh Formation). A clastic regime occupied the western part of the study area (well 1 and 2) with sandstone as the dominant lithology, and pushed the carbonate realm in front of it towards the east. The shallow shelf carbonates (mainly limestone) occupied the rest of the study area, whereas the margin with the open Tethys was probably located further to

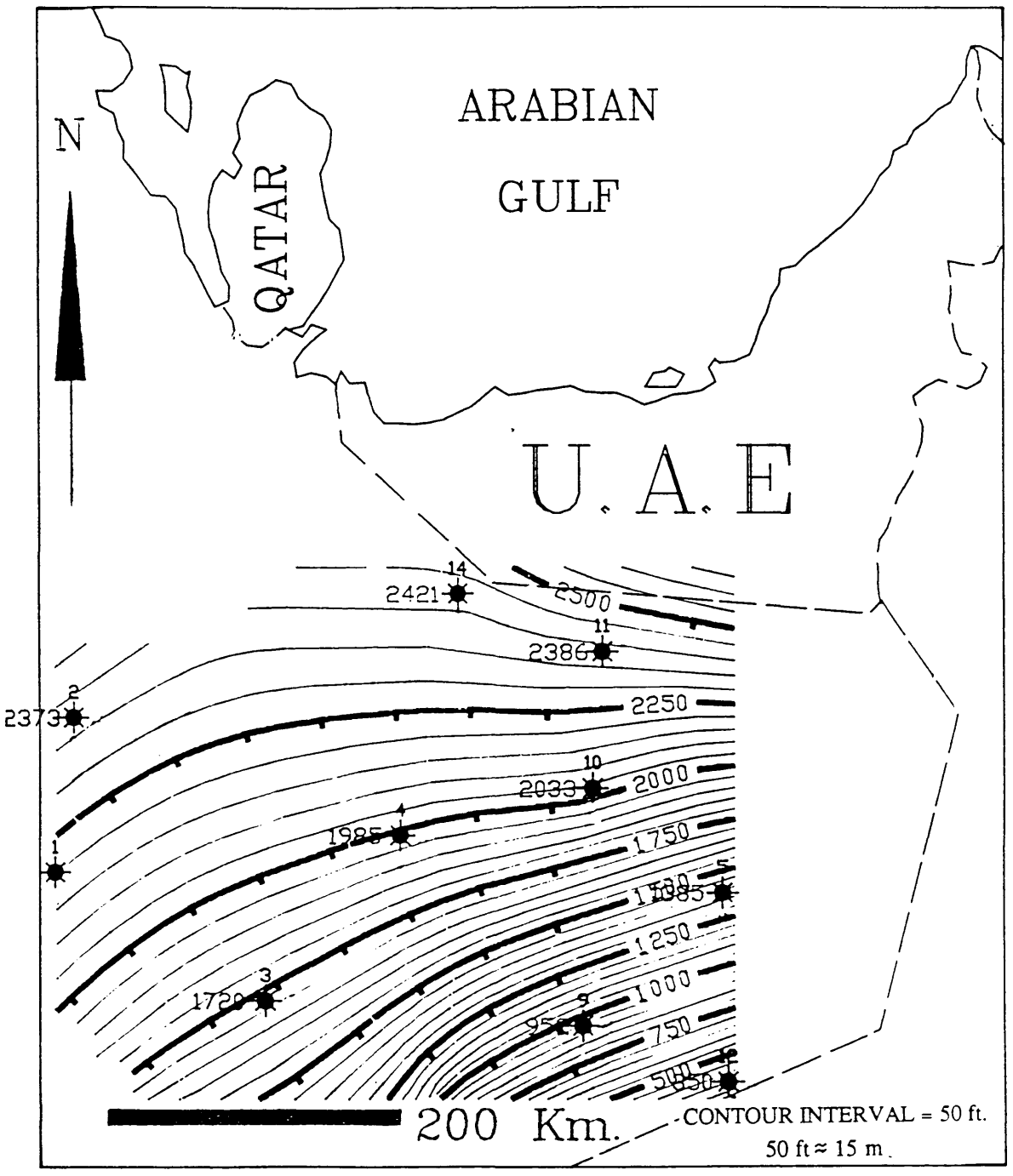


Figure 3.3A Isopach map of Biyadh, Buwaib, Yamama & Sulaiy Formations.

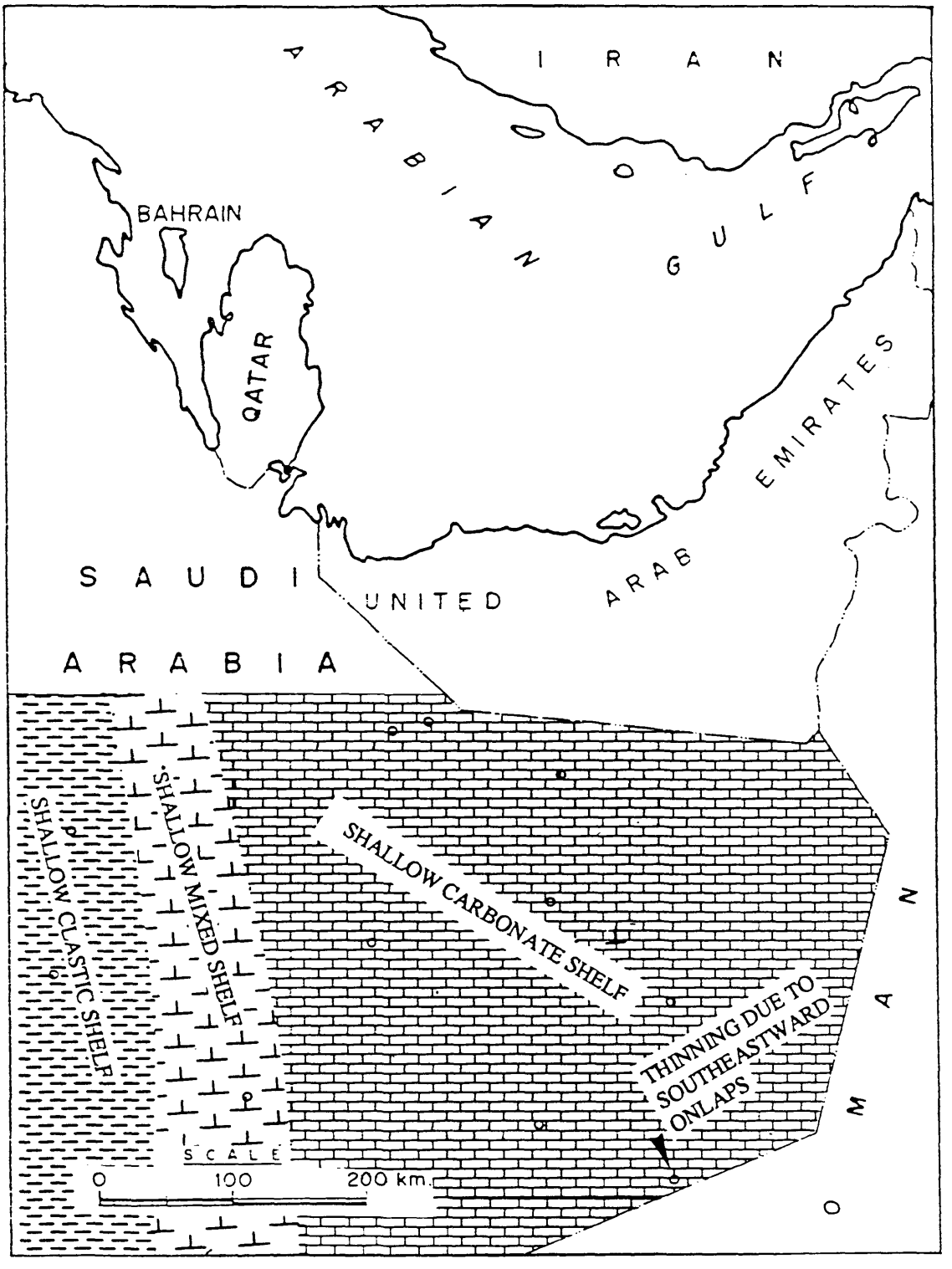


Figure 3.4 Barremain Environments of Deposition

(Biyadh Formation)

the east (today's Oman Mountains). The Biyadh Formation is thinning southeastward in well 12 area (basement high).

3.2.3 **Aptian (Shuaiba Formation)**

A marine transgression affected the Arabian Platform during the Aptian (Murris, 1984 ; Soliman and Al Shamlan, 1982 ; Alsharhan and Naim, 1986). As a result of this marine transgression (Figure 3.5) the study area of Al Rub Al Khali was covered with shallow shelf carbonates (mostly limestones) which were deposited during Aptian time (deposition of Shuaiba Formation). The presence of dolomitic limestone in the area of wells 1 and 2 most probably indicates a shallower environment of deposition closer to the paleoshoreline. However, a chalky limestone in the region of wells 11 and 14 could be an indication of a deeper environment of deposition.

The thickness map of the Shuaiba Formation (Figur 3.5A) reveals a considerably changed pattern of isopachs for the Aptian section. This was probably caused by the pre-Albian erosion where the section is thinning west and south-west of the study area. The basement high reported in the region of well 12 was still active receiving less ssediments, hence the section is thinning southeastward.

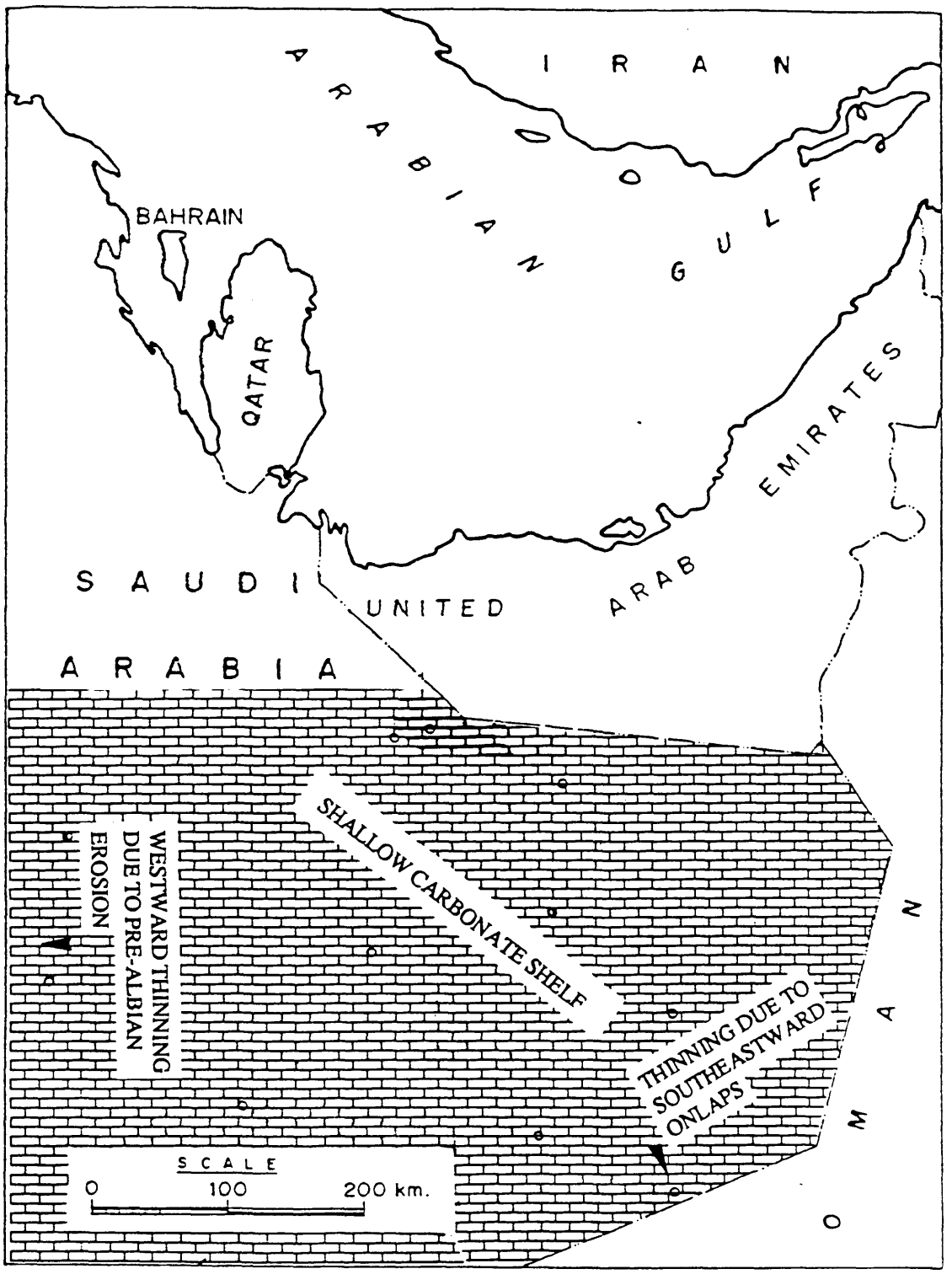


Figure 3.5 Middle Aptian Depositional Environments (Shuaiba Formation)

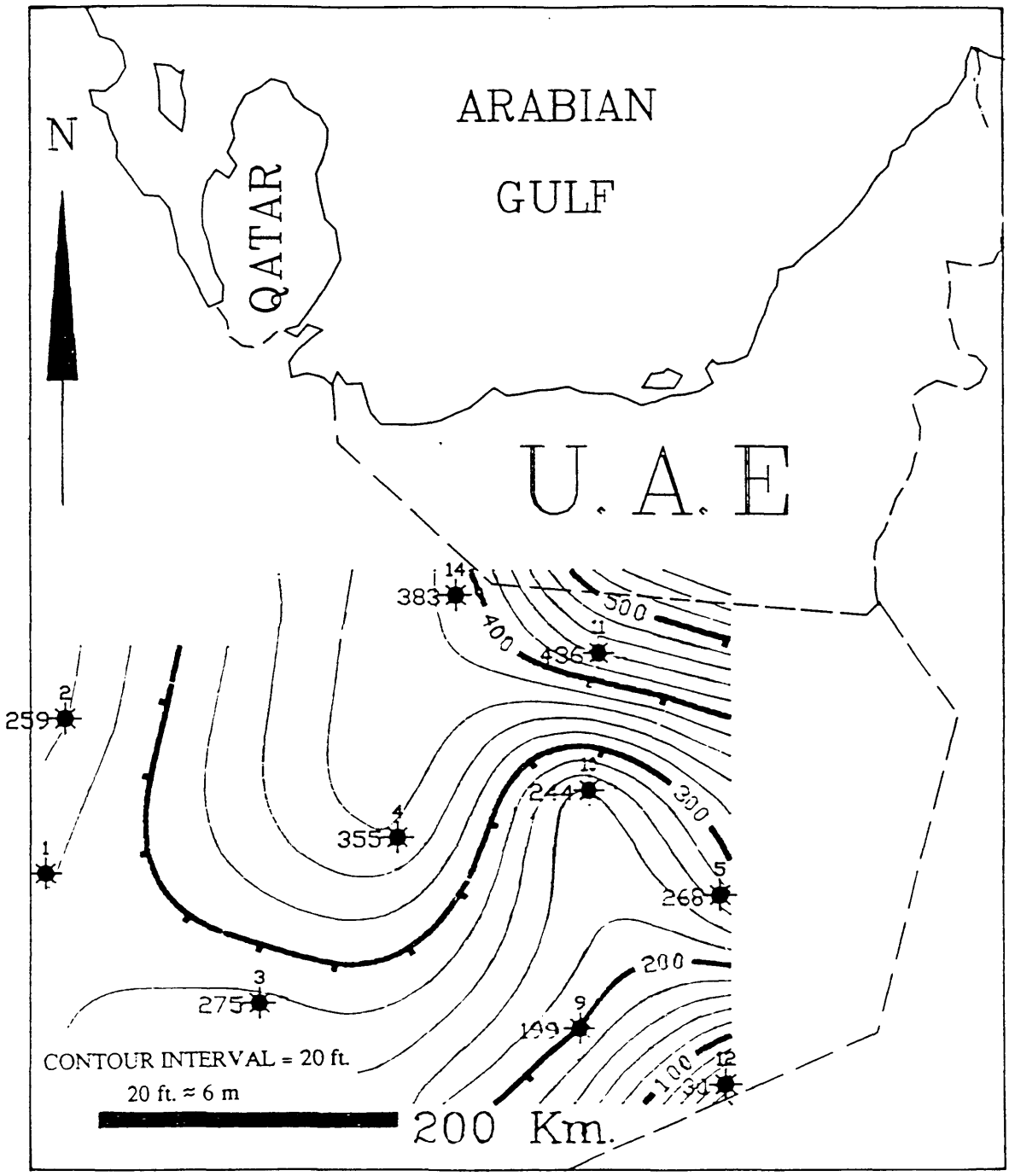


Figure 3.5A Isopach map of Shuaiba Formation (Lower Cretaceous)

3.2.4 **Early Albian (Khafji Member)**

The temporary flooding during the Aptian was followed by the most pronounced regression since the Triassic. During the early Albian there was a major sea-level drop believed to have been caused by a general uplift throughout the Arabian Platform (Murris, 1984; Entsminger, 1981; Soliman and Al Shamlan, 1982; Alsharhan and Naim, 1988). As shown in Figure 3.6, by early Albian time the clastic regime had spread across the whole study area with sandstone dominating the region of wells 1 and 2 while shale covered the rest of ALRub ALKhali area. The source for the clastics was the uplifted highlands of the Arabo-African continent to the west of the study area.

The Khafji isopach pattern shown in Figure 3.6A reveals a similar pattern to the Early Cretaceous. An increase in thickness towards the north-west (centre of the Arabian Platform) and thinning towards the southeast because of onlaps observed in wells 9 and 12 (basement high).

3.2.5. **Middle to Late Albian (Safaniya Member)**

A major change in the depositional system occurred in the study area during Middle to Late Albian (deposition of Safaniya Member). This is strongly believed to be the beginning of ALRub ALKhali basin development. In contrast to the similar isopach pattern discussed earlier, throughout the Early Cretaceous and up to Early Albian of the Middle Cretaceous, the isopach map of Safaniya Member (Figure 3.7A) shows

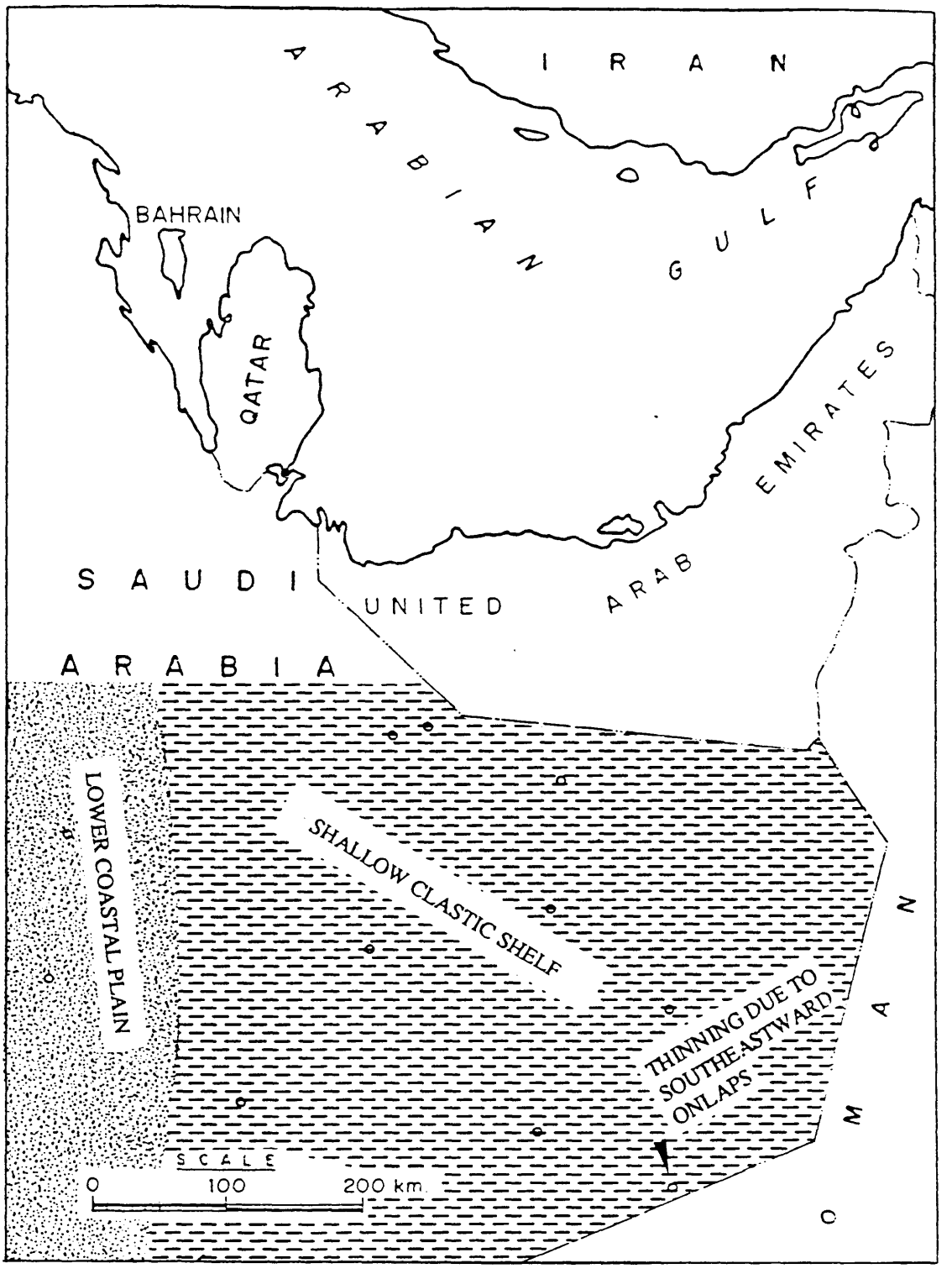


Figure 3.6 Early Albian Depositional Environments (Khafji Member)

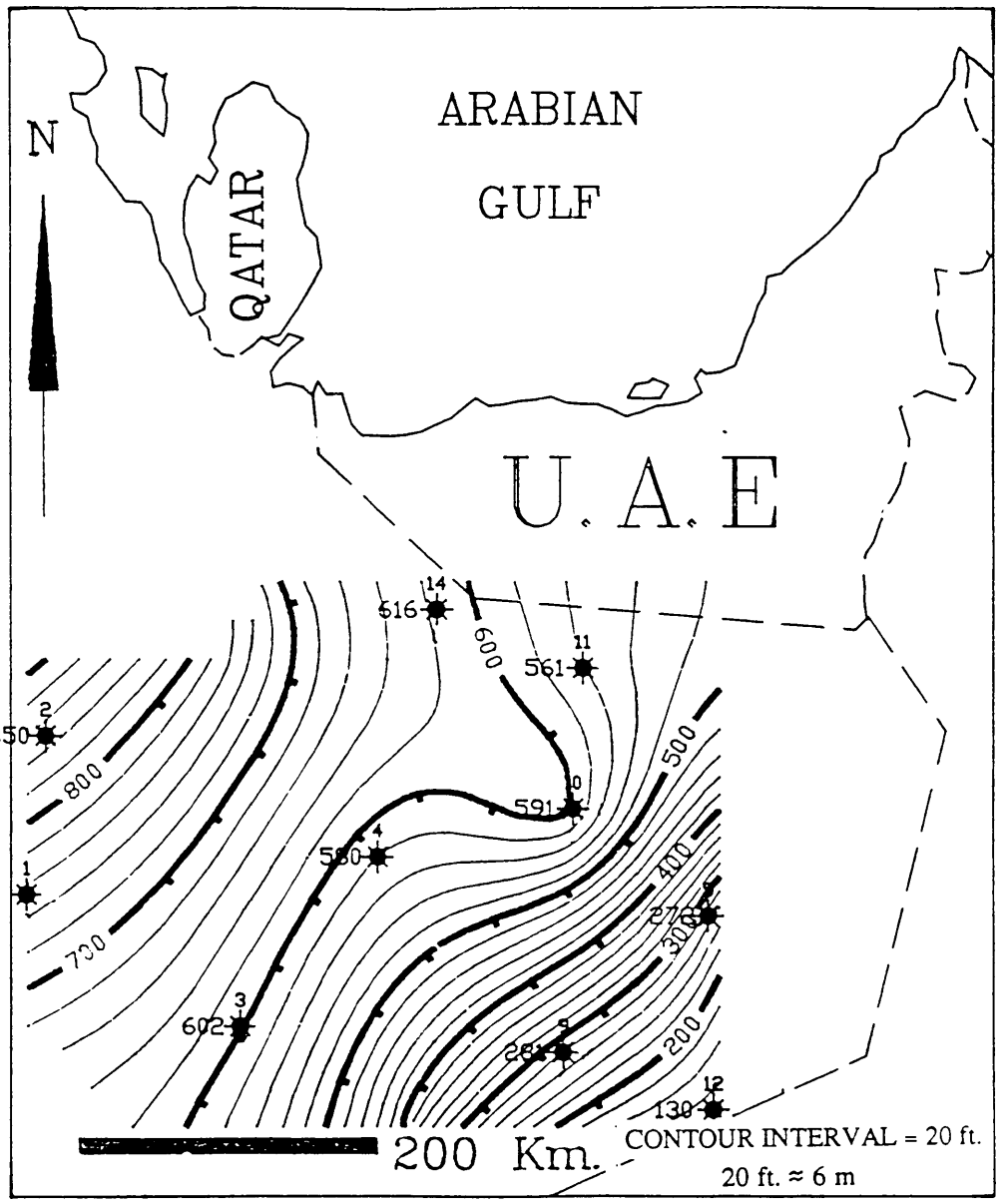


Figure 3.6A Isopach map of Khafji Member (Middle Cretaceous)

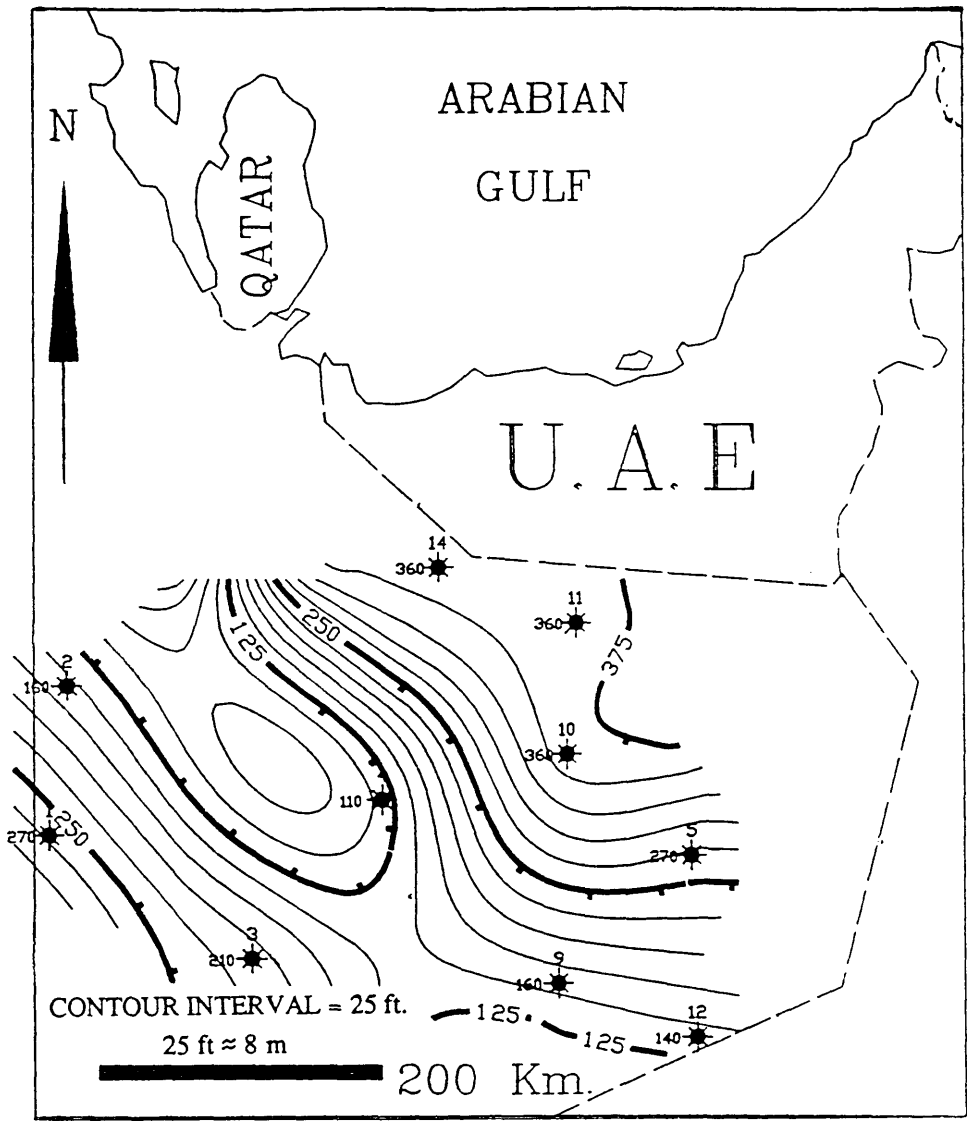


Figure 3.7A Isopach Map of Safaniya Member.

clearly that the study area became more differentiated with an intrashelf basin breaking up the shallow carbonate platform in the north-east. Far from the influence of land and currents (low energy environment), the settling out of fine-grained sediment and the tests of micro-organisms deposited pelagic muds, which are both calcareous and argillaceous. These intrashelf basin sediments give rise to high quality potential hydrocarbon source rocks. The intrashelf basinal development was related to shelf-edge carbonate buildups, subsiding shelf areas, and higher rates of carbonate sedimentation.

The regional upwarping in the foreland of the northern Oman Mountains (east and north-east of the study area) was an important feature of the Middle Cretaceous Arabian continental margin. Patton and O'Connor (1988) interpretted this upwarp as an early expression of a cratonward migrating peripheral swell associated with the emplacement of the Semail Ophiolite onto the margin. The Middle Cretaceous swell axis paralleled the present-day axis of the Oman Mountains. Shoal carbonates of Albian age tended to develop on the eastern extremity of ALRub ALKhali basin forming grainstone and rudist reservoirs for oil in the United Arab Emirates (Wilson, 1975; Burchette and Britton, 1985). It is suggested that the appearance of such reefal facies is the first evidence of convergence and records shallowing due to initial growth of the swell.

During Middle Albian to Middle Cenomanian, the Arabian Platform was probably affected by successive transgressions and regressions (Murris, 1984 ; Entsminger, 1981 ; Newell and Hennington, 1983).

In the Middle Albian the sea readvanced for a short interval, resulting in the deposition of the Lower Safaniya Member in the intrashelf basinal area. This is a dark organic-rich laminated lime-mud and argillaceous limestone. This strongly transgressive phase was followed by a regressive one which marked the deposition of the Upper Safaniya Member. This is composed of interbedded shale and limestone with increasing clastic sediments to the west (palaeoshoreline) as shown in Figure 3.7.

3.2.6 **Early Cenomanian (Mauddud Member)**

Figure 3.8 shows the depositional environments during Early Cenomanian (deposition of Mauddud Member). A shallow carbonate shelf spread throughout the study area as a result of a pronounced transgression. Limestone is the dominant lithology with shale intervals in the region of wells 1 and 2.

The thickness map of Mauddud Member (Figure 3.8A) reveals a different isopach pattern compared to the preceding interval (Safaniya Member) which is probably an indication of the tectonic instability dominating ALRub ALKhali area during the Middle Cretaceous. A shallow depression formed in the central part of the study area with limited clastic influx in the region of wells 1 and 2.

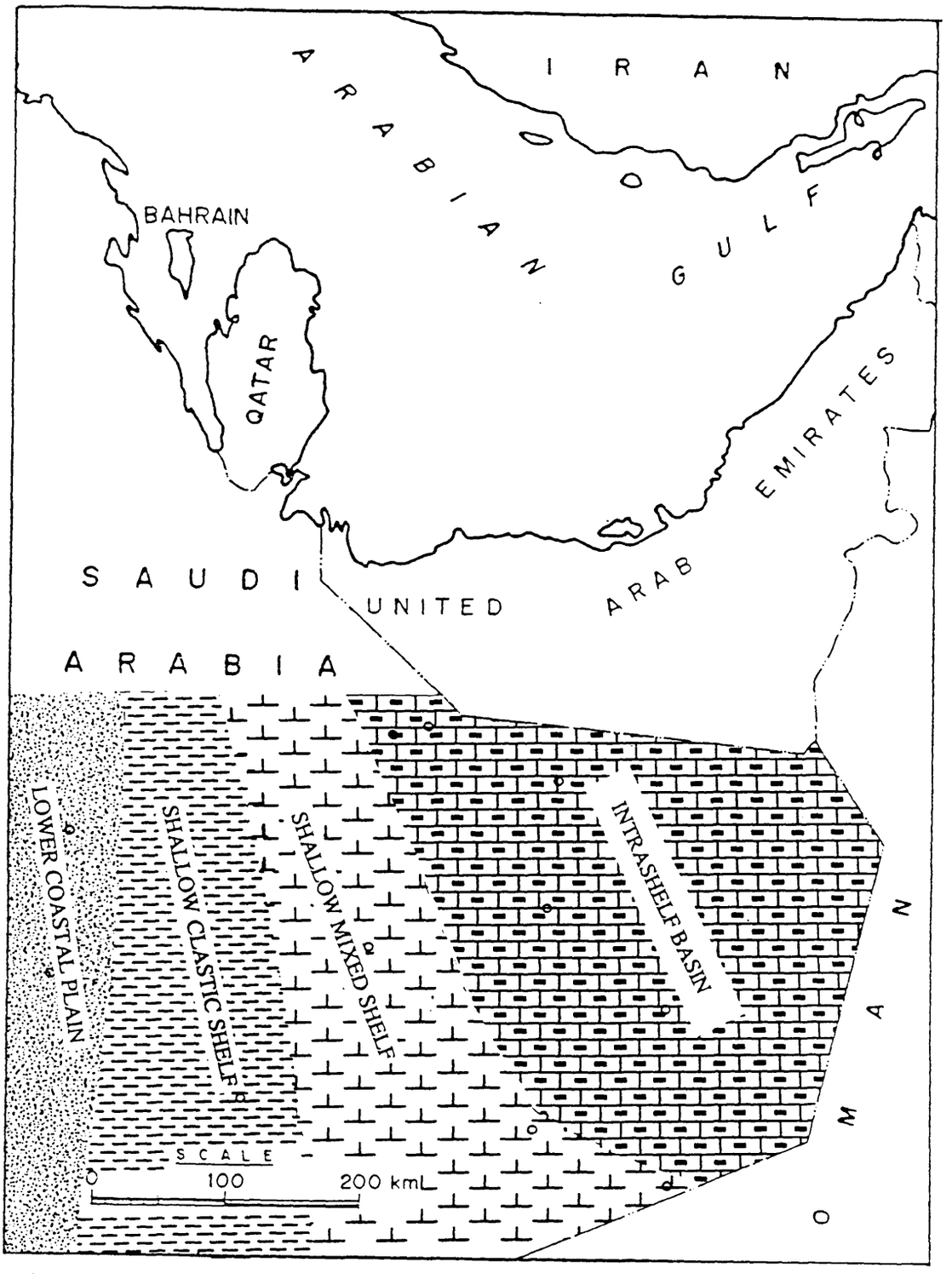


Figure 3.7 Middle to late Albian Depositional Environments (Safaniya Member)

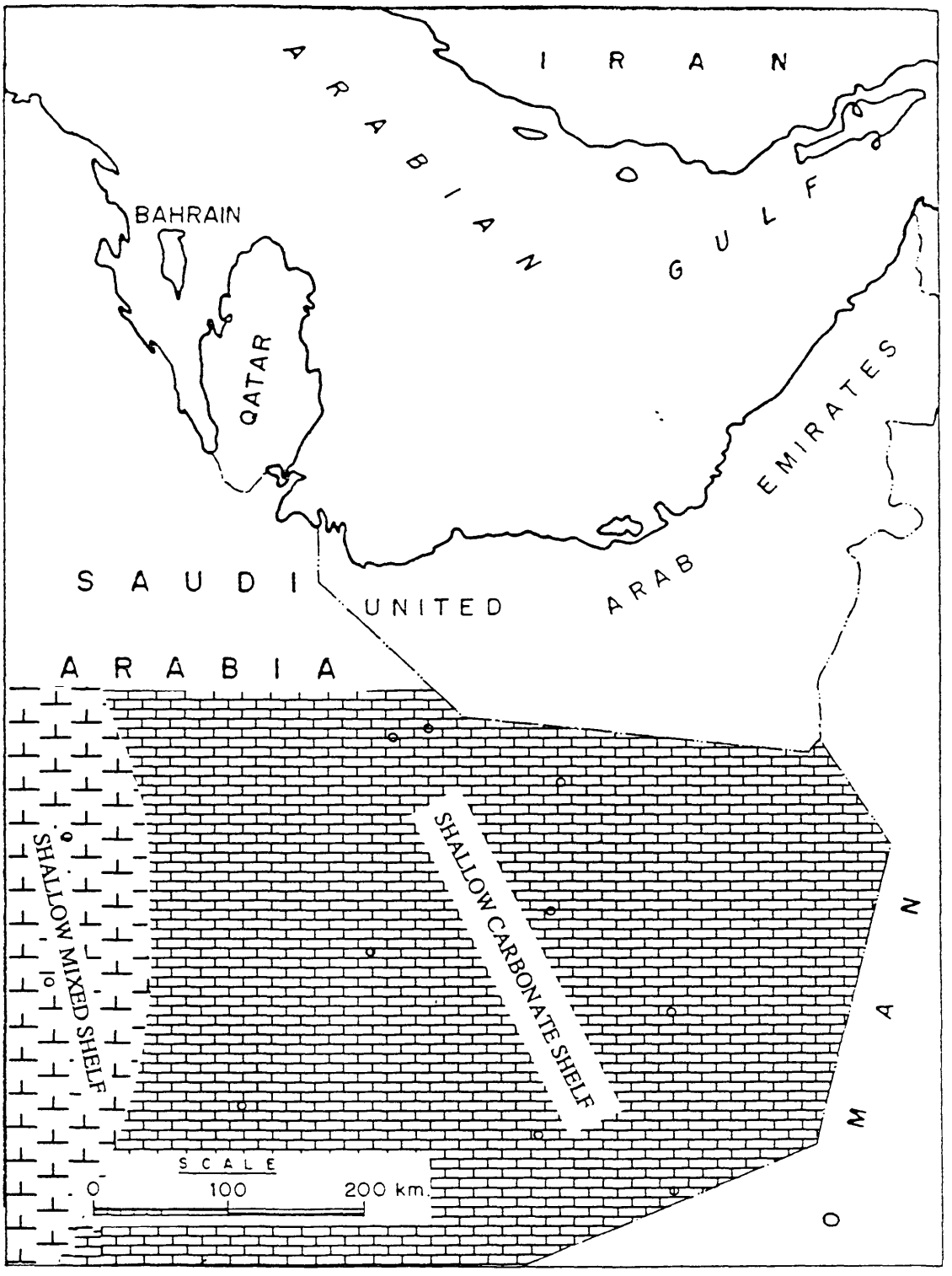


Figure 3.8 Early Cenomanian Depositional Environments (Mauddud Member)

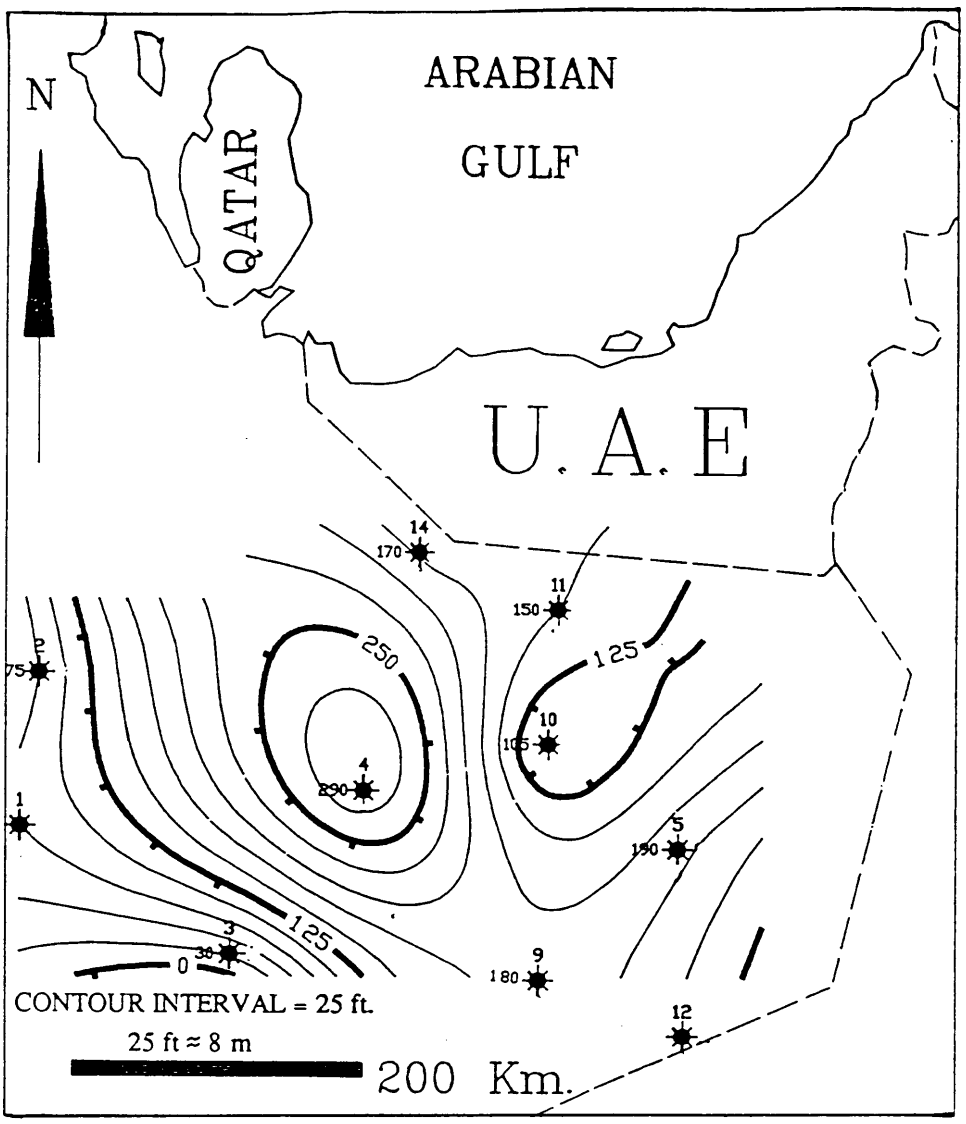


Figure 3.8A Isopach map of Mauddud Member.

3.2.7 Middle Cenomanian (Rumaila, Ahmadi, and Wara Members)

The temporary flooding during the Early Cenomanian (Mauddud Member) was followed by a pronounced regression during the Middle Cenomanian. The clastic regime occupied the western half of the study area pushing the carbonate realm in front of it towards the extreme north-east. As shown in Figure 3.9 the lower coastal plain sandstones of this interval occupied the area of wells 1, 2, and 3, while shale filled the central part of the study area (well 4).

The isopach pattern of the Middle Cenomanian in Figure 3.9A shows clearly the impact of the clastic influx coming from the west on sedimentation rate. The region of wells 1, 2, 3, and 4 was a high energy area where the sedimentation rate is high and gave rise to considerable thickness of sediments being deposited and separated from the shallow carbonate shelf (mainly limestone) in wells 11 and 14 area by a shallow mixed-carbonate shelf.

3.2.8 Late Cenomanian and Turonian (Mishrif Member)

A depositional setting similar to that of the Middle to Late Albian seems to have occurred during the late Cenomanian and Turonian, but with strong differential between subsidence rate and deposition rate. Wilson (1975) reported the presence of shoal areas during Cenomanian in the eastern part of ALRub ALKhali basin (shelf margin). He could not indicate whether these areas represent regional trends or merely represent local shoal facies

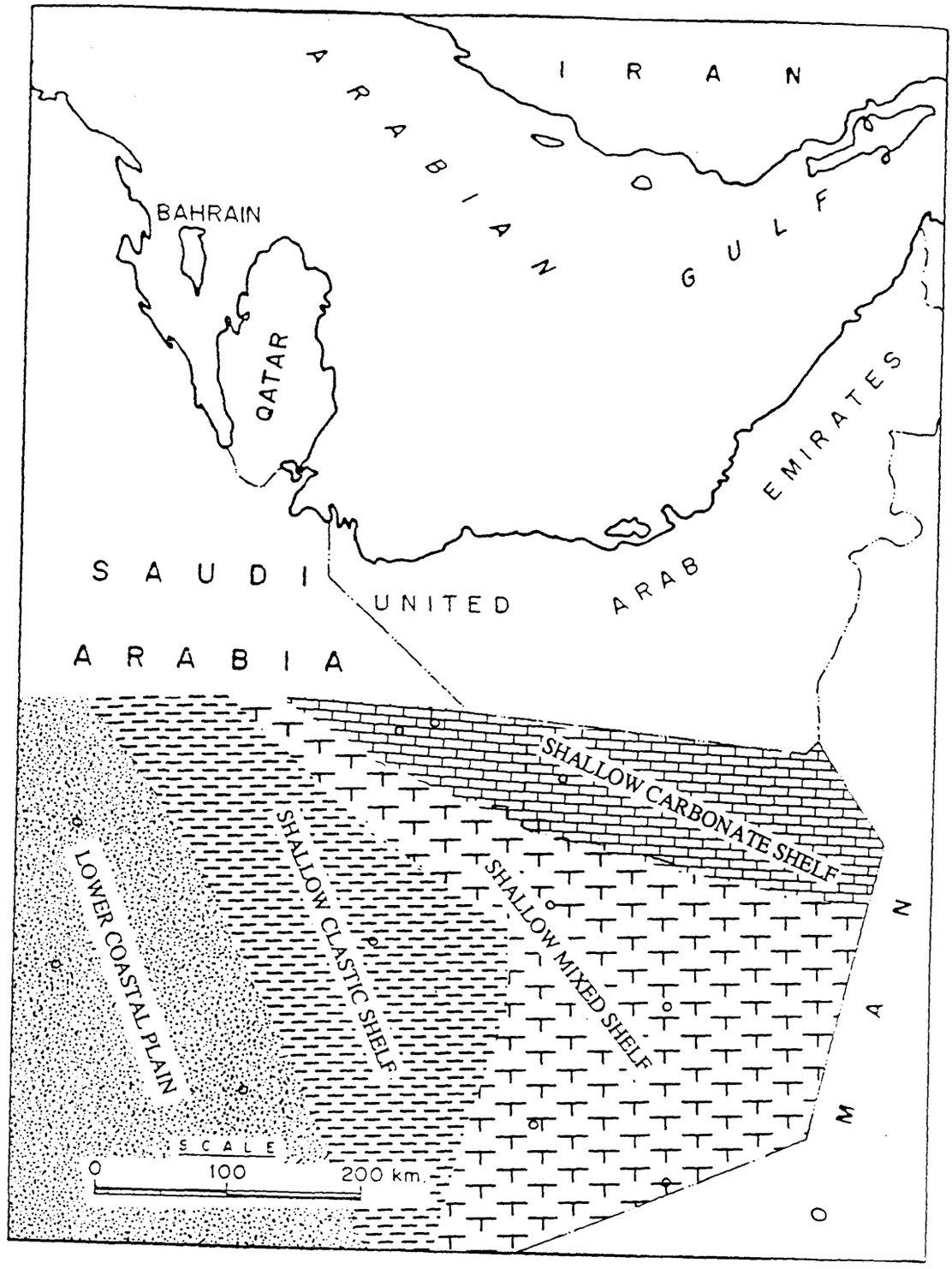


Figure 3.9 Middle Cenomanian Depositional Environments (Rumaila, Ahmadi, and Wara Members)

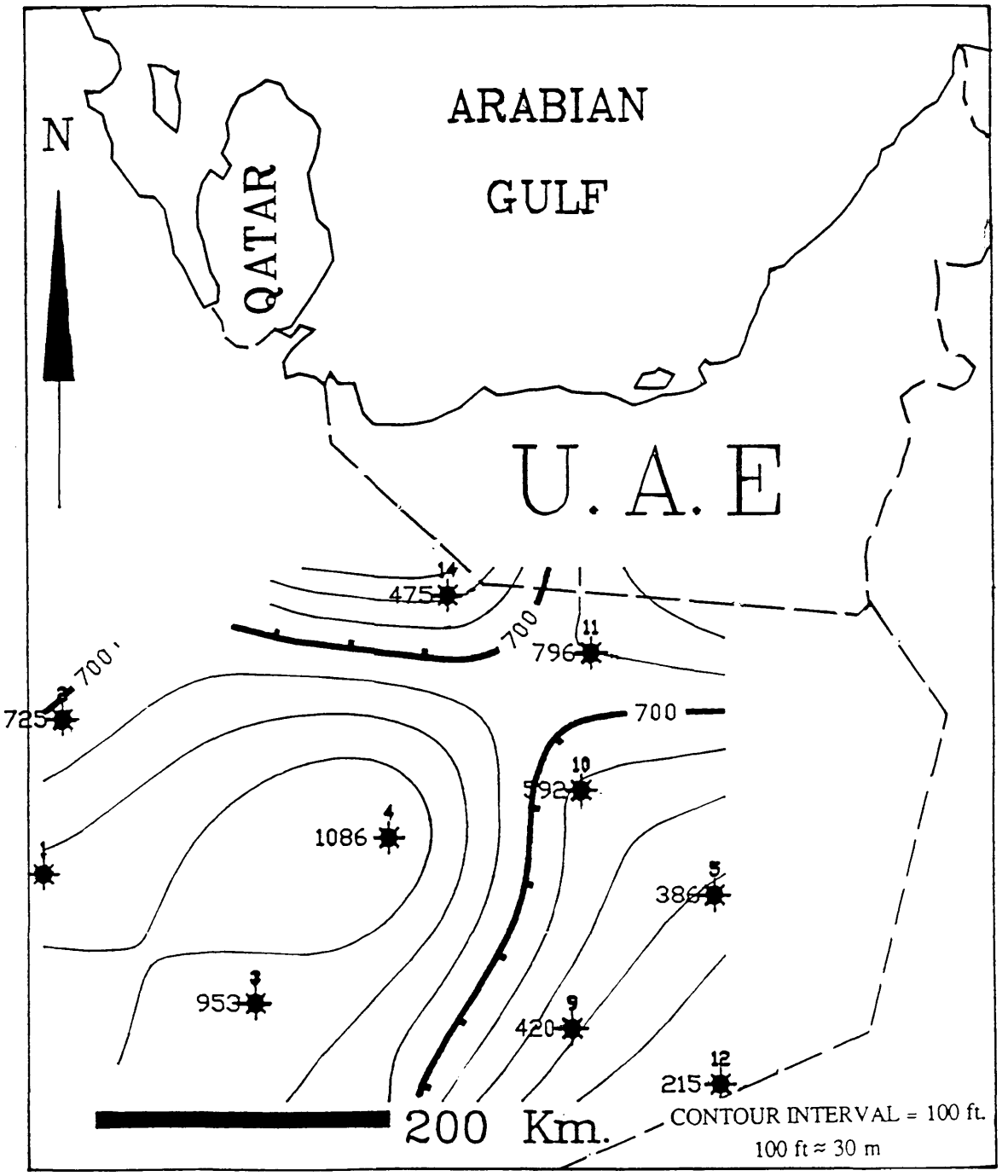


Figure 3.9A Isopach map of Rumaila, Ahmadi and Wara Members (Middle Cretaceous)

induced by structural growth over individual domes. He also indicated the existance of a series of thick grainstone-rudist buildups along this edge. Patton and O'Connor (1988) interpreted this feature to represent the flextural response of the continental lithosphere to subduction loading in an oceanic trench to the east (Oman Mountains).

Based on the above discussion, an abrupt differentiation of the carbonate platform occurred resulting in the development of an intrashelf basin rimmed by the reefal and rudist buildups in the east and shallower shelf area as shown on the thickness map of Mishrif Member (Late Cenomanian to Late Turonian) in Figure 3.10A. The water-bottom relief on the swell (east of the study area) may restrict shelf-water circulation sufficiently to allow the deposition and preservation of organically rich facies (e.g. Safaniya and Mishrif Members) which will be discussed in more detail in a later chapter.

The lithofacies map of Mishrif Member (Figure 3.10) shows an intrashelf basin occupying the eastern part of the study area and characterized by organic-rich lime-mud deposits. Shallow mixed shelf sediments dominate the central part, while coastal sandstone deposits dominate the western region of the study area (wells 1, 2, and 3).

3.2.9 **Campanian and Maestrichtian (Aruma Formation)**

The closing stages of the Turonian saw the start of the most active phase of orogenic activity to affect the Phanerozoic sequence of the Arabian Platform (Wilson, 1969 ; Glennie *et al.*, 1973 ; Gealey, 1977 ; Murris,

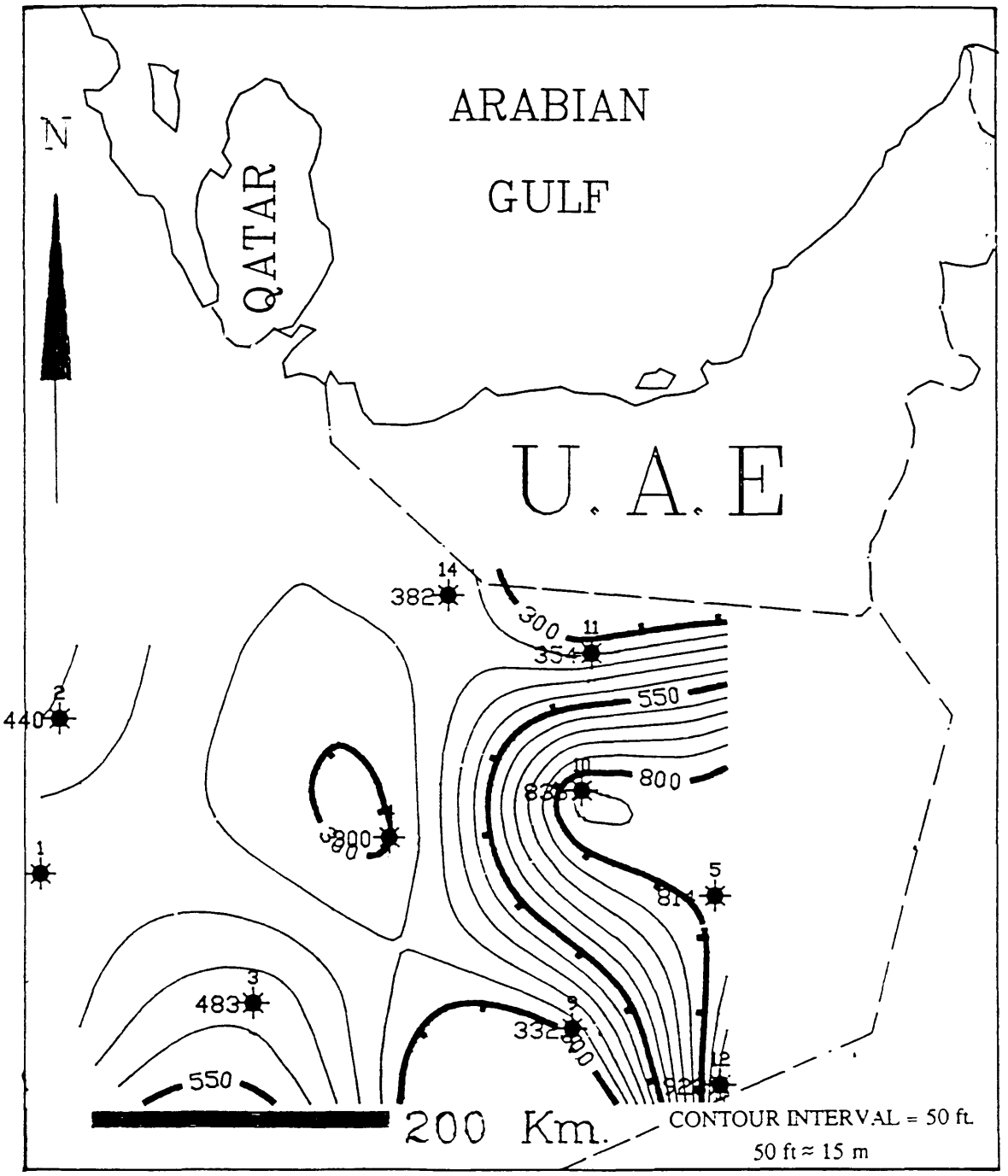


Figure 3.10A Isopach map of Mishrif Member

(Middle Cretaceous)

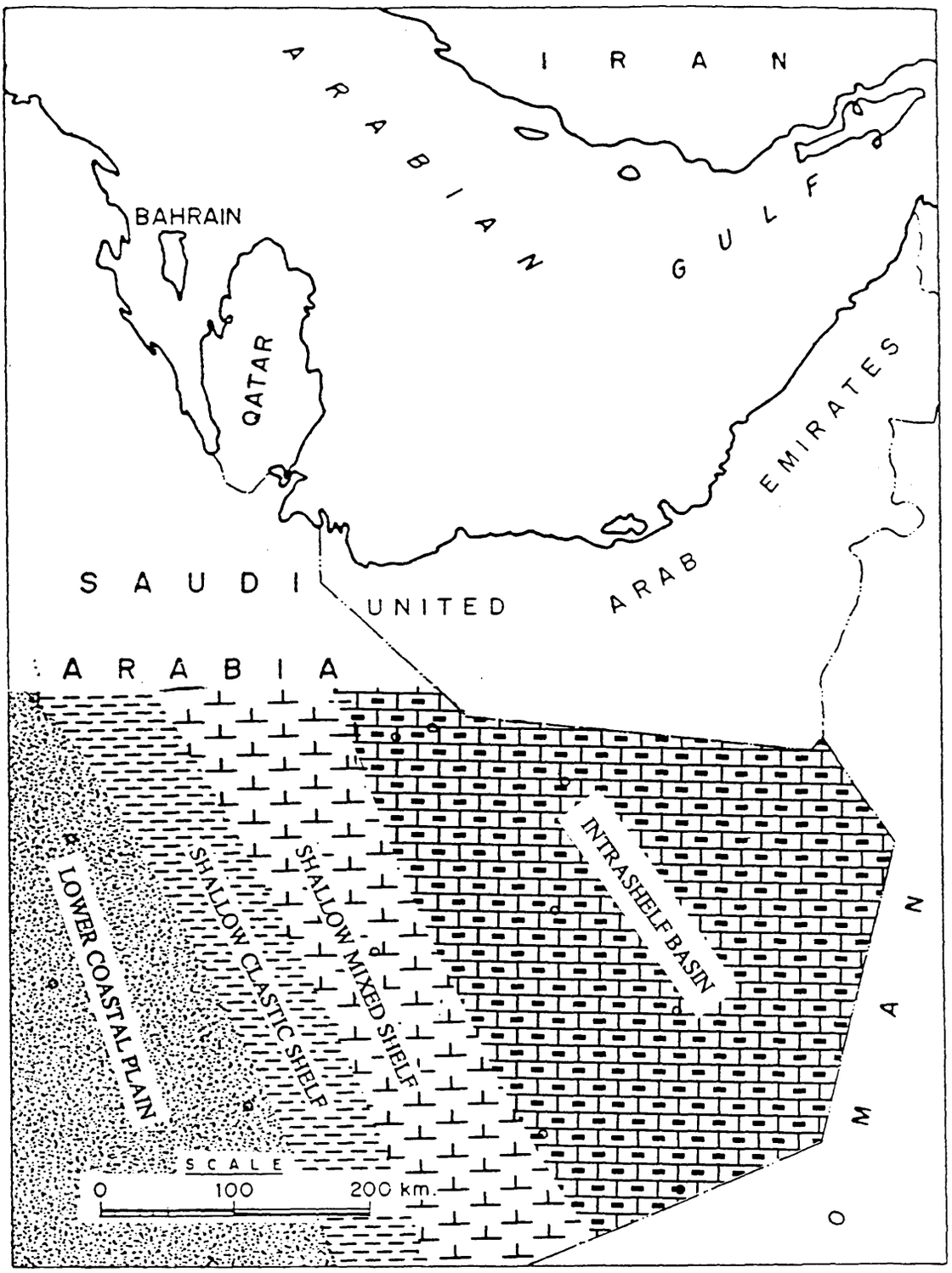


Figure 3.10 Late Cenomanian to late Turonian Depositional Environments (Mishrif Member)

1984 ; Garfield, 1985 ; Patton and O'Connor, 1988). This activity was related to the Alpine Orogeny.

A major unconformity separates the Wasia Formation from the overlying Aruma Formation. Coniacian and Santonian sediments are apparantly absent over much of ALRub ALKhali basin (Newell and Hennington, 1983). A foredeep was formed along the present Oman Mountains (Harris et al, 1980). The Aruma Formation consists of two distinctive lithologic units : Lower Aruma shale and Upper Aruma limestone. Figure 3.11 depicts the deposition of Lower Aruma shale during Campanian. The study area is covered with shallow shelf clastic sediments (mainly shale) except in the region of wells 1 and 3 where it is dominated by coastal sandstone deposits.

During the Maestrichtian, there was a rise in sea level (Murris, 1984; Glintzboeckel, 1981; Garfield, 1985). ALRub ALKhali basin was covered with shallow carbonate shelf sediments (mainly limestone) as shown in Figure 3.12. The isopach map of the Aruma Formation is shown in Figure 3.11A. It appears that the highest sedimentation rate occurred in the well 14 area, while the region of wells 10 and 11 received the least sediments, probably indicating a local depositional high in that area.

A regional Post-Maestrichtian unconformity marks the boundary between the Cretaceous and Tertiary sediments (Harris *et al.*, 1984).

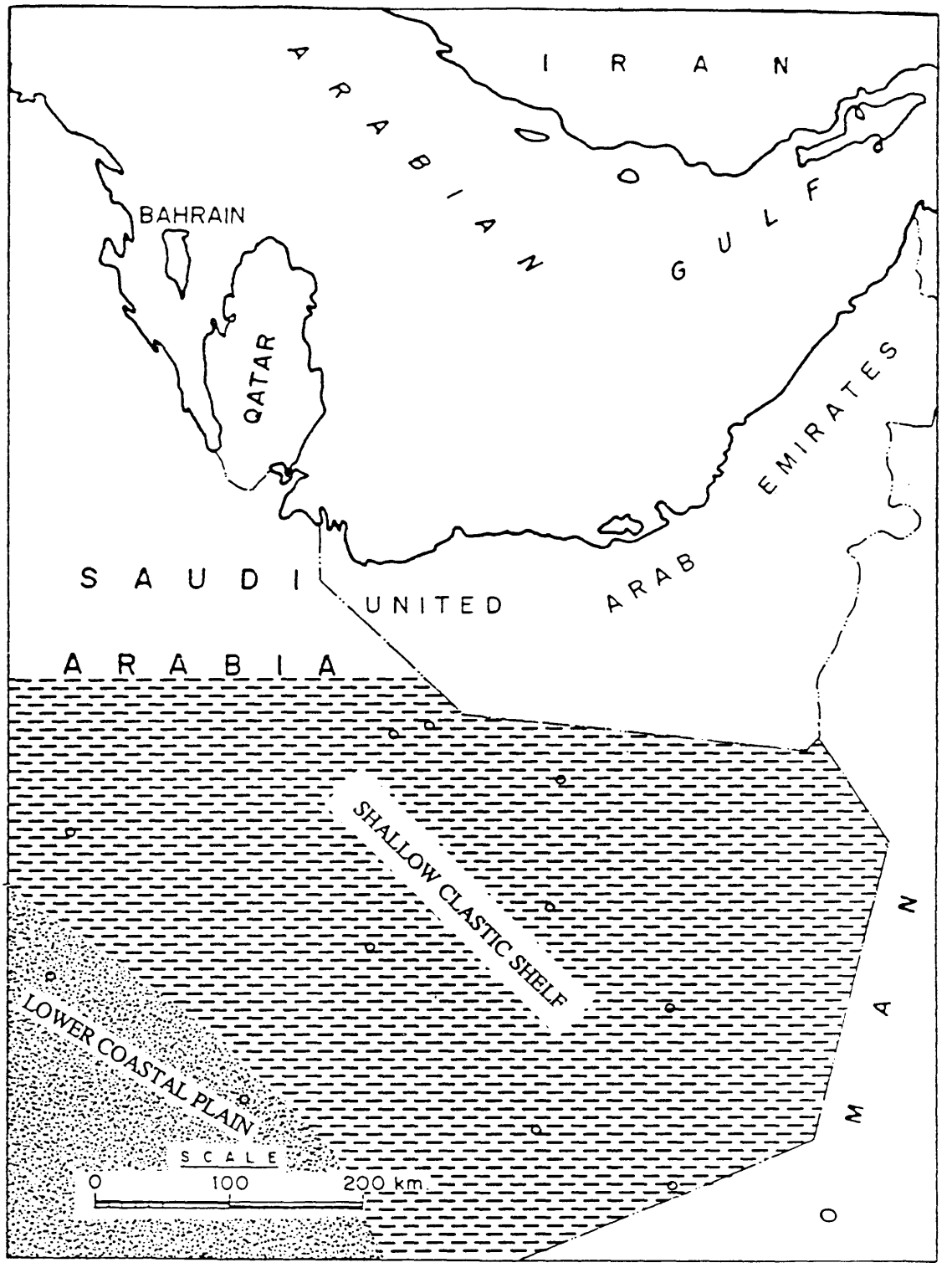


Figure 3.11 Campanian Depositional Environments (Lower Aruma Shale)

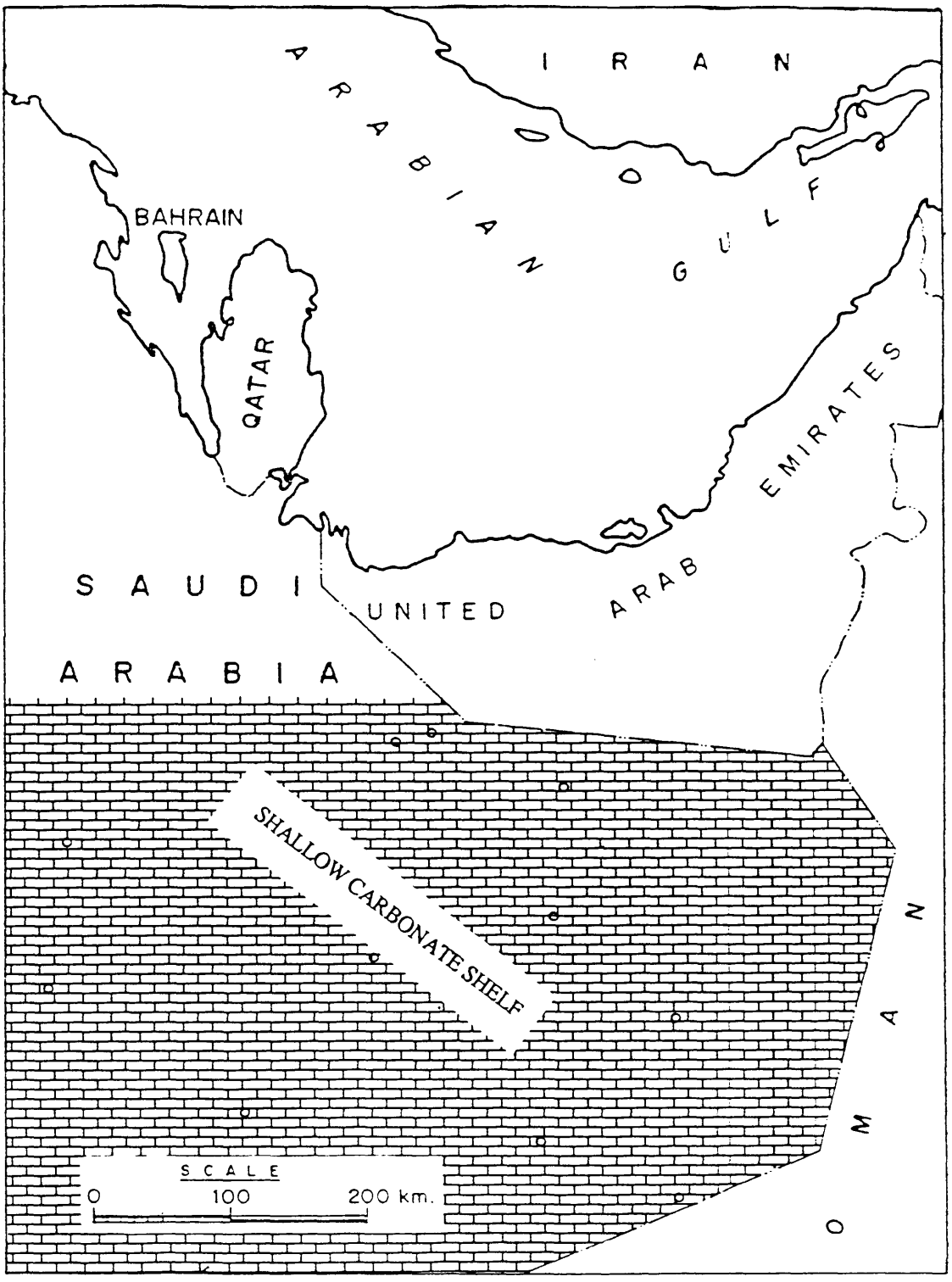


Figure 3.12 Maestrichtian Depositional Environments (Upper Aruma Limestone).

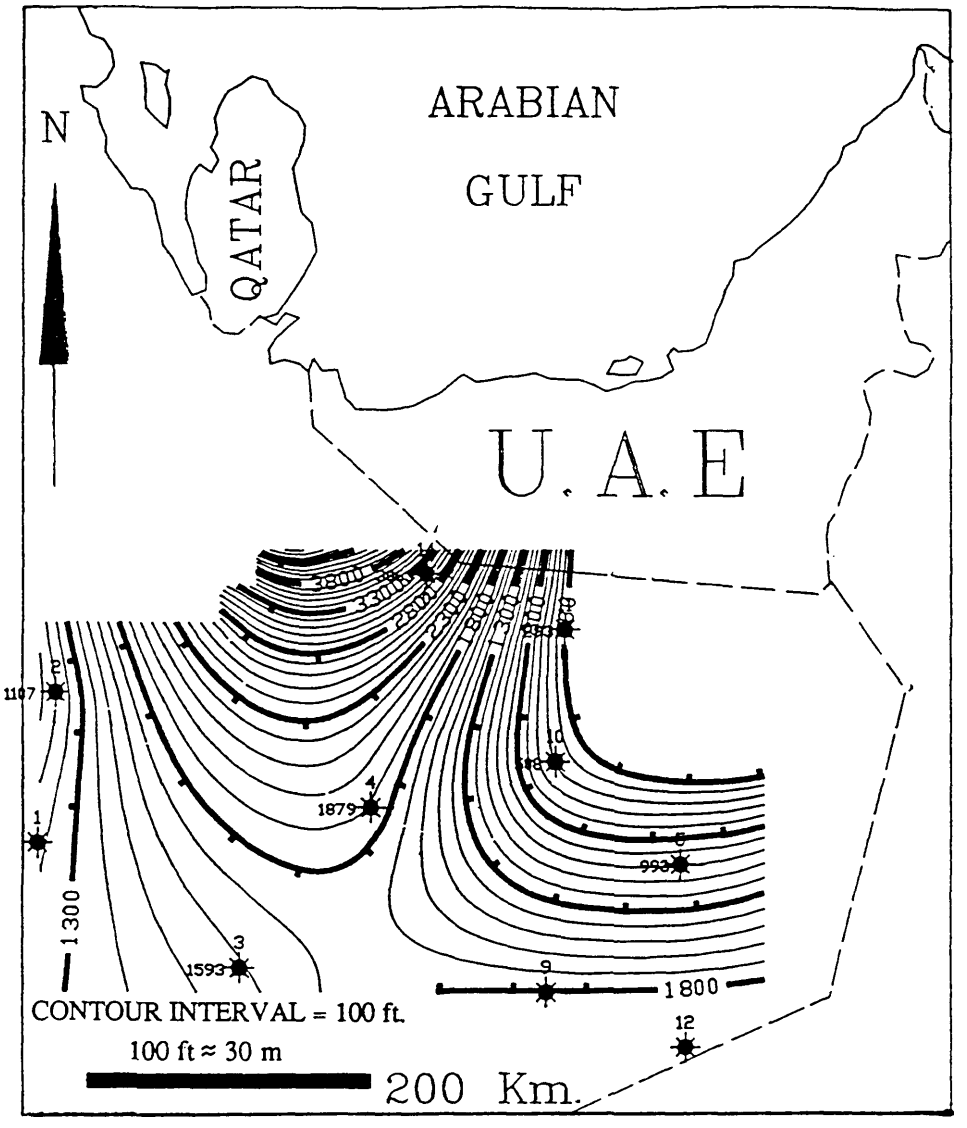


Figure 3.11A Isopach map of Aruma Formation

3.3 *GEOLOGICAL MODELLING OF THE BASIN*

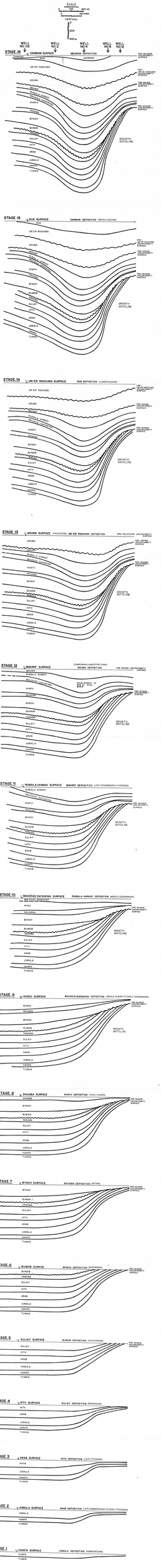
Since the thickest part of the sediment occurs in the basinal part, while the thickness of the beds thin out progressively towards well 9 and well 12 area, a presumably basement high was assumed to occur in the well 12 area. To define clearly the morphology of the structure and the basin with regards to its origin and the time of formation, geological models were constructed through wells H2 (outside the area of the basin) to Well 2, Well 4, Well 9 and Well 12 as shown in Figure 3.13, starting from the deposition of Hanifa Formation (Late Oxfordian) on the Tuwaiq Mountain Formation surface.

Sixteen sections representing the 16 stages of models tracing back the development of the basement high and also the time of the formation of ALRub ALKhali Basin, as shown in Figure 3.13.

From Stage 1 to stage 5, it may be seen that although the structural growth was developing progressively with beds thinning towards the crest, sedimentation was uninterrupted, except that the rate of sedimentation seemed to be much lower on the crest of the growth structure than in the basinal part. However, as can be seen in Stage 6 to Stage 7, the structural growth exceeded sedimentation during or after the Yamama time deposition (Valanginian), resulting in erosion of the crestal part. The crestal portion remained high throughout the Buwaib deposition

Figure 3.13

GEOLOGICAL MODELLING OF RUB AL KHALI BASIN SAUDI ARABIA



(Hauterivian) so that, Buwaib is not represented on the structural high region although its sedimentation was in progress in the basinal part. As can be seen in the sections, in the Well 12 area, Biyadh Formation (Barremian) overlies the Arab Formation (Late Kimmeridgian to Early Tithonian) with a sharp unconformity during which sedimentation reoccurred as the growth development slowed down adjusting itself to receive sediments again. The structural growth was continuous or contemporaneous with sedimentation and it had continued as far as the deposition of Khafji Member (Early Albian).

Looking at the basinal part, ALRub ALKhali Basin was undefined and it remained as part of the major Arabian Shelf depositional domain. From Stages 1 to 10, the thickness of beds in well 4, which is considered to be the basinal well, do not differ from that of the H2 well in the north (outside the basinal area), starting from the Hanifa (Late Oxfordian) to the Mauddud deposition (Early Cenomanian). The Arabian Arch until that time remained the site of major sediment accumulation and the structural dip between the well H2 to well 4 area is represented by rather flat or gentle surface. However, starting from the deposition of Rumaila, Middle Cenomanian (Stage II) the Central Arabian Arch started to rise, while ALRub ALKhali Basin started to mould up into a very gentle downward basin shape, receiving the thickest sedimentary deposit in the well 4 area. The basinal shape continued its development right up till the deposition of Mishrif (Late Cenomanian and Turonian) when later the region was uplifted to undergo erosion as indicated by the Pre-Aruma Unconformity. It is during these stages and in the Paleocene, Um Er Radhuma and Lower

Eocene, Rus Formation, that the basin continued to subside receiving more sediments in the central part of the basin. Past-Neogene deposition were merely the filling up of the basin.

CHAPTER FOUR

ANALYTICAL TECHNIQUES

4.1 INITIAL SAMPLE PREPARATION 90

4.2 MACERATION 90

4.3 DENSITY SEPARATION 92

4.4 TOTAL ORGANIC CARBON DETERMINATION 95

4.4.1 Sample Preparation 95

4.4.2 Instrument Description 95

4.4.3 Operating Procedure and Sample Analysis 100

4.4.4 Presentation of Results 101

4.4.5 Sample Reproduceability 101

4.5 CHN ANALYSIS OF KEROGEN 101

4.5.1 Sample Preparation 101

4.5.2 Instrument Description 103

4.5.3 Operating Procedure and Sample Analysis 103

4.5.4 Presentation of Results 103

4.5.5 Sample Reproduceability 104

4.6 OXYGEN ANALYSIS OF KEROGEN 104
4.6.1 Sample preparation 104
4.6.2 Instrument Description 104
4.6.3 Operating Procedure and Sample Analysis 107
4.6.4 Presentation of Results 109
4.6.5 Sample Reproduceability 110

4.7 PROGRAMMED TEMPERATURE PYROLYSIS OF WHOLE ROCK SAMPLE 110
4.7.1 Principles of the Method 110
4.7.2 Sample Preparation 110
4.7.3 Instrument Description 112
4.7.4 Operating Procedure and Sample Analysis 114
4.7.5 Presentation of Results 115
4.7.6 Sample Reproduceability 117

4. 1. *INITIAL SAMPLE PREPARATION*

The ditch cuttings of every sample were hand sorted to remove caving materials. One portion, sieved clean of the fines, was then stored in a labelled plastic bag for acid maceration after recording its weight. The other portion with the fines was reduced to a particle size of less than 75 microns using a Pascal Engineering Mortar and Pestle-Mill and a 200 mesh sieve. The rock powder was then stored in labelled glass vials to be used for organic carbon determination and whole rock pyrolysis.

Every possible precaution was taken to prevent possible contamination throughout each stage of sample preparation. This included thorough cleaning of the sieves using brushes, a jet of compressed air in between samples and thorough washing of the mortar and pestle using detergent followed by rinsing with water and drying them with a jet of compressed air after each sample.

4. 2. *MACERATION*

Maceration is the removal of the rock mineral matrix and the extraction of insoluble organic matter from sedimentary rocks through various chemical and physical processes. The maceration method employed in this project was adapted from that described by Bostick and Alpern (1977), and Durand and Nicaise (1980).

Each selected and prepared rock sample described in Sec. 4.1 was placed into a clean 500 ml polypropolene beaker. Approximately 100 ml of 10% hydrochloric acid (technical grade) was added to each sample to eliminate any carbonates present. Each sample was stirred regularly and left. The spent hydrochloric acid was then removed by decantation and a further fresh portion of hydrochloric acid was added and left, to be stirred at regular intervals. The hydrochloric acid treatment continued until the reaction ceased. The residue of each sample was then washed in distilled water to neutrality in an attempt to remove any soluble calcium ions released by the acid treatment. Each sample was allowed sufficient time to settle, before decanting the clear distilled water. The residue was acidified with a few milliltres of 5% hydrochloric acid (technical grade) prior to hydrofluoric acid treatment to reduce the possibility of any calcium ions that may have been present in the residue from forming a flouride precipitate upon addition of hydrofluoric acid (Saxby, 1970; Bostick and Alpern, 1977).

Approximately 50 ml portions of 60% hydrofluoric acid (technical grade) was then added to each sample and left with stirring at regular intervals, to completely digest the silicate minerals for a period of 48 hours. The acid was then decanted and fresh portions of 60% hydrofluoric acid were added to each sample and left for another 48 hours with regular stirring. The acid was again removed by decantation and the hydrochloric/hydrofluoric acid insoluble residue from each sample was washed to neutrality between washings to allow any organic matter present to settle. Finally the insoluble organic matter concentrate was then transferred into clean labelled 30 ml

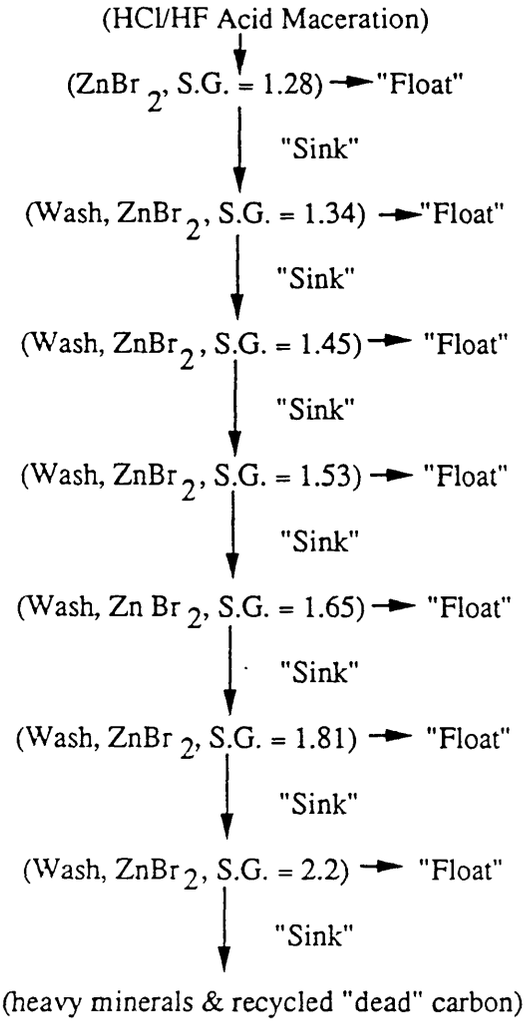
plastic centrifuge tubes. A total of 108 samples were macerated in this project.

4.3. *DENSITY SEPARATION*

Density separation has been used to separate organic matter from acid, insoluble, and inorganic heavy minerals remaining after the rock sample maceration in hydrochloric and hydrofluoric acids (Bostick and Alpern, 1977; Durand and Nicaise, 1980). Kinghorn and Rahman (1980, 1983) have noted that the different maceral groups of sedimentary organic matter could be separated using centrifuging in zinc bromide solutions of sequentially higher specific gravities. In addition their density fractions could be also related to their state of maturation.

The procedure followed in this project is similar to the one described by Kinghorn and Rahman (1980) using zinc bromide solutions with specific gravities fo 1.28, 1.34, 1.45, 1.53, 1.65, 1.81 and 2.2 (see Figure 4.1). These solutions were prepared from technical grade zinc bromide by the addition of appropriate volumes of 5% hydrochloric acid (technical grade).

Each sample of acid insoluble organic matter obtained through the maceration procedure described earlier were sequentially centrifuged at 2000 r.p.m. for 20 minutes in each solution of zinc bromide of specific gravities 1.28, 1.34, 1.45, 1.53, 1.65, 1.81 and 2.2. After each centrifugation in each $ZnBr_2$ solution the *float* and *sink* fractions were separated by decantation into new labelled tubes and the percentage



All samples were centrifuged in each $ZnBr_2$ solution for 20 minutes at 2000 r.p.m.

Figure 4.1 Method used for fractionating acid insoluble organic matter

separation of the floats were then volumetrically estimated each time. The *float* fraction from each density grade was decanted and washed three times by centrifuging in 0.1 N hydrochloric acid (technical grade) and then a further three times in distilled water. The *sink* fraction from each density grade was decanted and washed twice by centrifuging in 0.1 N hydrochloric acid (technical grade) before being centrifuged in the next higher specific gravity. The *sink* fraction of 2.2 specific gravity is believed to be the acid insoluble heavy minerals (commonly pyrite) and recycled *dead* carbon (Kinghorn and Rahman, 1980).

Thus, seven fractions of the insoluble organic matter were obtained from this fractionation process : of density less than 1.28, 1.28-1.34, 1.34-1.45, 1.45-1.53, 1.53-1.65, 1.65-1.81, and 1.81-2.2. A representative part of each of these seven fractions was mounted in glycerine jelly on standard glass slides for microscopic or optical examination.

Finally, for each sample equal portions of all seven float fractions were recombined to produce an acid insoluble total sedimentary organic matter (kerogen) sample and a representative part was mounted in glycerine jelly on standard glass slides for optical examination.

4. 4. *TOTAL ORGANIC CARBON DETERMINATION*

4. 4. 1. **Sample Preparation**

For TOC determinations of powdered whole rock samples of less than 75 microns grain size, prepared as described in sec. 4.1, between 1 to 4 milligrams of each sample were accurately (∓ 0.001 mg) weighed into a clean platinum boat using a Perkin-Elmer AD-2 Autobalance. Each sample was then treated with 10% HCl in an attempt to remove any carbonate carbon. Addition of the HCl acid continued until no further reaction was visible. The acid treated sample was then oven dried at 40 °C ∓ 2°C for a minimum of three hours before being subjected to the TOC analysis.

4. 4. 2. **Instrument Description**

The model 240C Perkin-Elmer elemental analyzer can be used to determine the carbon, hydrogen and nitrogen contents of organic matter, and total organic carbon (TOC) of whole rock samples. The machine consists of three main parts. These are the combustion train, the analytical system, and the electronics. Figure 4.2 shows a simplified diagram of the combustion train and the analytical system.

As shown, a pure supply of oxygen and helium gases is required. The oxygen supply is used for sample combustion, while helium is to carry the combustion products from the combustion train, through the analytical system, to atmosphere. Gas flow is determined by valves A through G (see

Figure 4.2).

The combustion train, shown in Figure 4.3, consists of combustion (heated by a high heat coil) and reduction furnaces maintained during analysis at about 950°C and 650°C, respectively. Each furnace has its appropriate reaction tube.

The analytical system consists of the following parts : (a) a mixing volume where the sample combustion products, carbon dioxide, water and nitrogen are mixed with the carrier gas (helium) to form a homogeneous and equilibrated mixture, (b) a pressure switch, (c) sample volume, (d) detectors, and (e) adsorption traps. Detection for water, carbon dioxide and nitrogen is carried out by three pairs of thermal conductivity cells which are surrounded by a helium bath to guard against any possible small leaks. Each cell within a cell pair is interconnected to the other cell in a bridge circuit so that any difference in content of the mixture of gases passing through the two cells of each pair will result in an electrical signal. As shown in the detector flow diagram (Figure 4.4), the mixture of gases pass through a magnesium perchlorate trap, located between the first pair of cells, which adsorbs any water from the gas mixture before entering the second cell. The corresponding bridge circuit releases a signal which is proportional to the amount of water removed. A similar thing happens where an adsorbing trap, between the second pair of cells, eliminates the carbon dioxide from the gas mixture resulting in a signal proportional to the gas removed. Finally, the third pair of cells detects nitrogen by giving a signal proportional to the difference in thermal conductivity between the

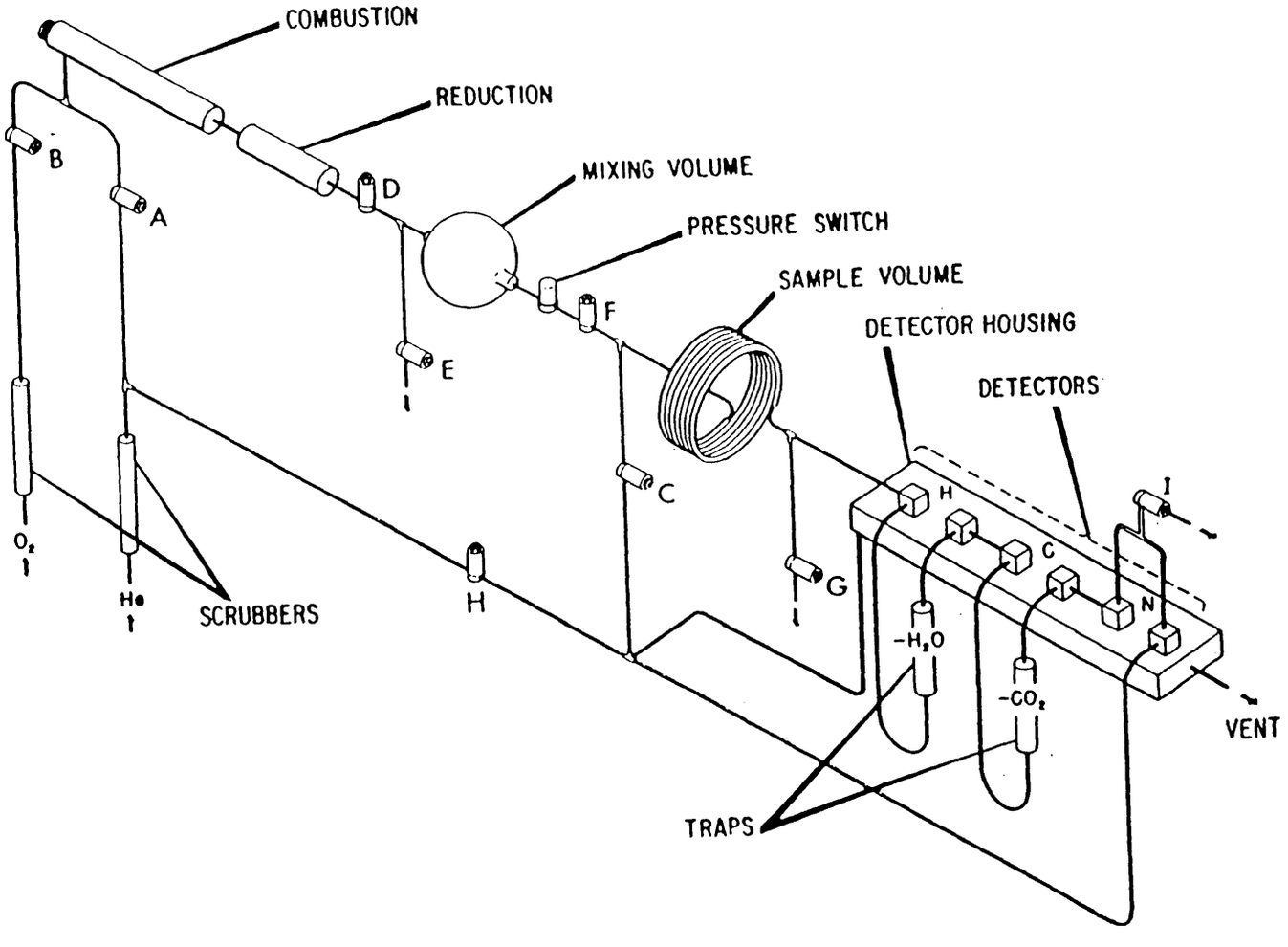


Figure 4.2 Simplified diagram of combustion and analytical system. (From Perkin Elmer Manual)

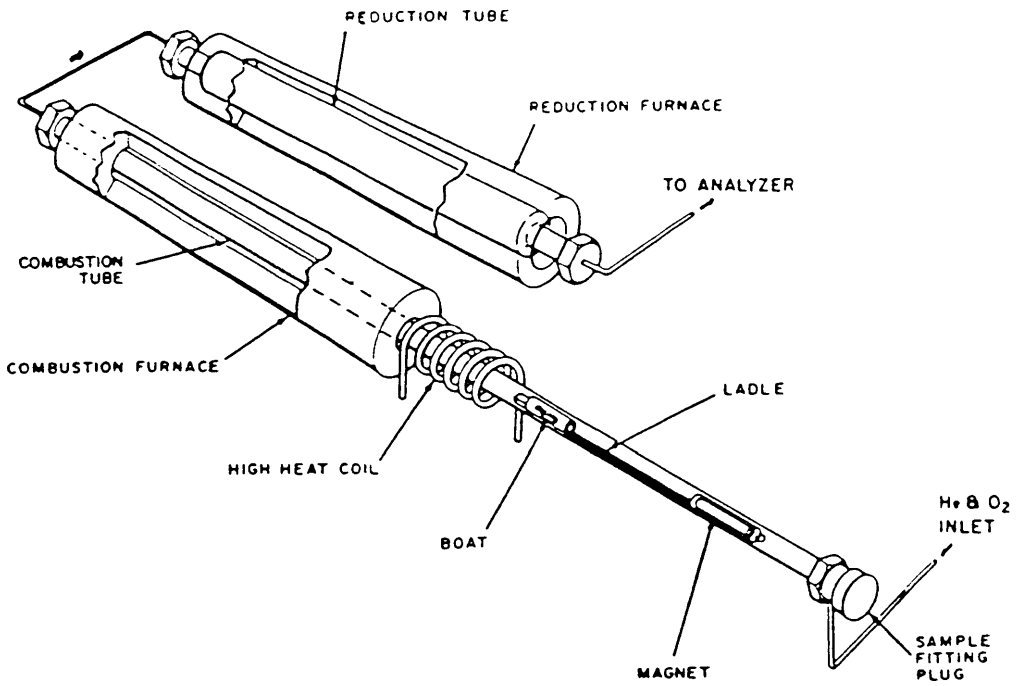


Figure 4.3 Combustion Train (From Perkin Elmer Manual)

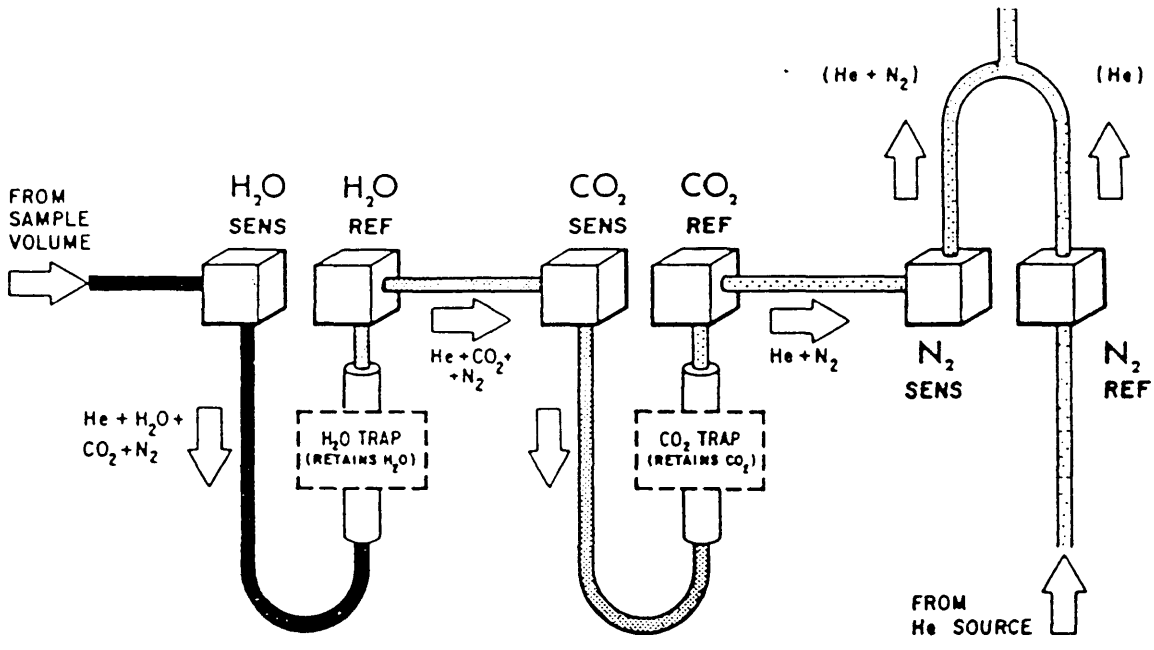


Figure 4.4 Detector Flow Diagram

(From Perkin Elmer Manual)

first cell with nitrogen and helium gases and the second cell with pure helium, as shown in Figure 4.4.

The output signals from the bridge circuits are passed, through adjustable attenuators to either a Perkin-Elmer Model 56 1-millivolt recorder or to an automatic data hadling computing calculator where results are presented in weight percentages of carbon, hydrogen and nitrogen.

4. 4. 3. **Operating Procedure and Sample Analysis**

Between analysis, the machine is in a standby mode. Prior to any calibration or sample determination, the instrument was flushed with an unweighed conditioning sample of acetanilide (microanalytical grade). A series of blanks were run to stabalize the machine. Next, acetanilide (composition : C = 79.09% ; H = 6.71% ; N = 10.36% ; O = 11.84%) was used as a standard to calibrate the instrument. Between 1-4 milligrams of Acetanilide in a clean platinum boat was accurately (+ 0.001 mg) weighed using the AD-2 autobalance and analyzed and results were used to calculate machine sensitivities. The calibration values have to be within certain recommended limits. After establishing the μV/μg blank and sensitivity values of the instrument, each sample, which was prepared as described in Sec. 4.1, was introduced into the analyser, and the analyses proceeded automtically. The sample was combusted under static conditions in the presence of excess oxygen at about 950°C in the combustion furnace. The combustion products were then moved over copper held at about 650°C in the reduction furnace, where nitrogen oxides were reduced to nitrogen and

any residual oxygen removed. The remaining gases (H_2O, CO_2, N_2) were then homogenized and displaced using helium (carrier gas) into the detection system as described in part (4.4. 2) above.

4.4.4. **Presentation of Results**

The signal outputs are proportional to the amount of carbon dioxide which are in turn proportional to the total organic carbon of the sample. The calculations ($\mu V/\mu g$) are handled automatically by the automatic data handling system and results are presented in weight percent of organic matter. Total of 108 samples were analysed and their TOC determined.

4.4.5. **Sample Reproduceability**

Table 4.1 shows that samples were found on average to be reproduceable to the 1.79% absolute level, based upon 16 replicate analyses.

4. 5. *C H N ANALYSIS OF KEROGEN*

4. 5. 1. **Sample Preparation**

The acid insoluble total sedimentary organic matter (kerogen) samples, obtained by combining equal portions of all seven float fractions of each sample from the density separation described in Sec. 4.3, were dried in an oven at 40°C + 2°C in a nitrogen atmosphere. Drying continued until each sample reached a fairly constant weight. The dried organic matter of each

Table 4.1 Total Organic Carbon, Sample Reproduceability

Sample Number	% TOC	% TOC	Reproduce-ability	% Error
RA-W/3-3	0.41	0.40	0.41 ± 0.001	2.44
Su/3-2	0.44	0.41	0.43 ± 0.002	3.49
R-A-W/4-2	0.45	0.43	0.44 ± 0.01	2.27
Sa/4-1	0.50	0.48	0.49 ± 0.01	2.04
Su/4-1	0.48	0.46	0.47 ± 0.01	2.13
Mi/5-2	4.68	4.99	4.84 ± 0.16	3.20
R-A-W/5-1	0.48	0.49	0.49 ± 0.01	1.02
Sa/5-2	4.96	5.03	5.00 ± 0.04	0.70
Mi/9-1	1.78	1.80	1.79 ± 0.01	0.56
Sa/9-1	0.82	0.77	0.80 ± 0.03	3.13
Sa/11-1	2.70	2.82	2.76 ± 0.06	2.17
Kh/11-2	0.34	0.33	0.34 ± 0.01	1.47
Bu/11-1	0.46	0.46	0.46 ± 0.00	0.00
Mi/12-2	7.21	7.11	7.16 ± 0.05	0.69
Mi/14-1	1.30	1.32	1.31 ± 0.01	0.76
Sa/14-2	2.77	2.92	2.85 ± 0.08	2.63

Average Sample Error = 1.79% absolute

sample was then hand crushed in a clean mortar using an agate pestle to ensure homogeneity before being stored in a stoppered glass tube in a dessicator ready for elemental analysis.

4. 5. 2. **Instrument Description**

The model 240C Elemental Analyzer described in part 4. 4. 2 was used to analyse kerogen samples for their carbon (C), hydrogen (H), and nitrogen (N) contents.

4. 5. 3. **Operating Procedure and Sample Analysis**

Between 1-4 milligrams of each sample of kerogen prepared as described in part 4. 5. 1 were accurately ($\mp$ 0.001 mg) weighed into a clean platinum boat using AD-2 Autobalance. Each sample was then placed in a dessicator ready to be analyzed. The same operating procedure and sample analysis described in part 4. 4. 3 for total organic carbon determination were followed to stabilize and calibrate the machine before being ready to analyze kerogen samples for their carbon (C), hydrogen (H), and nitrogen (N) contents.

4. 5. 4. **Presentation of Results**

The calculations are handled automatically by the automatic data handling system and results are presented in weight percentages. Total of 58 kerogen samples were analysed and their carbon, hydrogen, and nitrogen contents

were expressed as percentages by weight for each kerogen sample.

4. 5. 5. **Sample Reproduceability**

Carbon : Table 4.2 shows that carbon determinations in kerogen elemental analyses were found on average to be reproduceable to the 1.37% absolute level, based on 11 replicate analyses.

Hydrogen : Table 4.3 shows that hydrogen determinations in kerogen elemental analyses were found on average to be reproduceable to the 1.57% absolute level, based on 11 replicate analyses.

4. 6. *OXYGEN ANALYSIS OF KEROGEN*

4. 6. 1. **Sample Preparation**

Kerogen samples were prepared for oxygen analysis as described in part 4.5.1.

4. 6. 2. **Instrument Description**

The kerogen oxygen analysis was performed using Perkin Elmer Model 240 Elemental Analyser after a modificatioon to the combustion train. The analytical and the electronic systems described in part 4. 4. 2 remain unchanged. The oxygen supply during CHN analysis is shut off and the sample pyrolysis is carried out in an oxygen-free atmosphere.

Table 4.2 Carbon Determinations, Sample Reproduceability

Sample Number	% C	% C	Reproduce-ability	% Error
RA-W/1-1	39.71	41.01	40.36 ± 0.65	1.61
Su/1-2	65.29	68.35	66.82 ± 1.53	2.29
Mi/5-1	71.20	73.37	72.29 ± 1.09	1.50
Mi/5-2	71.61	70.11	70.86 ± 0.75	1.06
Mi/10-2	70.18	70.12	70.15 ± 0.03	0.04
Mi/11-1	66.64	65.07	65.86 ± 0.79	1.19
Kh/11-1	59.09	57.15	58.12 ± 0.97	1.67
Mi/12-1	68.65	71.31	69.98 ± 1.33	1.90
Mi/14-1	71.26	69.05	70.16 ± 1.11	1.58
Sa/14-2	66.24	64.65	65.45 ± 0.80	1.21
Kh/14-1	58.52	57.34	57.93 ± 0.59	1.02

Average Sample Error = 1.37% absolute

Table 4.3 Hydrogen Determinations, Sample Reproduceability

Sample Number	% H	% H	Reproduce-ability	% Error
RA-W/1-1	3.89	3.99	3.94 ± 0.05	1.27
Su/1-2	7.48	7.23	7.36 ± 0.13	1.70
Mi/5-	8.18	8.11	8.15 ± 0.04	0.43
Mi/5-2	7.58	7.99	7.79 ± 0.21	2.63
Mi/10-2	7.85	7.67	7.76 ± 0.09	1.16
Mi/11-1	7.19	6.91	7.05 ± 0.14	1.99
Kh/11-1	5.85	5.56	5.71 ± 0.15	2.54
Mi/12-1	7.60	7.50	7.55 ± 0.05	0.66
Mi/14-1	6.83	7.25	7.04 ± 0.21	2.99
Sa/14-2	6.65	6.87	6.76 ± 0.11	1.63
Kh/14-1	5.40	5.37	5.39 ± 0.02	0.28

Average Sample Error = 1.57% absolute

The combustion train for oxygen analysis is shown in Figure 4.5. The sample is pyrolysed in a helium atmosphere at about 975°C over platinized carbon in the pyrolysis tube and the oxygen in the sample is converted to carbon monoxide. Using helium as a carrier gas, the carbon monoxide and other gases produced during this oxidation are then passed through free copper at about 900°C and through an external "U" tube of colorcarb where any acid gases were removed. This acid gases removal is important to prevent an erroneously high readout from the carbon detector. The carbon monoxide and remaining gases are then passed through copper oxide held at about 670°C in the oxidation tube, where carbon monoxide was converted to carbon dioxide. Any basic gases are removed by a water trap as shown in the detector flow diagram in Figure 4.4. As explained earlier, if the acid or basic gases were permitted to pass into the carbon detector that will result in an incorrect (high) readout. Finally, the readout of the carbon detector was then recorded, and the oxygen analysis is complete.

4. 6. 3. **Operating Procedure and Sample Analysis**

Between analysis, the machine is in a standby mode. Prior to any calibration or sample determination, the instrument was flushed with an unweighed conditioning sample of benzoic acid (microanalytical grade). A series of blanks were run to stabalize the machine. Next, benzoic acid (composition : C = 68.84% ; H = 4.95% ; O = 26.20% ; N = 0%) was used as a standard to calibrate the instrument. Between 1-4 milligrams of benzoic acid in a clean platinum boat, weighed to an accuracy of $\mp$ 0.001

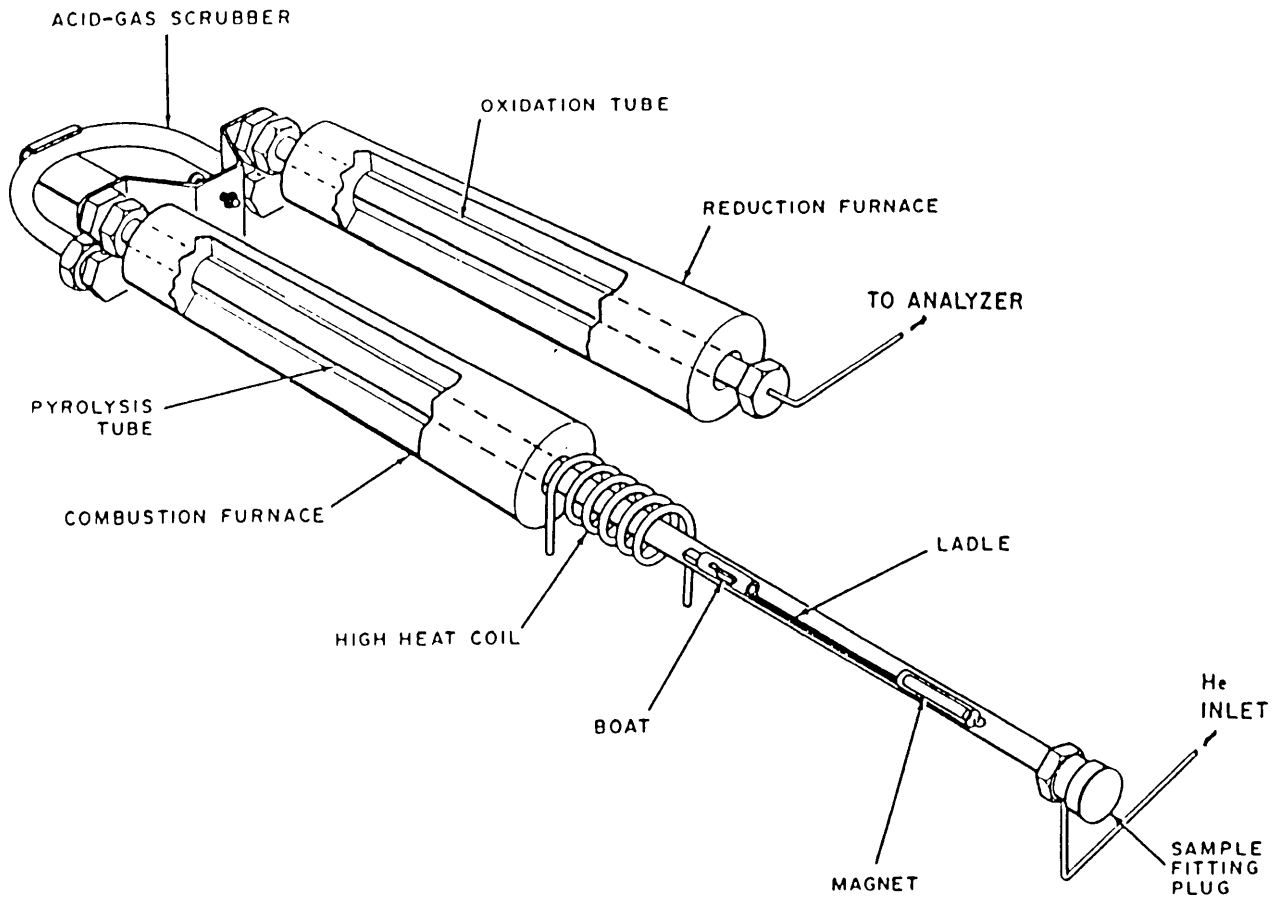


Figure 4.5 Combustion Train, Oxygen Analysis

(From Perkin Elmer Manual)

milligrams using the AD-2 autobalance, was analyzed and the result was used to calculate machine sensitivities. The calibration values having to be within certain recommended limits. After establishing the blank and sensitivity values of the instrument, each kerogen sample which was prepared as described in part 4. 5.1 was introduced into the analyser, and the analyses proceeded automatically. The readout of the carbon detector was recorded and transmitted on a Perkin-Elmer model 561 - millivolt recorder.

4. 6. 4. **Presentation of Results**

The signal output from the carbon detector was recorded in bar format using a Perkin-Elmer model 561 - millivolt recorder. The difference in microvolts between the signal output of the carbon detector and its background level (blank value) is directly proportional to oxygen concentration in the sample.

A simple arithmatic computation using determined oxygen concentration and machine sensitivity values then allowed calcualtion of oxygen weight percentage for each kerogen sample. Total of 58 kerogen samples were analysed and their oxygen contents were determined to be used with CHN results to calculate H/C and O/C ratios for each kerogen sample.

4.6.5. **Sample Reproduceability**

Table 4.4 shows that oxygen determinations in kerogen elemental analyses were found on average to be reproduceable to the 2.21% absolute level, based on 9 replicate analyses.

4. 7. *PROGRAMMED TEMPERATURE PYROLYSIS OF WHOLE ROCK SAMPLES*

4.7.1. **Principles of The Method**

Hydrocarbons in sedimentary rocks are usually composed of two phases. These are - the hydrocarbons already present in the rock in the form of solvent - extractable bitumen, and the partially converted (thermal-decomposition) solid kerogen. Thus, when a rock sample is slowly heated in the absence of oxygen, the first to volatilize at low temperatures is the free, already generated, hydrocarbons present in the rock and then as the temperature continues to rise, the second phase of hydrocarbons is released by thermal decomposition of kerogen present in the rock sample. The artificial heating of rock samples in the absence of oxygen in the laboratory is referred to as pyrolysis (Kinghorn, 1983; Waples, 1985).

4. 7. 2. **Sample Preparation**

Samples of powdered whole rock of less than 75 microns grain size were prepared as described on Sec 4.1. About 5 milligrams of each sample were

Table 4.4 **Oxygen Determinations, Sample Reproduceability**

Sample Number	% O	% O	Reproduce-ability	% Error
RA-W/4-1	13.11	12.41	12.76 ± 0.35	2.74
Mi/5-2	8.69	8.97	8.83 ± 0.14	1.59
Sa/5-1	10.76	10.22	10.49 ± 0.27	2.57
Sa/9-1	9.94	10.37	10.16 ± 0.22	2.12
Mi/10-2	10.56	11.34	10.95 ± 0.39	3.56
Mi/12-1	9.87	10.12	10.00 ± 0.13	1.25
Mi/14-1	9.00	9.41	9.21 ± 0.21	2.23
Sa/14-2	8.02	8.22	8.12 ± 0.10	1.23
Kh/14-2	8.85	9.32	9.09 ± 0.24	2.59

Average Sample Error = 2.21% absolute

accurately (∓ 0.001 mg) weighed into a clean platinum boat using a Perkin-Elmer AD-2 autobalance.

4. 7. 3. **Instrument Description**

The pyrolysis equipment used for this analysis was made in the Organic Geochemistry Laboratory at Imperial College. Figure 4.6 shows a schematic diagram of the instrument. It consists of a 16 cm long stainless steel pyrolysis tube lined on the outside with a quartz tube, and brazed at one end to a rectangular heated block which is maintained at about 300°C by a heating coil. As shown in Figure 4.6, the pyrolysis tube has a variable internal diameter, 5 mm diameter from the open end to about the end of the heated zone (oven) and it then narrows to a diameter of 1.5 mm where it passes through the heated block to the flame ionization detector (FID) in the Perkin-Elmer 8320 Gas Chromatograph. The heated block and the fine size of the diameter of the pyrolysis tube were designed to avoid excessive temperature drop, thus preventing any possible condensation if the gases are released by pyrolysis. A small tubular oven (about 2.5 cm long) with a heating coil wound round the quartz liner on the steel tube is controlled via a transformer by a temperature programmer and controller unit. The heating coil is covered by a ceramic tube which is filled with TRI-MOR air setting cement to prevent any significant heat loss. A steel ladle and its holder are fitted tightly to the open end of the pyrolysis tube to prevent entry of air into the pyrolysis tube and at the same time allow a free movement of the steel ladle in and out of the pyrolysis tube carrying the rock sample. Oxygen-free Nitrogen (OFN), used as a carrier gas, is

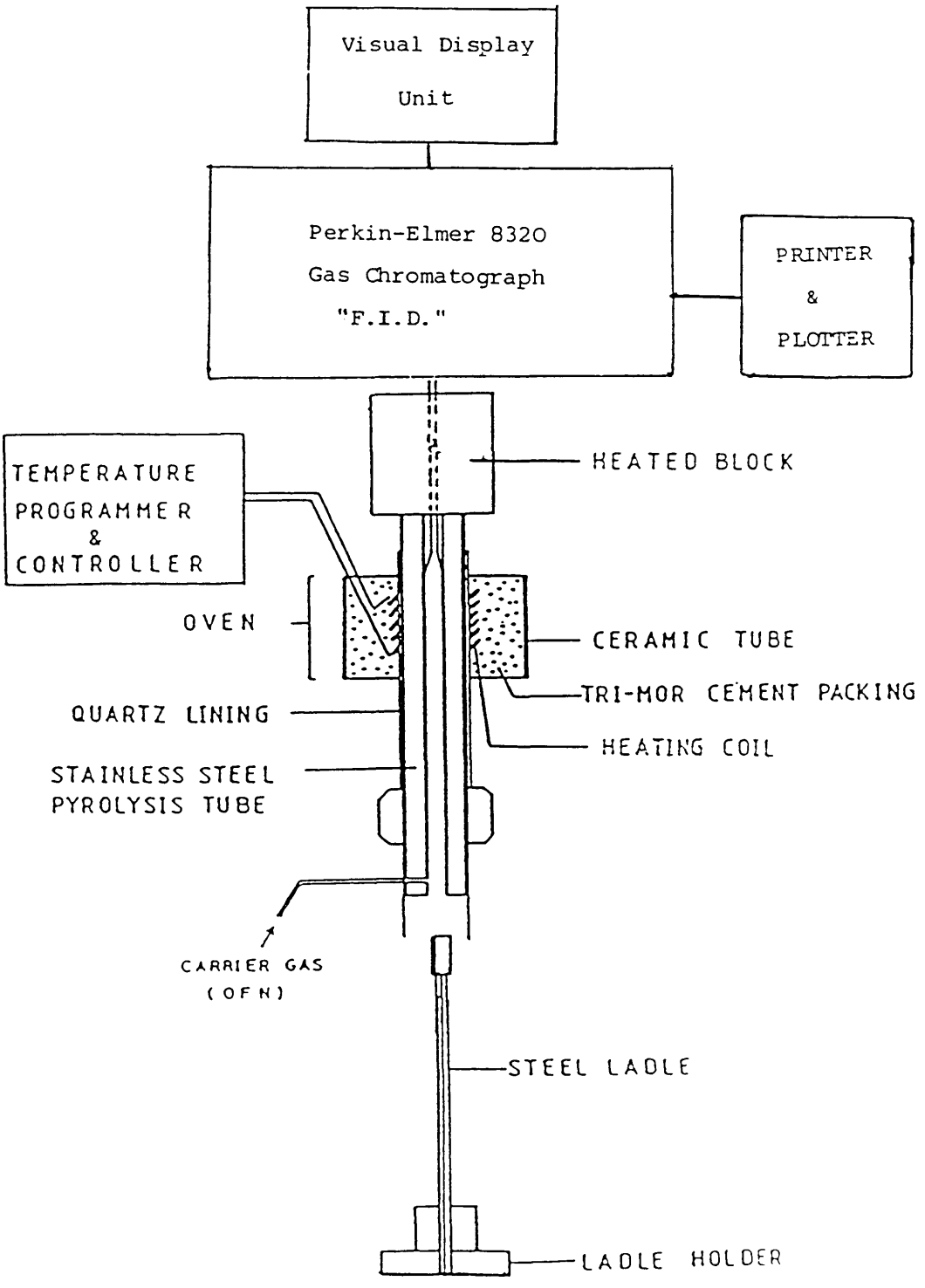


Figure 4.6 Schematic Diagram of Whole-Rock Programmed-Temperature.

introduced at the opening end of the pyrolysis tube.

4. 7. 4. **Operating Procedure and Sample Analysis**

Prior to any sample analysis, the instrument was calibrated using 3% Squalane as a standard. After making sure the equipment has attained its optimum operating conditions, the steel ladle was removed from the pyrolysis tube and left to cool to room temperature. The boat with the sample, prepared as described in part 4.7.2, was loaded into the steel ladle and introduced into the cold part of the steel pyrolysis tube. The ladle holder was then tightly fitted to the open end of the pyrolysis tube. The instrument was purged with oxygen-free nitrogen for 3 minutes to sweep out any oxygen introduced into the system during the loading and unloading of the sample. Next, the sample was injected using the steel ladle into the hot zone (oven) at about 200°C and left at this temperature for 5 minutes. During this time, the already generated free hydrocarbons (bitumen) in the rock sample were volatilized and swept by the carrier gas (OFN) to the flame ionization detector (FID) in the gas chromatograph. The first peak (P_1) was recorded and the temperature programmer was then started. The rock sample was progressively heated from 200°C to 550°C at the rate of 25°C/minute. As the temperature continued to rise, the second phase of hydrocarbons (P_2) was released by the thermal decomposition of kerogen present in the rock sample and detected continuously by the "FID".

A diagramatical illustration of the analytical steps described above and example of a recorded detector response are shown in Figure 4.7.

At the end of the temperature programme, the programmer was switched off and sufficient time was allowed for the detector response to return to the background level and also for the oven to cool gradually back to 200°C.

A total of 16 whole rock samples were analysed and the P_1, P_2, and T_{max} were determined.

4. 7. 5. **Presentation of Results**

The Perkin-Elmer 8320 Gas chromatograph used with the Pyrolysis Instrument is equipped with a data handling system. The results are presented on a visual Display Unit which is linked to a printer/plotter.

P_1 and P_2 are expressed in terms of kilograms of hydrocarbons per tonne of whole rock. The temperature at which the second peak reaches maximum detector response (i.e. T_{max}) was determined. Figure 4.7 depicts an example of a recorded detector response of a programmed-temperature pyrolysis of a whole rock sample.

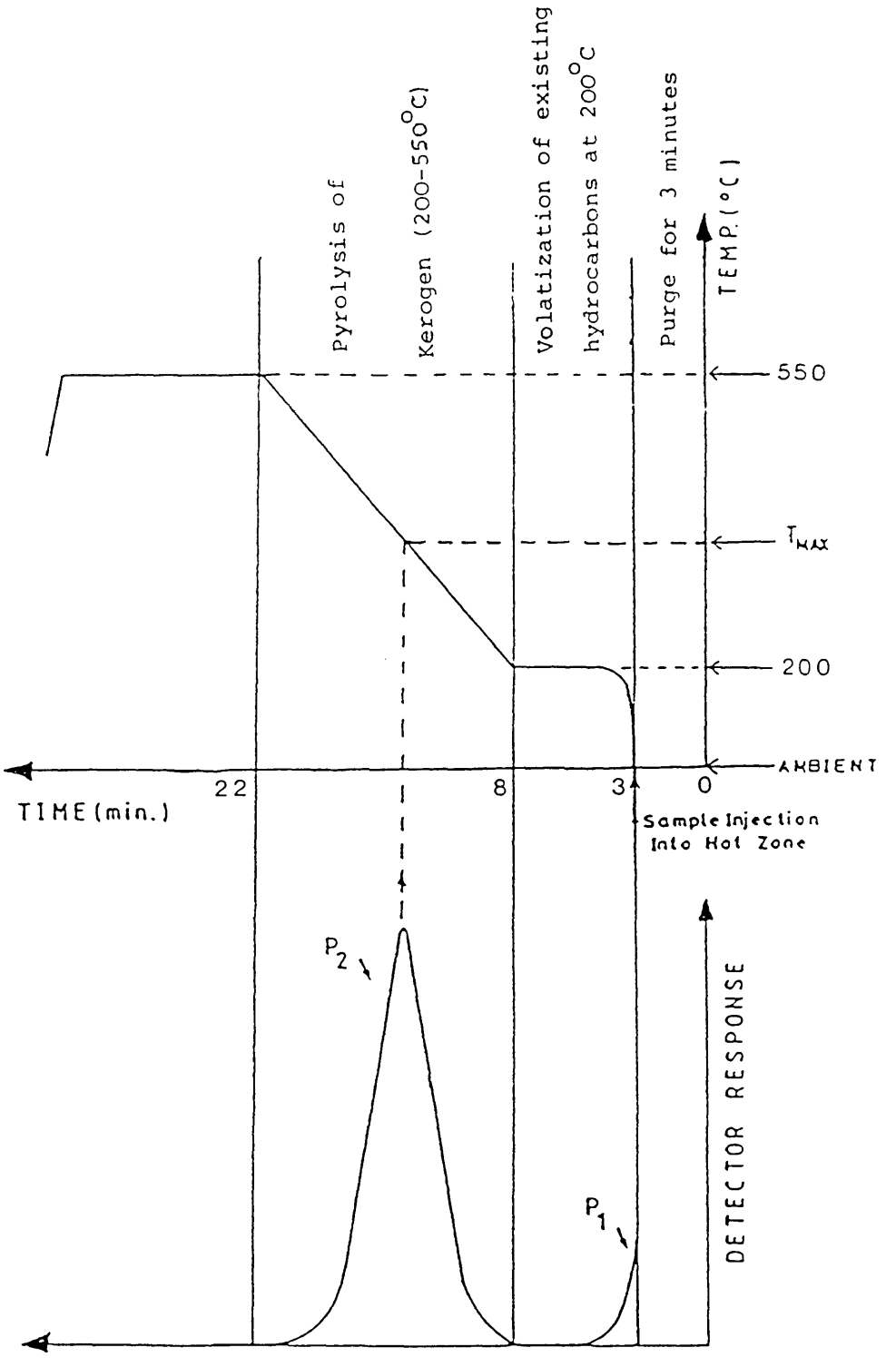


Figure 4.7 A diagramatical illustration of analytical steps and an example of a recorded detector response.

4. 7. 6. **Sample Reproduceability**

Everyday, before any sample run, the machine accuracy was checked by analyzing a standard rock sample. Table 4.5 shows that the standard rock sample was found on average to be reproduceable to the 0.45% absolute level, based upon 8 separate analyses throughout the sample runs.

Table 4.5 The Standard Rock Sample Reproduceability

Weight of the Sample (mg.)	P_2 (kg./tonne)	Diff. from Average	% Error
5.023	31.8189	0.1037	0.32
5.008	32.1652	0.2426	0.75
5.032	32.03	0.1074	0.33
5.035	31.8176	0.1050	0.32
5.022	31.928	0.0054	0.01
5.007	32.146	0.2234	0.69
5.006	31.7878	0.1348	0.42
5.030	31.687	0.2356	0.73

Average of eight P_2 results = 31.9226
Average Sample Error = 0.45 %

CHAPTER FIVE

ORGANIC RICHNESS OF THE CRETACEOUS INTERVALS

5.1 INTRODUCTION 120

5.2 TOTAL ORGANIC CARBON (TOC) CONTENT OF SAMPLES 121

5.3 FACTORS INFLUENCING ORGANIC RICHNESS OF THE SAFANIYA AND MISHRIF 126

5.3.1 Bottom Water Oxygenation 128

5.3.2 Primary Biologic Productivity 131

5.3.3 Rate of Sediment Accumulation 132

5.3.4 Sediment - Particle Size 135

5.3.5 Palaeobathymetry (Water Depth) 138

5.3.6 Oceanic Anoxic Events 139

5. 1. *INTRODUCTION*

The origin of petroleum is one of the most controversial questions in the geological sciences. There is a wide range of conflicting views and speculations regarding this problem (Pratt, 1956; Gaucher, 1972; Porfir'ev, 1974; Gold, 1979). Most geologists, however, believe in some form of the "organic theory" which indicates that petroleum is the product of physiochemical changes in sedimentary organic matter (Tissot and Welte, 1984).

The organic richness of sedimentary rocks is expressed in terms of weight percent total organic carbon. This is often designated the abbreviation TOC. It is generally accepted that an amount of 0.5% organic carbon content is the minimum requirement to classify a clastic rock as a potential source rock, whereas carbonate potential source rocks must contain at least 0.3% TOC (Kinghorn, 1983; Tissot and Welte, 1984). Cooper and Cornford (1984) have stated that an organic carbon content up to 2% is needed to qualify a rock as a possible source rock in petroleum exploration.

It should be noted that the measurement of TOC in sediments alone is insufficient to identify the oil potential of source rocks. Transported terrestrial organic matter, ozidized aquatic organic matter, and reworked organic matter (dead carbon) can create high levels of organic carbon in marine sediments. However, this concentrated organic matter is hydrogen-poor, gas prone, and without significant oil generating potential (Tissot *et*

al., 1974; Dow, 1977; Demaison and Moore, 1980). Primary organic constituents such as phytoplankton are more hydrogen-rich and oil-prone than terrestrial organic constituents such as higher plant fragments. The petroleum generating potential of a sediment depends on its volume, organic content, type of organic constituents, and degree of thermal maturation.

In this study the term potential source rocks is used to describe a volume of sediments which contains a sufficient amount of a suitable type of organic matter to generate significant quantities of hydrocarbons, but has not yet reached sufficient organic maturation.

This chapter is concerned with establishing which of the Cretaceous intervals of ALRub ALKhali are organicly rich enough to qualify as a potential hydrocarbon source rock and the factors which might have influenced this organic richness.

5. 2. *TOTAL ORGANIC CARBON (TOC) CONTENT OF SAMPLES*

The Cretaceous section in the study area has been extensively screened by total organic carbon analysis to try to establish which intervals of the Cretaceous are organic rich to qualify to be regional potential hydrocarbon source rocks in ALRub ALKhali basin. The results of the TOC analysis of the rock samples are shown in Table 5.1 together with the locality, interval, and the lithologic descriptions. From this table, it is noted that, apart from some local small variations, only two units of the Middle Cretaceous in

Table 5.1 Results of the total organic carbon analysis of the rock samples with their lithological descriptions.

Locality/ Borehole	Formation/ Interval	Sample Number	Total Organic Carbon (TOC) (wt.%)	Lithology
WELL 1	Mishrif	Mi/1-1	0.38	White to cream limestone
	Rumaila, Ahmadi and Wara	R-A-W/1-1	0.69	Greenish grey shale
	Yamama	Ya/1-1	0.44	Light grey limestone
	Sulaiy	Su/1-1	0.34	Light tan to grey limestone
		Su/1-2	0.54	Light tan to grey limestone
WELL 2	Aruma	Ar/2-1	0.31	White to cream limestone
	Yamama	Ya-2-1	0.46	Mixture of tan to light grey limestone and grey shale
	Sulaiy	Su/2-1	0.26	Tan to light grey limestone
		Su/2-2	0.4	Grey limestone
WELL 3	Aruma	Ar/3-1	0.89	Grey claystone/stringers of lignite
		Ar/3-2	0.74	Brown lignitic shale
		Ar/3-3	0.77	Red and grey shale
	Mishrif	Mi/3-1	0.67	Grey, brown shale
	Rumaila, Ahmadi and Wara	R-A-W/3-1	0.58	Red-brown, brown, olive grey shale
		R-A-W/3-2	0.56	Grey shale
		R-A-W/3-3	0.43	Red-brown and greyish shale
	Safaniya	Sa/3-1	0.4	Red brown and green-grey shale
	Khafji	Kh/3-1	0.77	Red brown and green-grey shale
		Kh/3-2	0.46	Red brown and green-grey shale
	Yamama	Ya/3-1	0.67	Olive-grey shale
	Sulaiy	Su/3-1	0.34	Grey limestone
		Su/3-2	0.43	Grey limestone

Table 5.1 Cont.

Locality/ Borehole	Formation/ Interval	Sample Number	Total Organic Carbon (TOC) (wt.%)	Lithology
WELL 4	Aruma	Ar/4-1	0.6	Cream limestone
		Ar/4-2	0.93	Grey to dark grey shale
		Ar/4-3	0.62	Grey to green grey shale
		Ar/4-4	0.62	Grey to green-grey shale
		Ar/4-5	0.56	Dark grey shale
	Mishrif	Mi/4-1	0.38	Grey shale + brown limestone
	Rumaila, Ahmadi and Wara	R-A-W/4-1	0.53	Dark grey shale
		R-A-W/4-2	0.48	Dark grey shale
		R-A-W/4-3	0.85	Light brown limestone
		R-A-W/4-4	0.49	Red-brown shale
		R-A-W/4-5	0.7	Red-brown shale
	Mauddud	Ma/4-1	0.58	White to light brown limestone
	Safaniya	Sa/4-1	0.49	Red-brown shale
	Khafji	Kh/4-1	0.35	Grey brown shale
		Kh/4-2	0.41	Grey brown shale
	Biyadh	Bi/4-1	0.9	Brown to cream limestone
	Buwaib	Bu/4-1	0.41	Grey calcarenitic limestone
	Yamama	Ya/4-1	0.65	Brown to grey limestone
	Sulaiy	Su/4-1	0.5	Brown to grey limestone
		Su/4-2	0.65	Brown to grey limestone
WELL 5	Aruma	Ar/5-1	0.75	Tan limestone
		Ar/5-2	0.78	Grey to green shale
	Mishrif	Mi/5-1	5.61	Dull brown lime mud
		Mi/5-2	4.99	Dull brown lime mud
	Rumaila, Ahmadi and Wara	R-A-W/5-1	0.49	Dark grey & brown shale
		R-A-W/5-2	0.58	Dark grey & brown shale
	Safaniya	Sa/5-1	0.4	Brown & grey shale
		Sa/5-2	5.03	Dark brown lime mud contaminated with grey shale
	Khafji	Kh/5-1	0.36	Brown to grey shale
	Buwaib	Bu/5-1	0.39	Grey to brown limestone

Table 5.1 Cont.

Locality/ Borehole	Formation/ Interval	Sample Number	Total Organic Carbon (TOC) (wt.%)	Lithology
WELL 9	Aruma	Ar/9-1	0.42	White to cream limestone
		Ar-9-2	0.69	Dark grey shale
		Ar/9-3	0.47	Brown, grey shale
		Ar/9-4	0.66	Dark grey shale
	Mishrif	Mi/9-1	1.8	Dark brown to grey impure limestone & shale
	Rumaila, Ahmadi and Wara	R-A-W/9-1	0.52	Grey to brown shale
		R-A-W/9-2	0.41	Dark brown shale
	Safaniya	Sa/9-1	0.82	Grey brown shale & white limestone
	Khafji	Kh/9-1	0.56	Red to brown, grey shale
WELL 10	Aruma	Ar/10-1	0.52	Tan to light brown lime stone
		Ar/10-2	0.58	Grey to greenish shale
		Ar/10-3	0.63	Grey to greenish shale
	Mishrif	Mi/10-1	1.27	Cream and grey limestone + brown & grey earthy lime mud
		Mi/10-2	3.46	Brown & grey earthy lime mud
		Mi/10-3	2.01	Brown, earthy lime mud + tan limestone
	Rumaila, Ahmadi and Wara	R-A-W/10-1	0.39	Brown & greenish grey shale
	Safaniya	Sa/10-1	2.74	Brown, grey lime mud
		Sa/10-2	4.07	Brown, earthy lime mud
	Khafji	Kh/10-1	0.39	Brown & grey shale
	Buwaib	Bu/10-1	0.47	Grey limestone
	Sulaiy	Su/10-1	0.43	Dark grey limestone
		Su/10-2	0.46	Dark grey limestone
WELL 11	Mishrif	Mi/11-1	0.91	Off-white to tan limestone
	Rumaila, Ahmadi and Wara	R-A-W/11-1	0.64	Off-white to light grey limestone
		R-A-W/11-2	0.35	Off-white to cream limestone
	Safaniya	Sa/11-1	2.82	Mixture of grey shale & grey brown limestone
	Khafji	Kh/11-1	0.73	Grey & red brown shale
		Kh/11-2	0.49	Red brown shale

Table 5.1 Cont.

Locality/ Borehole	Formation/ Interval	Sample Number	Total Organic Carbon (TOC) (wt.%)	Lithology
WELL 11	Biyadh	Bi/11-1	0.4	Tan & light grey limestone
		Bi/11-2	0.51	Off-white to light grey limestone
	Buwaib	Bu/11-1	0.46	Grey & tan limestone
	Yamama	Ya/11-1	0.45	Grey & tan limestone
	Sulaiy	Su/11-1	0.56	Light grey to grey limestone
		Su/11-2	0.67	Grey limestone
WELL 12	Aruma	Ar/12-1	0.66	Dark grey shale
	Mishrif	Mi/12-1	4.48	Dark grey-brown, thinly laminated lime mud
		Mi/12-2	7.21	Dark grey-brown, thinly laminated lime mud
	Safaniya	Sa/12-1	0.86	Brown, grey shale
	Khafji	Kh/12-1	0.47	Dark brown, grey shale
WELL 14	Aruma	Ar/14-1	0.71	Tan to grey limestone
		Ar/14-2	1.16	Light grey argillaceous limestone
		Ar/14-3	0.84	Light grey argillaceous limestone
		Ar/14-4	1.9	Grey to dark grey shale
		Ar/14-5	1.55	Grey to dark grey shale
		Ar/14-6	1.24	Grey to dark grey shale
	Mishrif	Mi/14-1	1.37	Grey, brown lime mud
		Mi/14-2	1.34	Grey, brown lime mud
	Rumaila, Ahmadi and Wara	R-A-W/14-1	0.46	Off-white, light brown limestone
	Safaniya	Sa/14-1	1.14	Dark grey shale
		Sa/14-2	2.92	Dark brown lime mud
	Khafji	Kh/14-1	0.71	Grey shale
		Kh/14-2	0.71	Grey shale
	Biyadh	Bi/14-1	0.66	Light grey limestone
	Buwaib	Bu/14-1	0.59	Light grey limestone
	Yamama	Ya/14-1	0.47	Light to dark brown limestone
	Sulaiy	Su/14-1	0.45	Light to dark brown limestone
		Su/14-2	0.54	Light to dark brown, grey limestone

ALRub ALKhali basin contain organic carbon in excess of the minimum required to qualify them as regional potential hydrocarbon source rocks. These two organic rich units are Safaniya and Mishrif Members. Figure 5.1 shows the variations of the organic carbon richness of Safaniya and Mishrif throughout all the sampled boreholes of the study area. Both units have low TOC values (0.38% to 0.67%) in the area of wells 1, 2, 3 and 4. However, the TOC values obtained for the Safaniya samples in wells 11, 14, 10 and 5 vary from 2.82% to 5.03%, while those for the Mishrif samples in wells 9, 10, 5 and 12 vary from 1.8% to 7.21%.

It should be noted that the high TOC values for the Safaniya Member in the area of wells 11, 14, 10 and 5 and also for the Mishrif Member in the area of wells 9, 10, 5 and 12 are associated with two large intrashelf basins (Figure 3.7A and Figure 3.10A) which developed in the eastern part of the study area during the deposition of the Safaniya (Middle to Late Albian) and the Mishrif (Late Cenomanian to Late Turonian). The organic richness is concentrated in the lower part of these two units. These organic rich intervals are composed mostly of dark coloured lime mudstone with thickness ranging from 15m to 76m.

5. 3. *FACTORS INFLUENCING ORGANIC RICHNESS OF THE SAFANIYA AND MISHRIF*

In order for potential hydrocarbon source rocks to be formed, significant amounts of organic matter must be deposited and protected from diagenetic destruction. Factors controlling and influencing the accumulation and

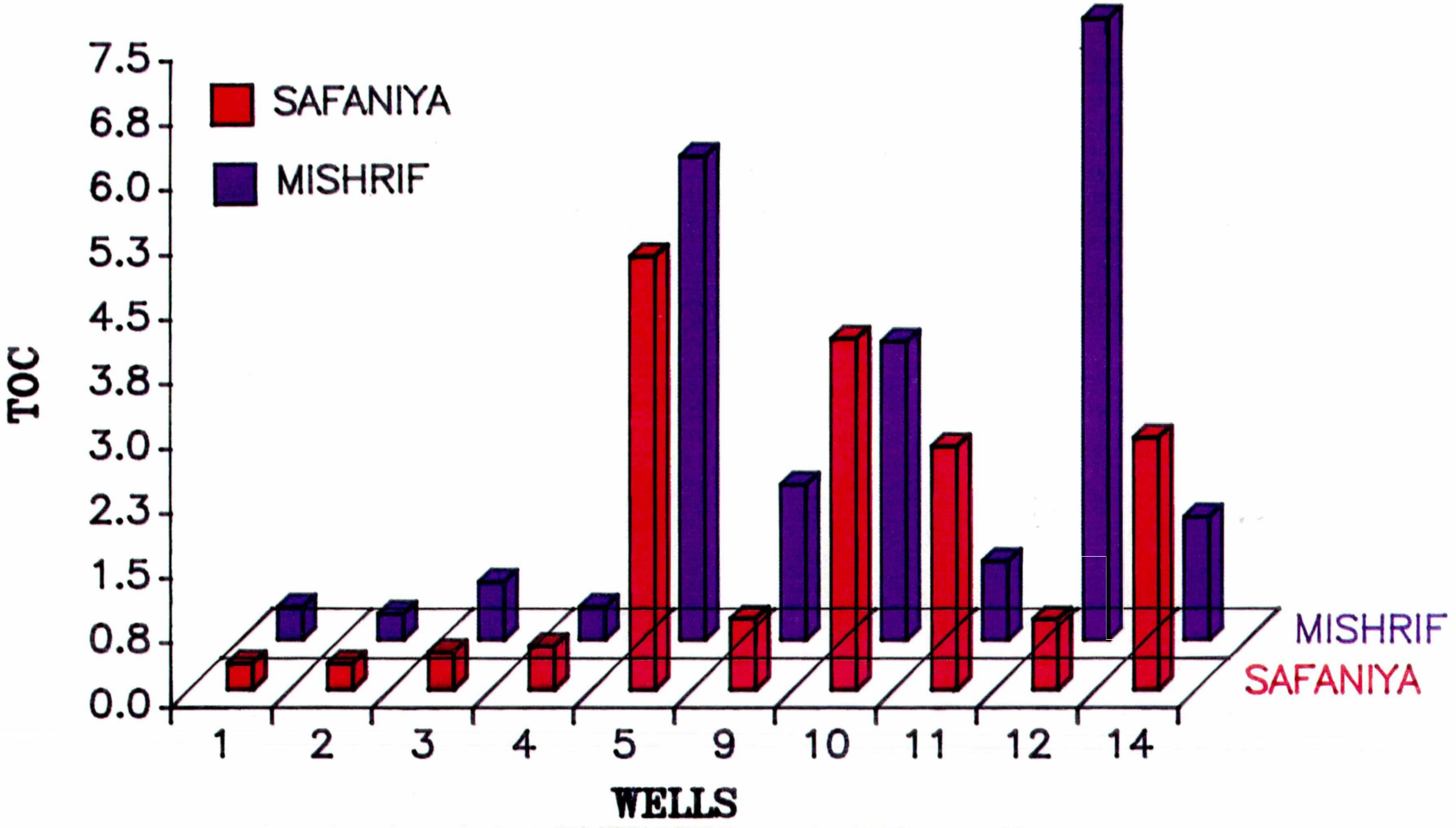


Figure 5.1 Variations of the organic carbon richness of the Lower Safaniya and Lower Mishrif throughout all the sampled boreholes.

preservation of organic matter in sediments could be divided into biological, chemical, physical, and geological. However, it is not posssible to point out simple processes which lead to sedimetary organic matter accumulation. All these divisions are interrelated and it is the interplay between them that controls the organic richness of the sediments.

In the eastern part of ALRub ALKhali basin, it has been determined through total organic carbon analysis that the Safaniya and Mishrif Members appear to be far richer in organic matter than all other units of the Cretaceous section. The following factors might help to understand the reasons for this organic richness :

5. 3. 1. **Bottom Water Oxygenation**

The zone in the water column in which oxygen content is high is called the oxic zone, whereas the anoxic zone is oxygen depleted or oxygen-deficient. Processes that occur in these two zones are called aerobic and anaerobic, respectively. The terminology describing levels of oxygenation in the literature is not standard. Many individual authors adopt different definitions (Demaison and Moore, 1980; Tyson, 1987). Despite this variation in definition, it is generally accepted that oil-prone organic matter is only preserved under oxygen-depleted or oxygen-deficient conditions (anoxic environment). At low levels of oxygenation, macrobenthic activity ceases or is inhibited, which leads to the cessation or inhibition of bioturbation and the minimization of bacterial oxidation of organic matter (Demaison and Moore, 1980; Kinghorn, 1983; Tyson,

1987). The benthic biomass is responsible for organic matter consumption and bioturbation at the sea floor. Thus, the organic matter in sediment's anoxic water is commonly more reduced (hydrogen-rich), more lipid rich, and more abundant than in oxic water. The organic residues of anaerobic bacterial degradation are more reduced (hydrogen-rich) and more lipid-rich than those resulting from oxidation by aerobic microbes (hydrogen-lean). Microbial degradation results in an elimination of functional groups on the organic molecules. The carboxyl groups and hydrocarbon chains are easily attacked and CH_4 or CO_2 is produced (Kinghorn, 1983; Tissot and Welte, 1984). The presence of long hydrocarbon chains in the organic matter is important to liquid oil formation. Reduction of these chains by microbial activity not only reduces the total organic carbon content of the sediment, it also reduces the ability of the organic matter to generate oil as thermal maturation occurs. Hence, bottom oxygenation is a major factor governing the accumulation of labile organic matter, and hence of potential oil-prone source rocks.

Samples Mi/12-1 (4.48 TOC) and Mi/12-2 (7.21 TOC) are interpreted as Mishrif intrashelf basinal sediments. They were described in a core sample as thinly laminated lime mudstone. This is a strong indication of a low energy environment where bioturbation (macrobenthic activity) was inhibited or ceased probably due to low levels of oxygenation (Demaison and Moore, 1980). The environment during the deposition of Safaniya and Mishrif units, therefore, was most probably anoxic. Hence, the organic matter deposited is well preserved giving rise to high organic carbon contents in the intrashelf basinal area which developed during the

deposition of both Safaniya and Mishrif (see Figure 5.1).

Demaison and Moore (1980), among many others, indicate that bottom oxygen deficiency as well as oxygen depletion is induced primarly by water stratification (restricted circulation). However, Calvert (1987) and Morris (1987) challenge this view and argue that primary productivity is the major factor in creating bottom oxygen deficiency through removal of oxygen by organic matter degradation. In this study, it appears that bottom oxygen deficiency was probably influenced by both primary productivity of organic matter and restriction of water circulation as discussed below.

Based on ALRub ALKhali basin evolution study (Chapter 3), an intrashelf basin developed in the eastern part of the study area during the deposition of Safaniya and Mishrif Members (see Figure 3.7A and Figure 3.10A). This intrashelf basin (depression) was located in the shelf area, away from the shoreline (terrestrial influence) and protected from the Tethys ocean to the east by the shallow shelf margin of the Arabian Platform. Hence, the water circulation was most probably restricted within the intrashelf basinal area. Primary productivity being high in the euphotic zone above (discussed in the following section), then most probably a bottom-water anoxia would develop. The greater the supply of organic matter from surface waters, the greater the demand for bottom-water oxygen as the organic matter is degraded. This will enhance organic matter preservation and give rise to organic rich laminated sediments (e.g. samples Mi/12-1 and Mi/12-2).

5. 3. 2. **Primary Biologic Productivity**

Productivity is important simply because without adequate productivity, accumulation of organic rich sediments cannot occur. Production of organic matter is the first stage in the incorporation of organic matter into sediments to form potential source rocks. The principal source of aquatic organic matter is the phytoplankton (Bordovsky, 1965). They are composed of single-cell microscopic algae residing in the uppermost layers of water (the euphotic zone). Light and the availability of certain mineral nutrients such as nitrates and phosphates are the two main limiting factors to phytoplanktonic productivity. Planktonic organisms are responsible for the transport to the sea floor of much organic material and fine-grained mineral matter in faecal pellets or flocs held together by excreted mucus (Degens and Ittekkot, 1987).

As discussed above, changes in the nutrient content can encourage marine organic matter production. Irving et al. (1974) argued that the renewal of mantle convection in the Middle Cretaceous activated the Tethys (east of the study area), abrubtly increased the rate of sea-floor spreading, and enlarged the oceanic ridges, causing maximum development of warm, shallow sea and releasing through igneous activity, greatly increased quantities of mineral nutrients. Upwelling of deep ocean water can introduce large quantities of nutrients into the euphotic zone, thus, promoting high photosynthetic productivity (Parrish and Curtis, 1982; Parrish, 1987). It has been suggested (Stoneley, 1987) that the shelf margin east of the study area might have been in a position to satisfy the conditions

required for oceanic upwelling during the Cretaceous. Also, Miller (1989) indicated a strong correlation of organic rich mud (Note: Safaniya and Mishrif organic rich samples are lime mud, see Table 5.1) with upwelling, which is sufficient to justify attempts to predict the sites of palaeo-upwelling.

Based on the discussion above and in section 5.3.1, the situation during the deposition of both Safaniya and Mishrif Members could be interpreted and summarized as shown in the schematic diagram in Figure 5.2.

5. 3. 3. **Rate of Sediment Accumulation**

Many authors indicate that the sediment accumulation rates have a significant effect on the total organic carbon content of marine sediments (Heath *et al.*, 1977; Mueller and Suess, 1979; Ibach, 1982; Bralower and Thierstein, 1987). Sedimentation rate is critical because fast burial of organic matter should remove labile organic compounds from the near surface sites of highest microbial degradation and therefore promote organic preservation (Calvert, 1987). At higher sedimentation rates, more organic matter is preserved (higher TOC) and oil-prone organic constituents are better preserved (increased oil-generation potential at thermal maturation).

For recent marine sediments, Mueller and Suess (1979) have shown that as the sedimentation rate increased, a higher percentage of the primary productivity, and oil-prone phytoplankton was preserved in the bottom

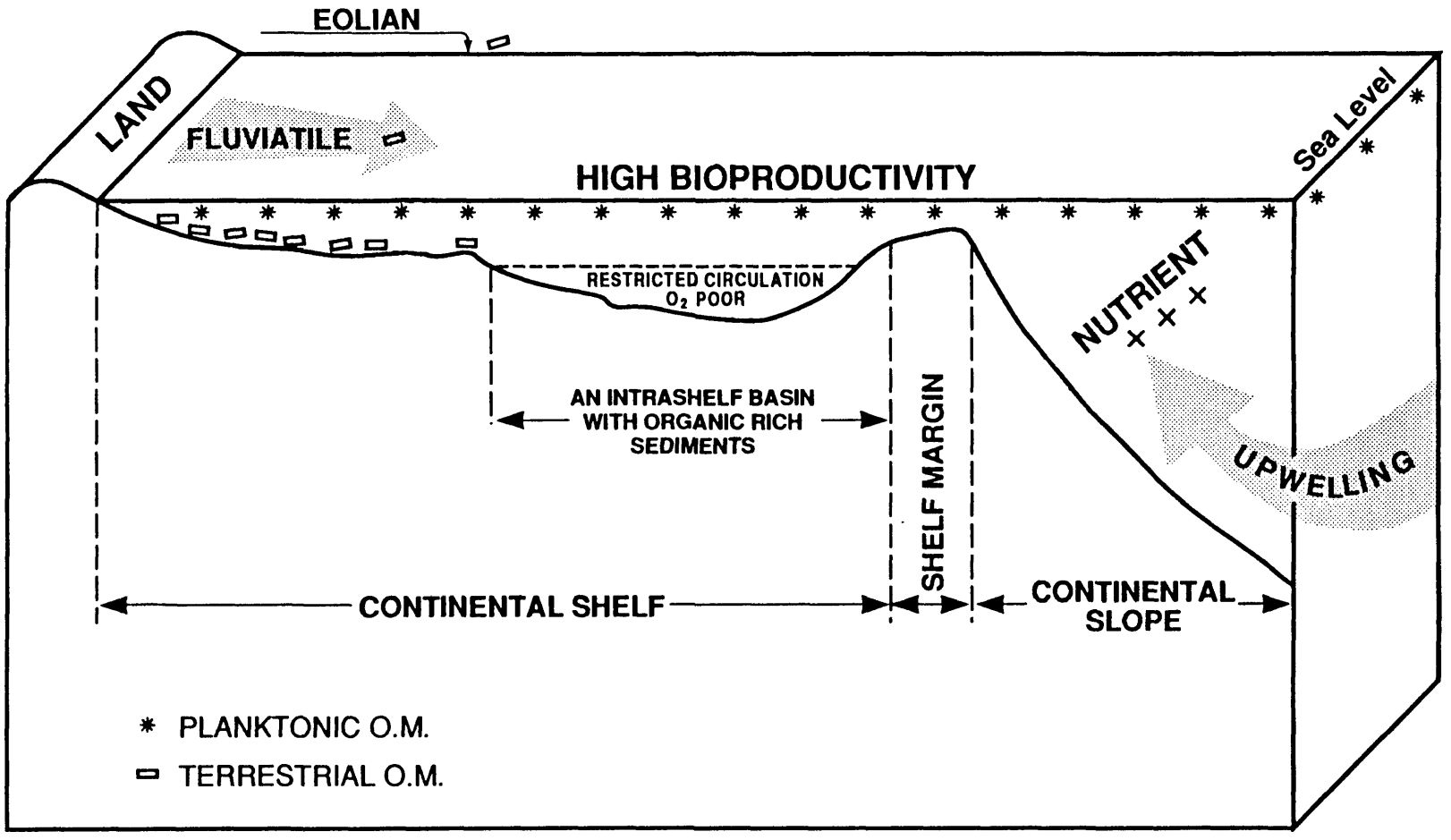


Figure 5.2 Schematic diagram showing depositional setting in an intrashelf basinal environment similar to the deposition of Safaniya and Mishrif.

sediments. The importance of sedimentation rate is further supported by Heath *et al* (1977). The results of their study indicate a relation between organic carbon content and sedimentation rate for fine-grained sediments in modern environments. Both studies demonstrate that the organic content of recent marine sediments increases quantitatively with sedimentation rate.

For ancient marine sediments, Ibach (1982) reached similar results in his study which indicate that a relation does exist between total organic carbon content and sedimentation rate for fine-grained ancient marine sediments. Differential compaction appears to have no significant effect on the relation between organic carbon content and sedimentation rate (Ibach, 1982).

High sedimentation rates can lead to the dilution of organic matter (Brumsack, 1980; Tyson, 1987). However, Mueller and Suess (1979) indicate two distinct trends at high rates of sedimentation. Where high sedimentation rates are associated with low primary biologic productivity, clastic dilution occurs and organic carbon content decreases with sedimentation rate. On the other hand, where high sedimentation rates are associated with a high primary productivity region (as the case in ALRub ALKhali basin), the organic carbon content continues to increase with increasing sedimentation rate.

Sedimentation rates for the Safaniya and Mishrif Members were calculated in all ten boreholes sampled in the study area. The time interval, in million years, for each member is based on the Geologic Time Scale compiled by Harland *et al* in 1982. The average sedimentation rates obtained for the

Safaniya and Mishrif are plotted with their TOC values as shown in Figure 5.3. There is a remarkable correlation between the increase in sedimentation rates and higher TOC contents.

5. 3. 4. **Sediment- Particle Size**

There is a broad correlation between particle size and organic richness in modern and ancient sediments. It appears that bacterial activity is influenced by granulometry. Fine-grained sediments represent low-energy environment of deposition. Diffusion of free oxygen and oxidizing salts dissolved in water in these fine-grained sediments is restricted. This limits the bacterial activity which in turn enhances organic matter preservation (Bordovsky, 1965). Coarser grained sediments have larger pore size and reflect deposition under more energetic hydrodynamic regimes. These sediments permit easy diffusion of free oxygen (dissolved in water) and oxidizing agents which give rise to high levels of bacterial activity (Tissot and Welte, 1984). They are always very low in organic carbon content.

An attempt was made to study the effects of lithology on influencing the organic richness in ALRub ALKhali basin. The $CaCO_3$ contents of representative samples from the Safaniya and Mishrif organic rich units have been determined in the laboratory of sedimentology of the Geology Department at Imperial College. The results together with the TOC values and the lithologic description of these samples are shown in Table 5.2. It is noted that, in general, the high TOC values are associated with dark colour

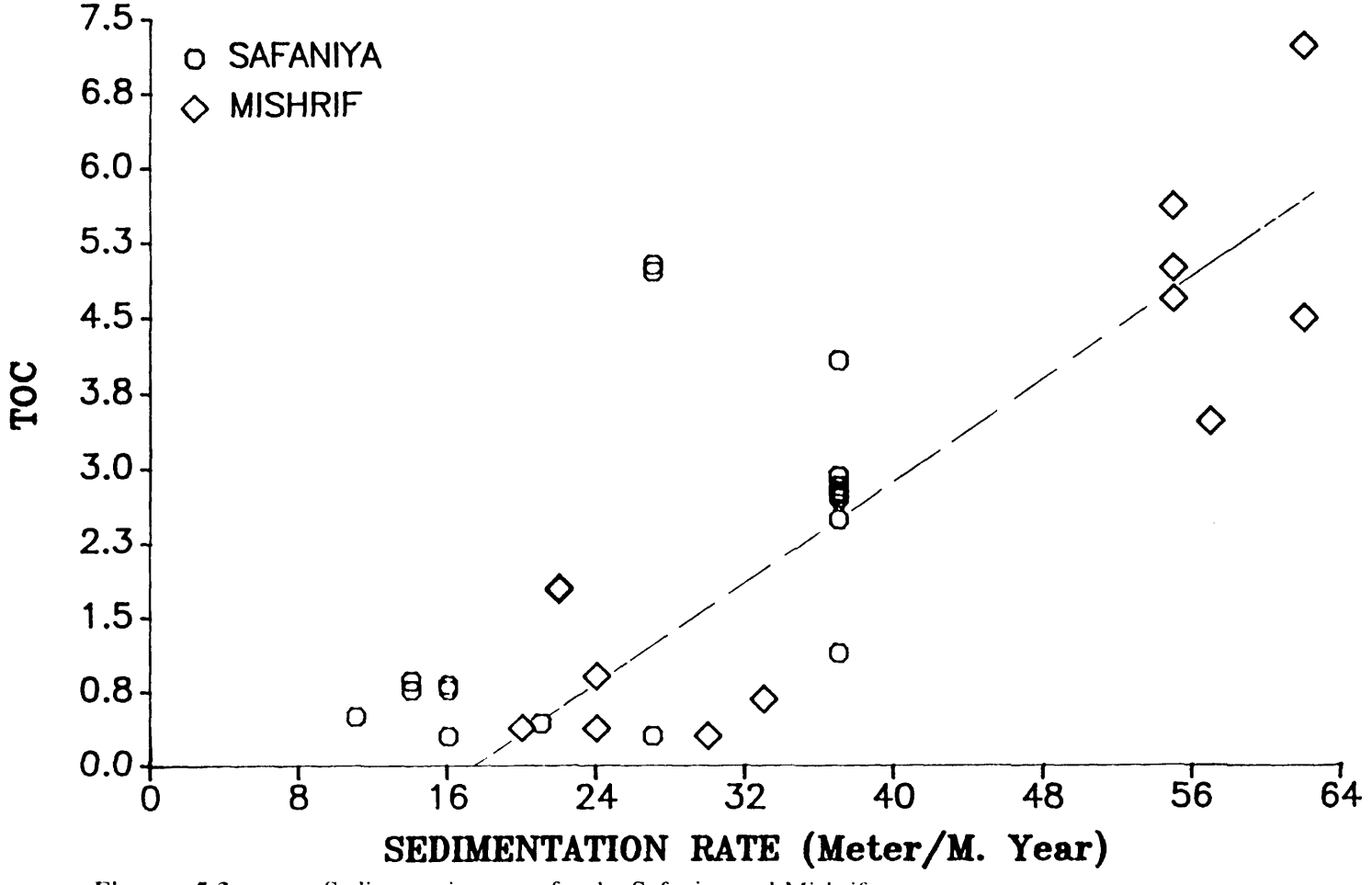


Figure 5.3 Sedimentation rates for the Safaniya and Mishrif plotted with their TOC values.

Table 5.2 Ca CO_3 contents of representative samples from the Safaniya and Mishrif organic rich units together with their TOC values.

A - MISHRIF

Sample Number	Lithology	CaCO3%	T.O.C.
Mi/12-2	Dark grey-brown, thinly laminated mud	84.3	7.21
Mi/5-1	Dull brown lime mud	81.2	5.61
Mi/10-2	Brown and grey, earthy lime mud	88.1	3.46
Mi/g-1	Dark brown to grey impure limestone and shale	44.4	1.8
mi/14-2	Grey, brown lime mud	93.5	1.34
Mi/11-1	Off-white to tan limestone	97.1	0.91

B - SAFANIYA

Sample Number	Lithology	CaCO3%	T.O.C.
Sa/14-2	Dark brown lime mud	76.4	2.92
Sa/10-2	Brown, earthy lime mud	72.4	4.07
Sa/11-1	Mixture of grey shale and grey brown lime mud	39.2	2.82
Sa/5-2	Dark brown lime mud contaminated with grey shale	61.9	5.03
Sa/12-1	Brown, grey, calcareous shale	41.3	0.86
Sa/9-1	Grey brown shale and white limestone	54.9	0.82

lime mud sediments. Wilson (1975) indicated that most lime mud is organically derived through the accumulation of planktonic biota. This is in line with earlier discussions that the organic rich units of the Safaniya and Mishrif were probably deposited during high surface biologic productivity. The settling out of fine -grained sediments and the tests of these micro-organisms deposited pelagic muds, which are both calcareous and argillaceous.

5. 3. 5. **Palaeobathymetry (Water Depth)**

Suess (1980) indicated in his study that significant decreases in carbon flux occur in water depths greater than 100 m. The accelerated sinking of organic matter to the sea floor by the formation of aggregates and flocs and incorporation within faecal pellets must be of critical importance in this respect (Spencer *et al*, 1978; Degens and Ittekkot, 1987). Long residence of organic matter in the water column before sedimentation adversely affects its preservation (Degens and Mopper, 1976).

The Safaniya and Mishrif organic rich units were shown to have been deposited in intrashelf basins flanked by shallow platform sediments (see Ch. 3). Murris (1984) and Harris *et al* (1984) have reported the development of such intrashelf basins in the Arabian Platform during the Jurassic and the Cretaceous. They have reported the water depth in these intrashelf basins to be about 100-150 m. This shallow water depth might have permitted fast arrival of the organic matter at the sea floor, thus promoting its preservation as discussed above.

5. 3. 6. **Oceanic Anoxic Events**

Widespread and synchronous anoxic conditions, leading to the deposition of organic rich sediments, have occurred in parts of the world ocean several times in the geologic past. The global extent and synchroneity of the Cretaceous anoxic events have been shown by the Deep Sea Drilling Project (Schlanger and Jenkyns, 1976; Arther and Schlanger, 1979; Tissot *et al*, 1980; Schlanger *et al*, 1987). During these events, oxygen-deficient water layers in the open ocean were significantly thicker and more widespread than normal resulting in the preservation of remarkably widespread organic rich sediments where this oxygen-minimum zone intersected the sediment-water interface.

These "oceanic anoxic events" have also been increasingly recognized on the continental shelves by petroleum exploration drilling (Demaison and Moore, 1980). Schlanger *et al* (1987) in their palaeobathymetric interpretation of Cretaceous strata from European and African shelf sequences and sections in the U.S. Western Interior Basin have shown that shallow embayments, flooded by the rapid Cenomanian-Turonian transgression, were particularly favourable to deposition of anoxic sediments as were the neighbouring shelves and cratonic shallow seaways. They indicated that, in most areas, the upper surface of the widespread, intensified Cenomanian-Turonian oceanic oxygen-minimum zone was 100 to 200 m below the surface of the sea.

In ALRub ALKhali basin, the Safaniya (Middle to Late Albian) and Mishrif (Late Cenomanian to Late Turonian) organic rich units are partly synchronous with two described "oceanic anoxic events" respectively occurring in Aptian to Albian time and Cenomanian to Turonian time (Schlanger and Jenkyns, 1976). It is possible that these two "oceanic anoxic events" might have extended to the shelf area of ALRub ALKhali during deposition of the Safaniya and Mishrif. This would have enhanced the preservation of the organic matter deposited in the intrashelf basinal area which helps to explain the high organic carbon values of these two units.

This credible time correlation of the Safaniya and Mishrif with oceanic anoxic events is further strengthened by tracing out these units to the vicinity of the Middle Cretaceous continental margin using published data from neighbouring countries to the east. In United Arab Emirates (offshore Abu Dhabi), the Shilaif Formation which ranges in age from Albian to Turonian has been identified as rich in organic matter with TOC values reaching up to 6% (Hassan and Azer, 1985). In Oman, the Natih Formation has organic rich facies which developed in the Late Albian and Cenomanian. These two zones produce good source rocks which have been extensively analysed and which correlate with a number of the northern Oman oils (Grantham *et al.*, 1987).

CHAPTER SIX

QUALITY AND MATURITY OF KEROGEN IN THE CRETACEOUS INTERVALS

6.1 INTRODUCTION 143

6.2 ELEMENTAL ANALYSES 145

6.2.1 Introduction 145

6.2.2 Results and Interpretation of the Elemental Analyses of the Cretaceous Kerogens 153

6.3 CHARACTERIZATION OF KEROGENS BY DENSITY FRACTIONATION 169

6.3.1 Introduction 169

6.3.2 Density Fractionation of the Cretaceous Kerogens 171

6.4 CHARACTERIZATION OF KEROGENS BY TRANSMITTED LIGHT MICROSCOPY 176

6.4.1 Introduction 176

6.4.2 Assessment of Cretaceous kerogens by Transmitted Light Miscroscopy 186

6.5 PROGRAMMED PYROLYSIS OF WHOLE-ROCK SAMPLES 219
6.5.1 Introduction 219
6.5.2 Results and Interpretation 222

6.6 RELATIONSHIP BETWEEN ORGANIC RICHNESS, KEROGEN TYPE, LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE CRETACEOUS SECTION 225

6. 1. *INTRODUCTION*

Kerogen appears to be an association of various kinds of organic debris. Heterogeneity of kerogen is common in sedimentary rocks except in certain types of sediments formed by massive accumulation of a single type of organism, such as the case in the organic units of Lower Safaniya and Lower Mishrif in ALRub ALKhali Basin. The organic matter present in these two units is believed to be the result of good preservation of massive accumulation of phytoplankton debris as explained in the previous chapter. The different types of kerogen particles are called macerals, a term taken from coal petrology. Kerogen is composed of different basic constituents in varying proportions. Some of them can be identified as macerals, the rest being frequently an amorphous mass. The physical appearance of kerogen in hand specimen, following acid treatment, is that of a fine soft powder, varying in colour from light to dark brown or black. McIver (1967) reported that kerogen is composed mainly of carbon, hydrogen, and oxygen with usually minor amounts of nitrogen and sulphur. The critical component in terms of convertibility to petroleum is hydrogen content (Dow, 1977). Marine organic matter contains high proportions of hydrogen-rich lipid and lipid-like components which are necessary organic precursors of petroleum. Terrestrial plant materials, on the other hand, contain dominantly hydrogen-deficient chemical components (e.g. lignin and cellulose) which have a greater capacity to produce large quantities of gas rather than oil. Hence, good oil-prone source rocks contain relatively high concentrations of marine produced organic matter compared to terrestrially derived materials.

The type and quality of kerogen can be differentiated and evaluated by organic petrographic and organic geochemical studies. Organic petrography uses optical methods to identify and estimate the abundance of organic particles or macerals in the kerogen, and their level of organic maturation can also be examined and estimated. In organic geochemical studies, physico-chemical analyses are used to determine the gross composition and degree of alteration of kerogen. Each of these procedures has its own advantages and preferred field of application (see Durand and Monin, 1980; Tissot and Welte, 1984; Brooks *et al.*, 1987). Optical methods allow visualisation of the organic matter and thus an appreciation of the mixing of organic sources with the ability to discriminate between autochthonous and reworked or altered organic material. However, optical techniques alone do not always offer a sufficient discrimination of the quality of organic matter (Powell *et al.*, 1982; Tissot and Welte, 1984). In contrast, chemical techniques involve the whole of the organic matter including possible mixing or reworking of the various organic materials which are often difficult to detect or to evaluate quantitatively. Therefore, a combination of optical and chemical methods should be capable of providing a more complete kerogen analysis than can be acheived from the use of one or other type of analysis in isolation.

In the previous chapter (chapter 5), the organic richness of the Cretaceous intervals in ALRub ALKhali Basin has been assessed. Also, the factors that might have influenced this organic richness have been discussed. The high concentration of organic matter has been shown to be associated with intrashelf basins developing in two intervals of the Cretaceous section (see

chapter 5). In this chapter, the quality or type and maturity of these organic rich units will be investigated. In addition, an attempt is made to interpret organic facies changes across the basin and the relationships between kerogen types, depositional environments, lithology, and organic richness of the Cretaceous intervals throughout the study area.

6. 2. *ELEMENTAL ANALYSES*

6. 2. 1. **Introduction**

Since carbon, hydrogen, and oxygen make up most of the kerogen (McIver, 1967), the diagrams which have been proposed for the interpretation of the elemental analysis are mainly variations in combinations of these elements. Following the work of van Krevelen (1961) on the thermal evolution of coal macerals, Tissot *et al* (1974), on the basis of elemental composition of kerogen (C, H, O) employing cross-plots of atomic H/C and O/C ratios, defined the first three types of kerogen, i.e. types I, II and III. They stated that these represent the three basic kerogen types, principally based upon elemental analyses. On the same basis, a fourth kerogen type has been identified and described (Tissot *et al*, 1980; Brooks, 1981; Kinghorn, 1983; Tissot and Welte, 1984; see Fig. 6.1). Durand and Monin (1980) recommend that the van Krevelen diagram is the most suitable for processing elemental analyses.

Type I kerogen is mainly composed of structured algal material. It is rich in aliphatic chains and consequently in hydrogen. The content of

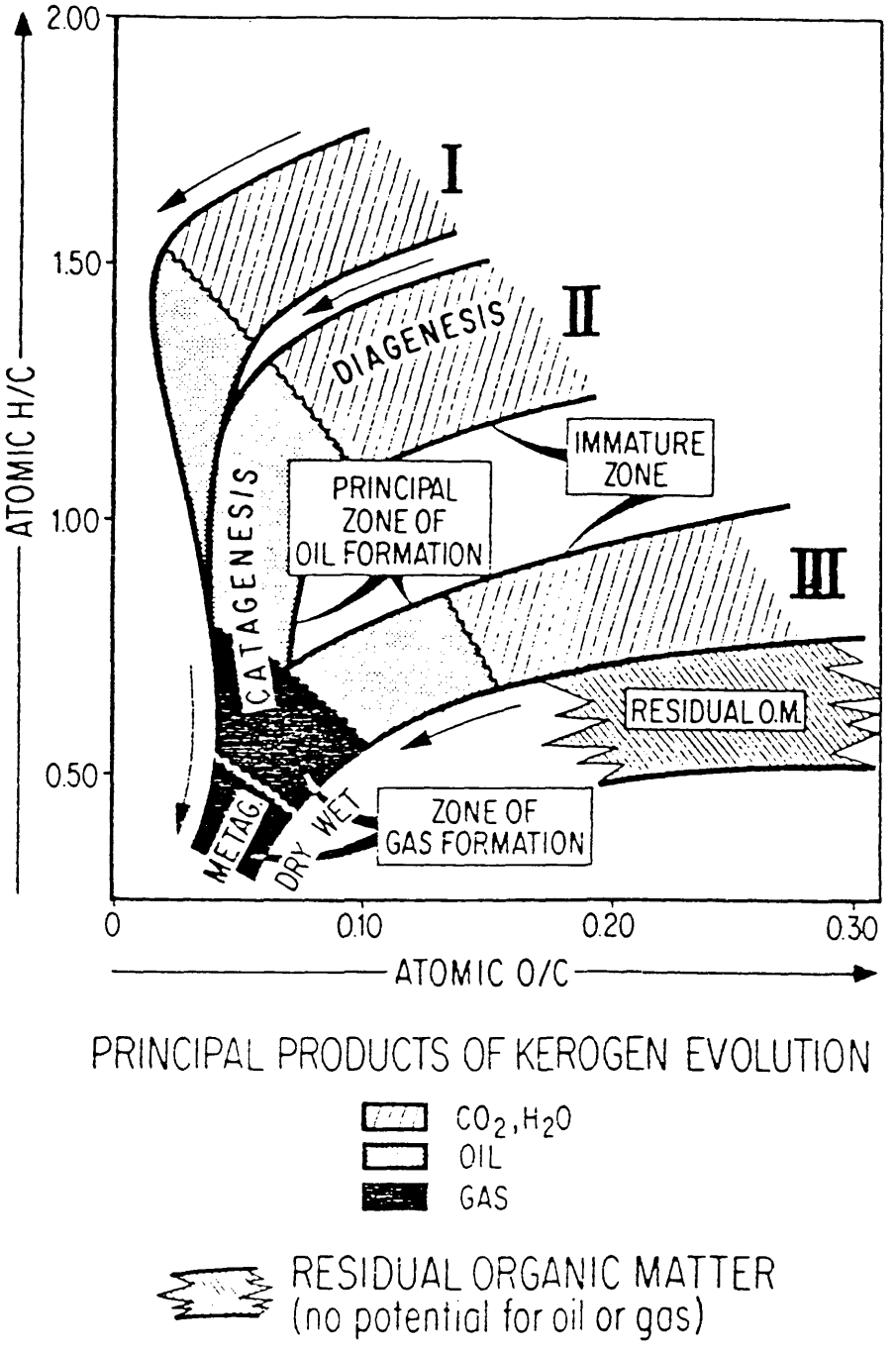


Figure 6.1 Van Krevelen diagram showing types of kerogen, and principal products generated during thermal evolution. (After Tissot et al, 1980)

polyaromatic rings and heteroaromatic bonds is low, compared with the other types of organic matter. Therefore, type I refers to kerogen with a high initial hydrogen content (atomic H/C ratio ≥ 1.5) and a low initial oxygen content (atomic O/C ratio generally smaller than 0.1). This type of kerogen is reported to have the greatest potential for oil generation with often up to 80% convertibility (Kinghorn, 1983; Tissot and Welte, 1984). Its occurrence is relatively rare compared to the other types. Tissot and Welte (1984) described its source as algal material of marine or lacustrine origin. It can also originate from the remains of disseminated organic matter which has been extensively reworked by microorganisms.

Type II kerogen is usually associated with marine sediments where autochthonous organic matter derived from phytoplankton, bacterial microorganisms and sometimes zooplankton is deposited in anoxic environments. It is composed mostly of naphthenes and aromatics. The polyaromatic nuclei and the heteroatomic ketone and carboxylic acid groups are more important than they are in type I, but less than in type III. It refers to kerogen with relatively high H/C and low O/C ratios. It has a good potential for oil generation with up to 60% convertibility (Kinghorn, 1983; Tissot and Welte, 1984). This kerogen type is the source material of the oil rich province of Saudi Arabia located to the north of ALRub ALKhali Basin (Ayres *et al*, 1982).

Type III kerogen is usually associated with deltaic sediments on continental margins. It is derived mostly from allochthonous terrestrial material containing vegetal debris and coaly material. This type of kerogen

comprises an important proportion of condensed polyaromatic nuclei and heteroatomic bonds, especially oxygen, while aliphatic groups are much less in evidence (Tissot and Welte, 1984). Type III refers to kerogen with a relatively low initial H/C ratio (usually less than 1.0) and high initial O/C atomic ratio (as high as 0.2 or 0.3). Kinghorn (1983) indicated that this type of kerogen is the main source of gas reserves, while its potential for the generation of liquid hydrocarbons, as shown by pyrolysis, is low with an overall maximum convertibility of about 35-40%.

Type IV kerogen is described as consisting mostly of residual organic matter, which is characterized by abnormally low H/C ratios associated with high O/C ratios. Tissot and Welte (1984) pointed out that this residual type of kerogen cannot generate any hydrocarbons and is considered therefore to be one form of "dead carbon" in terms of petroleum generation. Type IV kerogen is mostly derived from highly oxidized/altered material or high rank material recycled from older sediments.

In addition to the frequent occurrences of pure type II and III kerogens, the composition of kerogen may cover other areas in Fig. 6.1 between the evolution paths I and III. This situation is probably due to variability of contributing organisms, including mixture of marine and terrestrial inputs, and also to different conditions of preservation. For example, kerogens with a significant contribution of plant debris from the continent would show a relatively high O/C ratio. Also, biochemical and chemical degradation of the organic matter prior to or during deposition may result

in a decrease of the H/C ratio and an increase of the O/C ratio. It should be noted that lateral facies variations in sediments may cause a change of the kerogen from one type to another within a given horizon or formation. In the area close to the shore line at the time of deposition, kerogen shows low hydrogen content. This is attributed to organic material of terrestrial origin deposited in a relatively oxidizing environment. Away from the paleoshore line, i.e., basinward, the hydrogen values increase due to a higher proportion of marine phytoplankton and better preservation conditions.

As sedimentation and subsidence proceed, kerogen is subjected to a progressive increase of temperature and pressure. The process of kerogen degradation and transformation to petroleum hydrocarbons as a consequence of sediment burial is described by van Krevelen diagram (Fig. 6.1) in three successive stages; namely, diagenesis, catagensis, and metagenesis (Hunt, 1979; Kinghorn, 1983; Tissot and Welte, 1984). These three main geochemical processes can be followed from changes in C, H, and O compositions.

Diagenesis is the first stage occuring at conditions of shallow burial and relatively low temperatures (less than 60°C). The principal result of diagenesis is the production of kerogen. During this stage, there is a loss of oxygen (the formation of carbon dioxide and water) and a decrease in the O/C ratio, whilst the H/C ratio is only slightly decreased. In terms of petroleum exploration, the stage of diagenesis is known to correspond to an immature kerogen and hence little fluid hydrocarbon generation occurs in

the potential source rocks. However, biogenic methane (marsh gas) can be produced by microbiological activity.

Catagenesis is the second step of kerogen degradation, in which the majority of hydrocarbons are formed. It is marked by an important decrease of the hydrogen content and of the H/C ratio due to generation and release of hydrocarbons as the depth of burial (temperature) increases. In terms of petroleum exploration, the stage of catagenesis corresponds to the main zone of oil generation and also to the beginning of the cracking zone. As temperature rises, there is a progressive reduction in the aliphatic bonds and simultaneous increase in aromatics due to aromatization of naphthenic rings as hydrogen is used to saturate labile hydrocarbon molecules (Kinghorn, 1983). At the same time, the oxygen content decreases due to elimination of the carbonyl groups (C=O). The start of the catagenetic stage corresponds to a vitrinite reflectance value of 0.5% and a value of 2% at its conclusion (Kinghorn, 1983). The main products often associated with this stage are liquid petroleum, condensates and wet gas, in that order as the depth of burial increases. The relative importance of these three generative processes depends on the composition of the original kerogen (Dow, 1977). Vassoevich *et al* (1974) have pointed out that the most important factor controlling the convertibility of kerogen to petroleum is its hydrogen content. Kerogens with original atomic H/C ratios of more than 1.2 have a high petroleum generating potential, while those with H/C ratios of less than 0.8 have a very low potential.

The final stage in kerogen degradation is *metagenesis* (see Fig. 6.1). The start of this stage has been reported to correspond approximately with a vitrinite reflectance value of 2% (Tissot and Welte, 1984). This stage can be observed only in very deep kerogen samples or in locations with a high geothermal gradient. Kerogen is restructured and methane (dry gas) is the only hydrocarbon formed from both the kerogen degradation as well as the cracking of the previously generated liquid hydrocarbons. The H/C ratios of kerogens decrease very slowly during this stage with carbon content reaching 90%, while vitrinite reflectance increases in value to about 4% (Kinghorn, 1983; Tissot and Welte, 1984). The stage of metagenesis is equivalent to the dry gas zone in terms of petroleum exploration.

The elemental analysis of kerogen, i.e. H/C and O/C ratios, plotted on a van Krevelen diagram (Fig. 6.1) can give a fairly good indication of the maturation stage of kerogen (McIver, 1967; Laplante, 1974; Tissot et al., 1974; Tissot and Welte, 1984). It is observed that oxygen content is mostly affected during diagenesis, whereas hydrogen content changes mostly in the catagenetic stage (see Fig. 6.1). Harwood (1977) indicated in his study that kerogens with original atomic H/C ratios greater than 1.00 are oil and gas sources whereas those kerogens with H/C ratios between 1.00 and 0.80 are wet-gas sources, while those with H/C ratios less than 0.80 are dry gas sources. His results, being an indication of percent carbon and kerogen atomic H/C ratios for oil and gas generation, are shown in Table 6.1. Harwood stated that if samples are severely weathered and oxidized, the H/C values may be affected and can be misleading.

Table 6.1 Percent Carbonizations and atomic H/C ratios for Kerogen Catagenesis stage. (After Harwood, 1977).

Kerogen Type	Stage of Catagenesis			
	Pregeneration - Early Generation	Principal Oil or Liquids Generation	Principal Gas Generation	Expended Kerogen
Very High Hydrogen Oil (I)	<77%C H/C>~1.25	77-87%C H/C>0.80	87-92%C H/C 0.40-0.80	>92%C H/C<0.40
Normal Oil (II)	<79%C H/C>1.00	77-85%C H/C>0.80	85-90%C H/C 0.80-0.40	>90%C H/C<0.40
Normal Gas (III)	<81%C H/C>0.70	81-85%C H/C>0.80	85-90%C H/C 0.80-0.40	>90%C H/C<0.40
Penn. Coal Gas (IV)	<88%C H/C>0.70	Does Not Apply	88-93%C H/C>0.40	>93%C H/C<0.40

6. 2. 2. Results and Interpretation of the Elemental Analyses of the Cretaceous Kerogens

The elemental compositions (C,H,N,O) of the kerogen concentrates from the sampled intervals of the Cretaceous in ALRub ALKhali Basin are presented in Table 6.2. The van Krevelen diagrams (plots of H/C against O/C atomic ratios) for the kerogen samples are shown in Fig. 6.2.

As noted from Table 6.2 and Fig. 6.2, kerogen samples analyzed show wide variation in their elemental composition and can be classified into four types based on plots of their H/C against O/C atomic ratios. These are : type II, mixed type II/III, type III, and type IV. These types have been defined in the previous section (6.2.1). Despite this wide variation in kerogen type, it appears that there is a clear trend of regional changes in kerogen type associated with vertical/stratigraphic variations, lateral lithological facies variations, and organic richness across the basin. The changes in kerogen type can be related to the depositional environments and the evolution of the basin, which were interpreted and discussed in chapter 3.

In the area close to the shore line at the time of deposition, i.e. the area of wells 3 and 4, only kerogens type III and IV seem to dominate (see Figs. 6.2a and 2b). This is most probably due to an important contribution of plant debris from the continent, west of the study area. The terrestrial influence and the deposition in a relatively oxidizing environment resulted in organic matter which is poor in hydrogen and relatively rich in oxygen

Table 6.2 Elemental Composition and Typing of the Cretaceous Kerogen Samples

Locality Borehole	Sample Number	Depth (m)	Elemental Composition						Kerogen Type
			Wt. %				Atomic ratios		
			C	H	N	O	H/C	O/C	
Well 3	Ar/3-2	1533	32.73	2.83	2.12	13.12	1.04	0.30	III
	Ar/3-3	1599	53.64	3.28	1.94	15.25	0.73	0.21	III
	Mi/3-1	1742	54.65	3.57	1.81	18.26	0.78	0.25	III
	R-A-W/3-1	1841	52.66	2.85	1.81	15.65	0.65	0.22	III
	R-A-W/3-3	1960	49.39	3.15	1.49	15.62	0.77	0.23	III
	R-A-W/3-4	2076	48.5	2.72	1.43	15.86	0.67	0.24	III
Well 4	Ar/4-2	1468	52.12	3.81	2.28	15.66	0.88	0.22	III
	Ar/4-3	1586	39.59	3.25	1.65	13.86	0.99	0.26	III
	Ar/4-4	1678	44.15	2.17	2.03	14.15	0.59	0.24	IV
	Ar/4-5	1754	40.2	2.64	1.75	11.53	0.79	0.22	III
	R-A-W/4-1	1908	41.21	2.83	1.96	12.41	0.83	0.22	III
	R-A-W/4-2	1952	30.4	2.5	1.68	10.79	0.99	0.26	III
	Sa/4-1	2308	33.49	2.74	2.04	11.44	0.98	0.25	III
	Kh/4-1	2394	46.32	2.54	1.17	14.00	0.66	0.22	III
	Bu/4-1	2818	46.08	2.61	1.13	14.07	0.68	0.22	III
	Su/4-1	3080	33.92	2.65	1.77	12.31	0.94	0.27	III
	Su/4-2	3184	53.92	3.84	1.18	14.47	0.86	0.2	III
Well 5	Ar/5-2	1161	42.9	3.23	1.7	15.25	0.90	0.26	III
	Mi/5-1	1405	73.37	8.11	3.17	8.97	1.33	0.09	II
	Mi/5-2	1425	71.61	7.58	2.71	8.69	1.27	0.09	II
	R-A-W/5-1	1480	42.78	3.45	1.51	11.38	0.97	0.2	III
	Sa/5-1	1632	38.52	2.97	2.64	10.22	0.93	0.2	III
	Sa/5-2	1658	73.84	7.8	3.29	9.45	1.27	0.09	II
	Kh/5-1	1718	37.29	3.3	1.77	13.62	1.06	0.27	Mixed II & III
	Bu/5-1	2196	61.59	6.00	1.16	12.40	1.17	0.15	Mixed II & III
Well 9	Ar/9-2	1131	53.45	3.5	2.09	21.20	0.79	0.29	III
	Ar/9-3	1190	51.98	2.47	2.16	19.60	0.57	0.28	IV
	Ar/9-4	1318	49.23	2.64	2.62	17.99	0.64	0.27	IV
	Mi/9-1	1417	60.43	5.14	2.96	14.35	1.02	0.17	Mixed II & III
	R-A-W/9-1	1501	18.65	1.9	0.96	10.94	1.22	0.44	n.d.
	R-A-W/9-2	1541	16.13	2.25	1.2	13.13	1.03	0.37	n.d.
	Sa/9-1	1646	25.23	2.95	1.49	10.37	1.40	0.30	n.d.

n.d. = not determined

Table 6.2 Cont.

Locality Borehole	Sample Number	Depth (m)	Elemental Composition						Kerogen Type
			Wt. %				Atomic ratios		
			C	H	N	O	H/C	O/C	
Well 10	Ar/10-2	1065	40.78	2.64	2.9	13.28	0.78	0.24	III
	Mi/10-2	1241	71.7	7.39	3.06	10.56	1.24	0.11	II
	Sa/10-2	1693	74.11	7.87	3.17	8.79	1.27	0.08	II
	Su/10-1	2501	60.16	5.81	1.03	10.64	1.16	0.13	Mixed II & III
	Su/10-2	2562	53.62	5.13	0.87	11.17	1.15	0.15	Mixed II & III
Well 11	Mi/11-1	1210	66.64	7.19	2.29	10.40	1.30	0.11	II
	Sa/11-1	1282	65.53	6.95	2.69	10.42	1.27	0.11	II
	Kh/11-1	1695	59.09	5.85	3.03	14.85	1.19	0.19	Mixed II & III
	Bu/11-1	2271	51.38	4.71	4.91	13.29	1.10	0.19	Mixed II & III
	Ya/11-1	2336	46.16	4.78	4.27	12.13	1.24	0.19	Mixed II & III
	Su/11-1	2592	60.46	4.95	2.93	16.77	0.98	0.20	III
	Su/11-2	2670	69.61	5.92	2.7	12.87	1.02	0.13	Mixed II & III
Well 12	Ar/12-1	911	43.08	3.44	1.86	16.53	0.96	0.28	III
	Mi/12-1	1200	71.31	7.5	3.1	9.87	1.26	0.10	II
	Mi/12-2	1216	69.41	7.09	2.94	11.10	1.23	0.12	II
Well 14	Ar/14-4	1915	69.75	7.91	0.7	8.58	1.36	0.09	II
	Mi/14-1	2207	71.26	6.83	2.87	9.00	1.15	0.09	II
	Mi/14-2	2237	77.52	9.12	1.42	9.81	1.41	0.09	II
	Sa/14-1	2563	57.39	6.64	0.88	9.28	1.39	0.12	II
	Sa/14-2	2588	66.24	6.65	2.63	8.02	1.20	0.09	II
	Kh/14-1	2629	57.34	5.37	1.44	8.87	1.12	0.11	Mixed II & III
	Su/4-2	3630	62.19	5.68	1.79	16.22	1.10	0.19	Mixed II & III

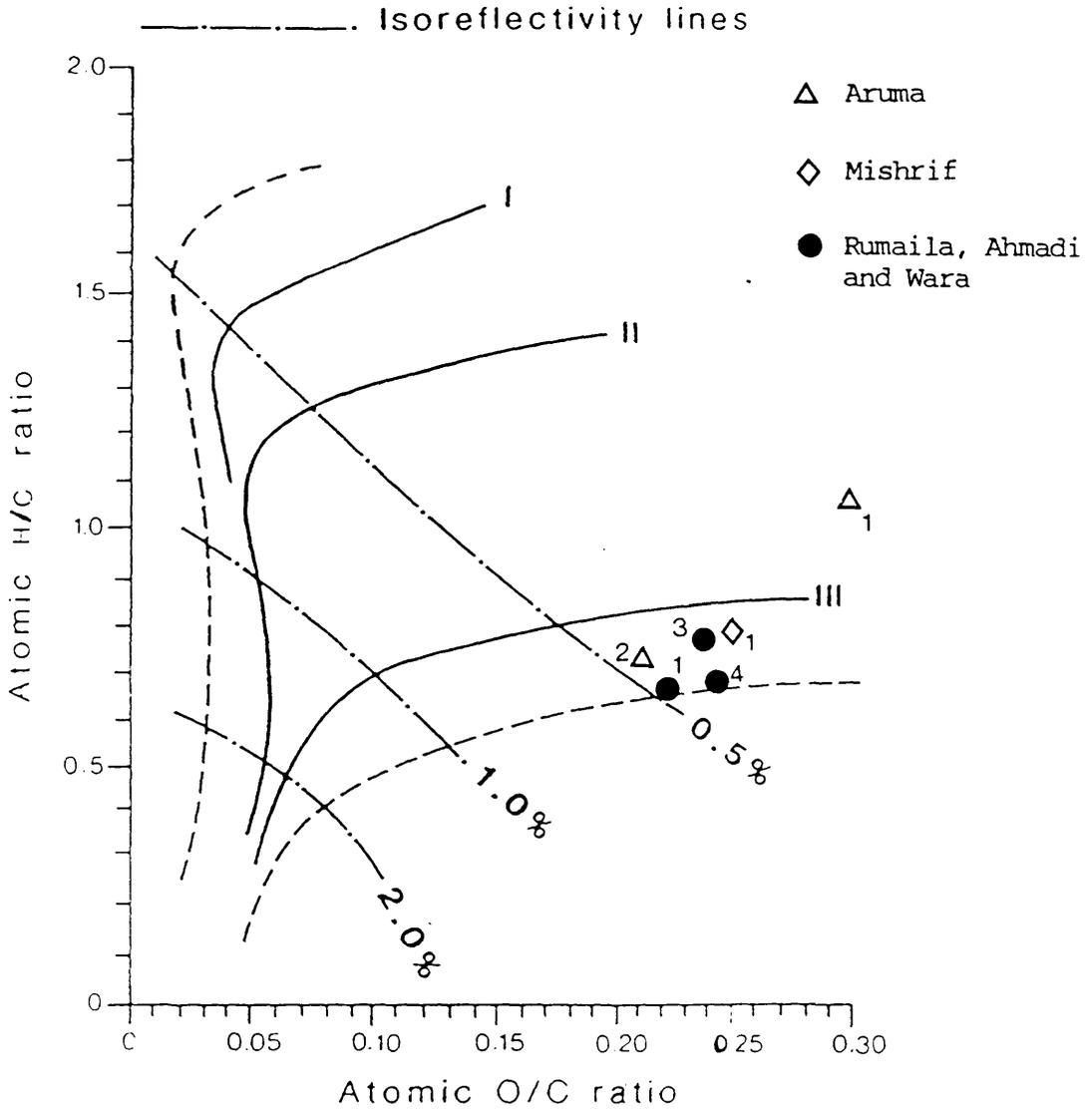


Figure 6.2(a) Van Krevelen diagram: Well. 3

(After Tissot & Welte, 1984)

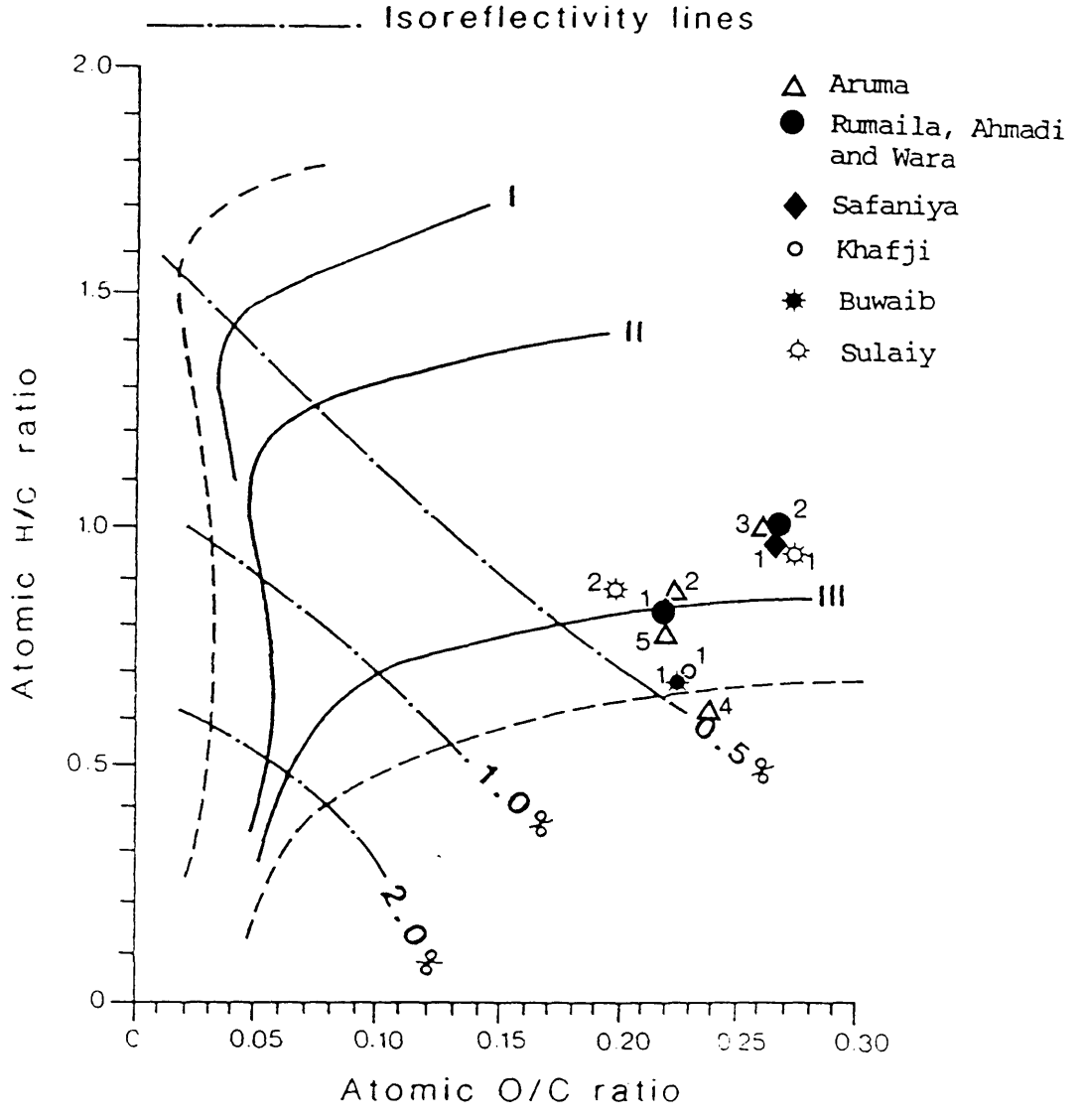


Figure 6.2(b) Van Krevelen diagram: Well. 4

(After Tissot & Welte, 1984)

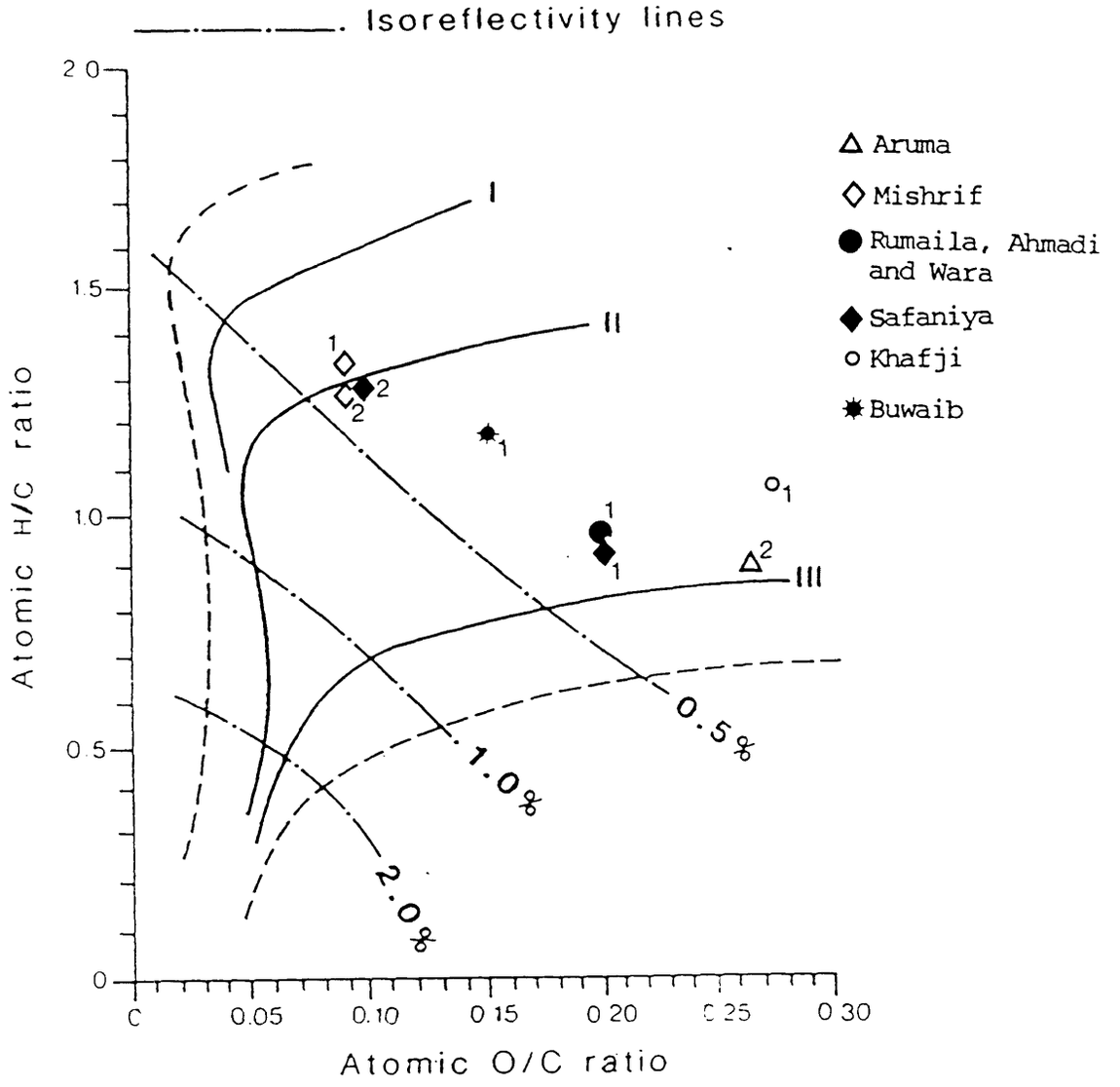


Figure 6.2(c) Van Krevelen diagram: Well. 5

(After Tissot & Welte, 1984)

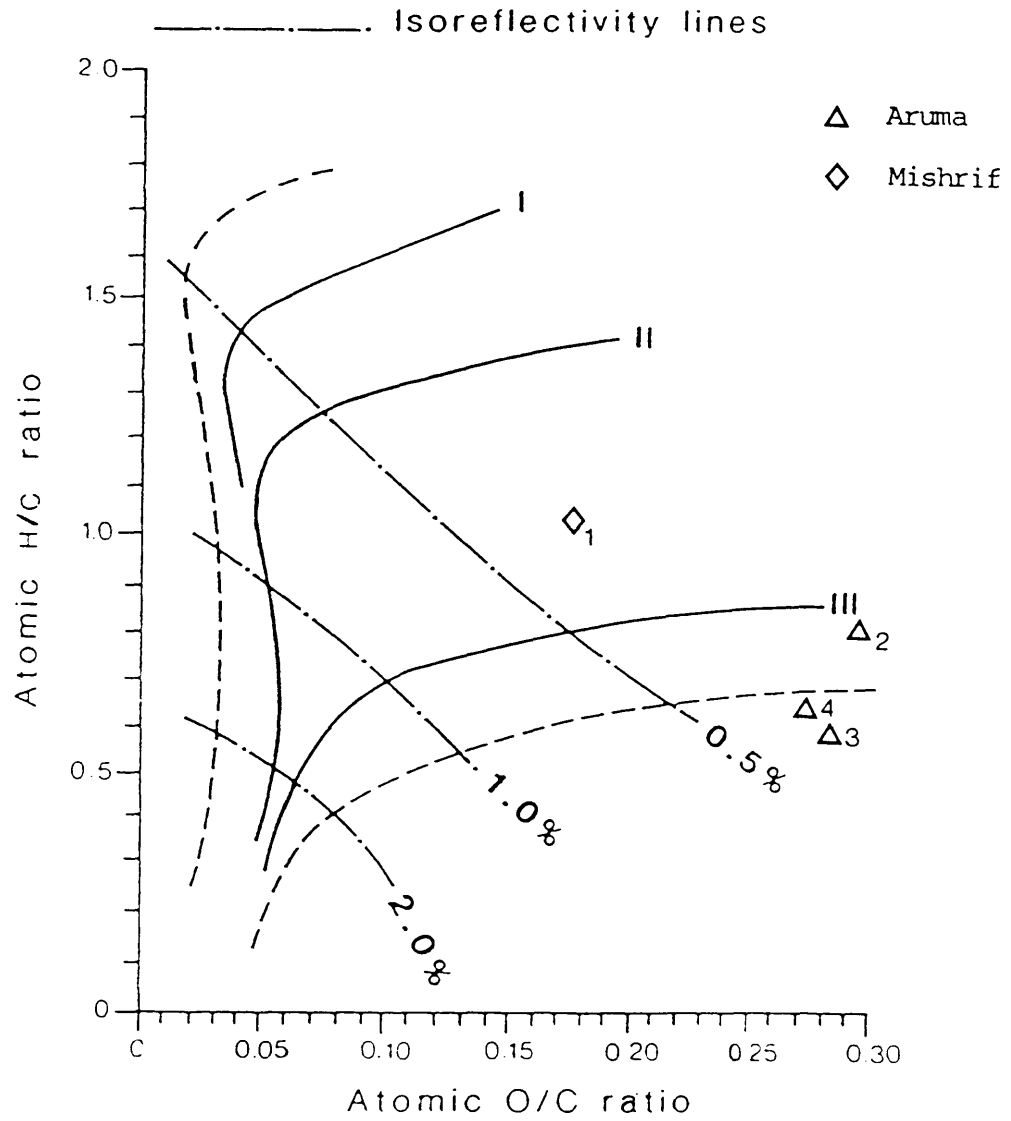


Figure 6.2(d) Van Krevelen diagram: Well. 9

(After Tissot & Welte, 1984)

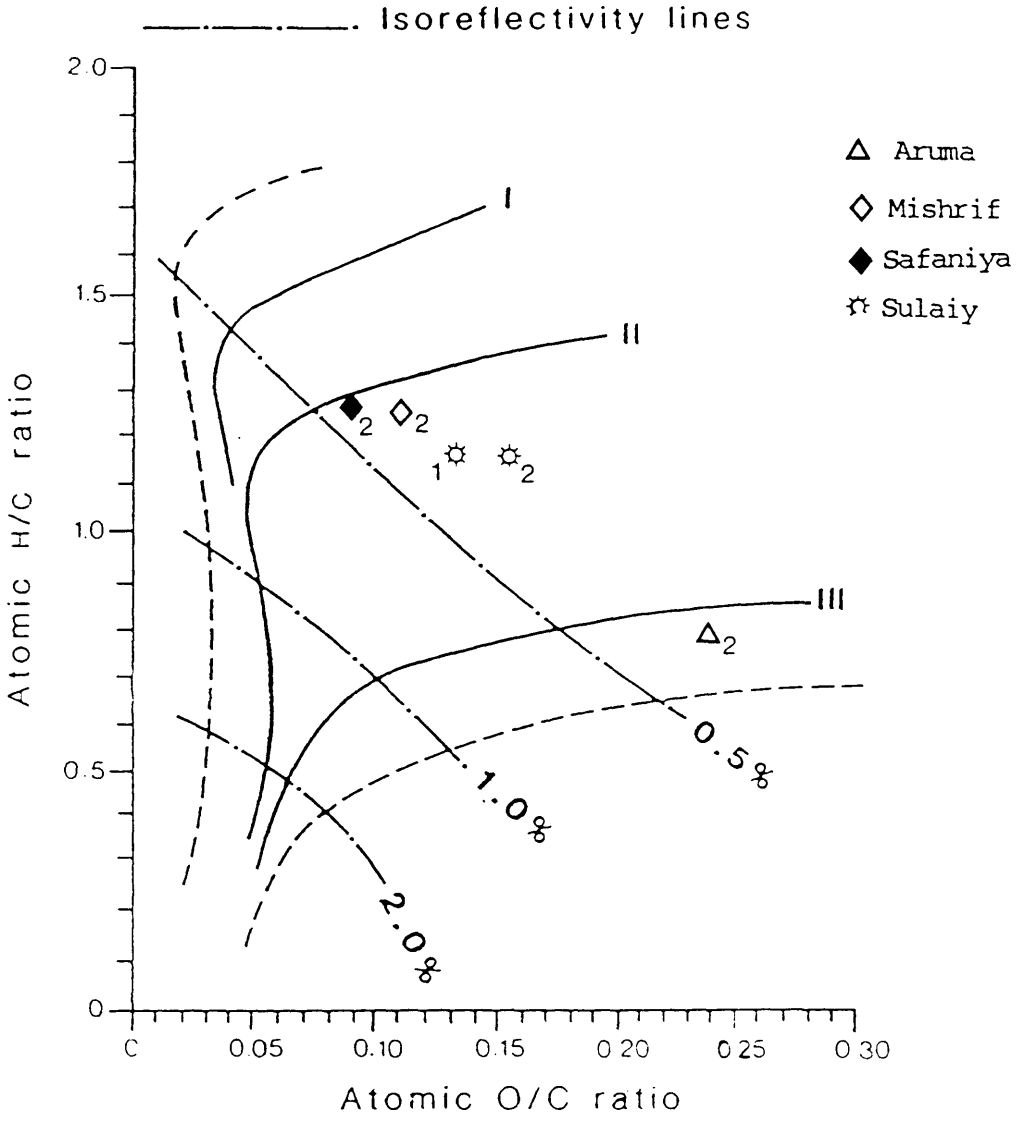


Figure 6.2(e) Van Krevelen diagram: Well. 10

(After Tissot & Welte, 1984)

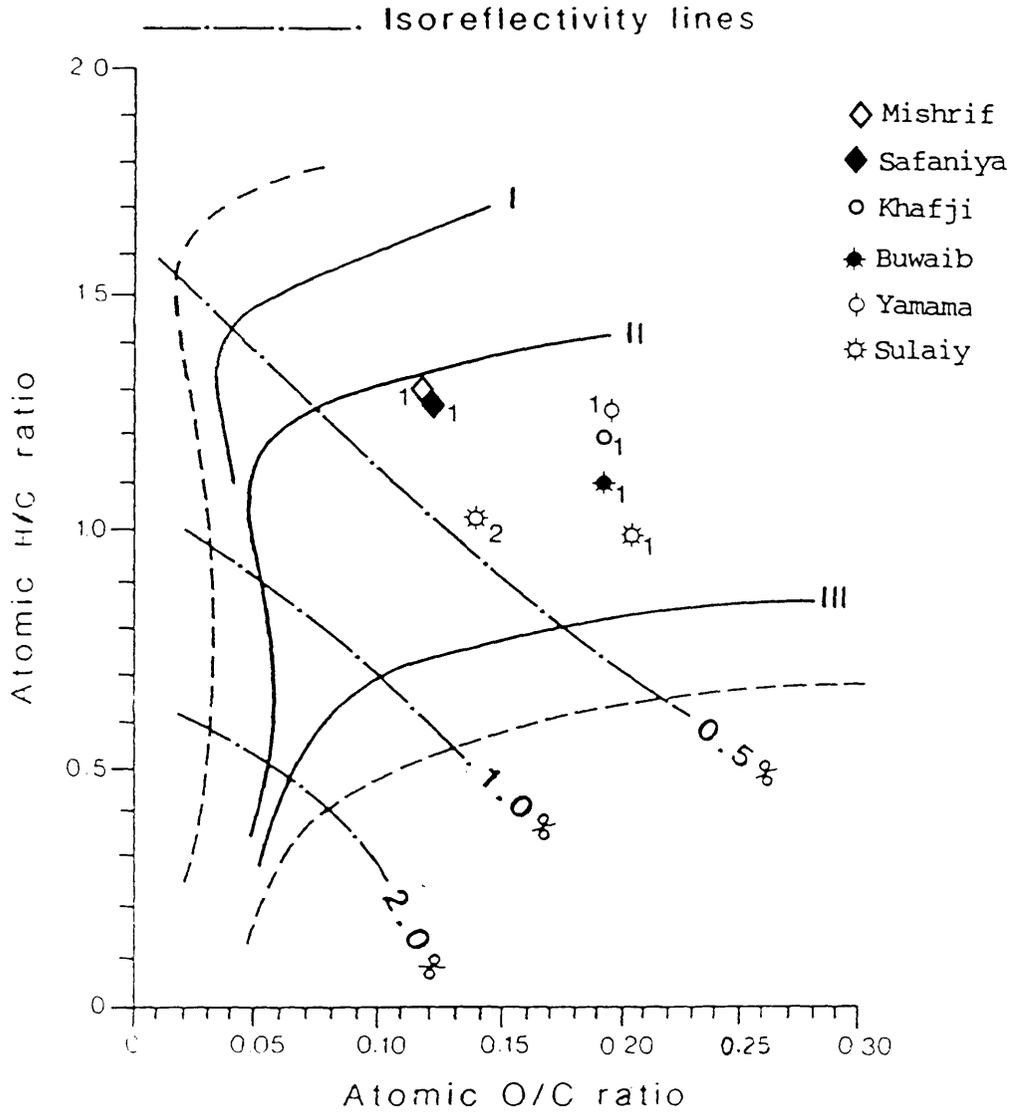


Figure 6.2(f) Van Krevelen diagram: Well. 11

(After Tissot & Welte, 1984)

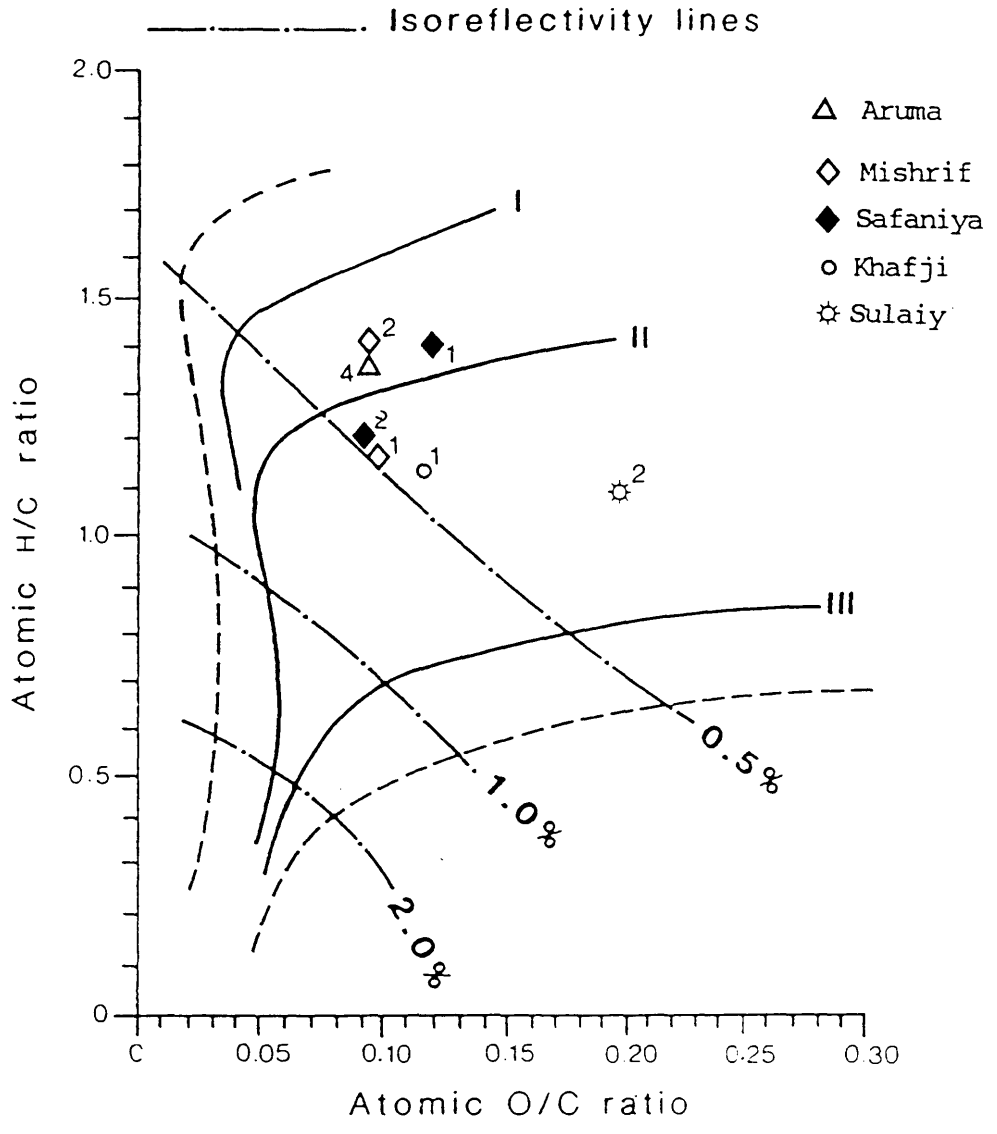


Figure 6.2(g) Van Krevelen diagram: Well14

(After Tissot & Welte, 1984)

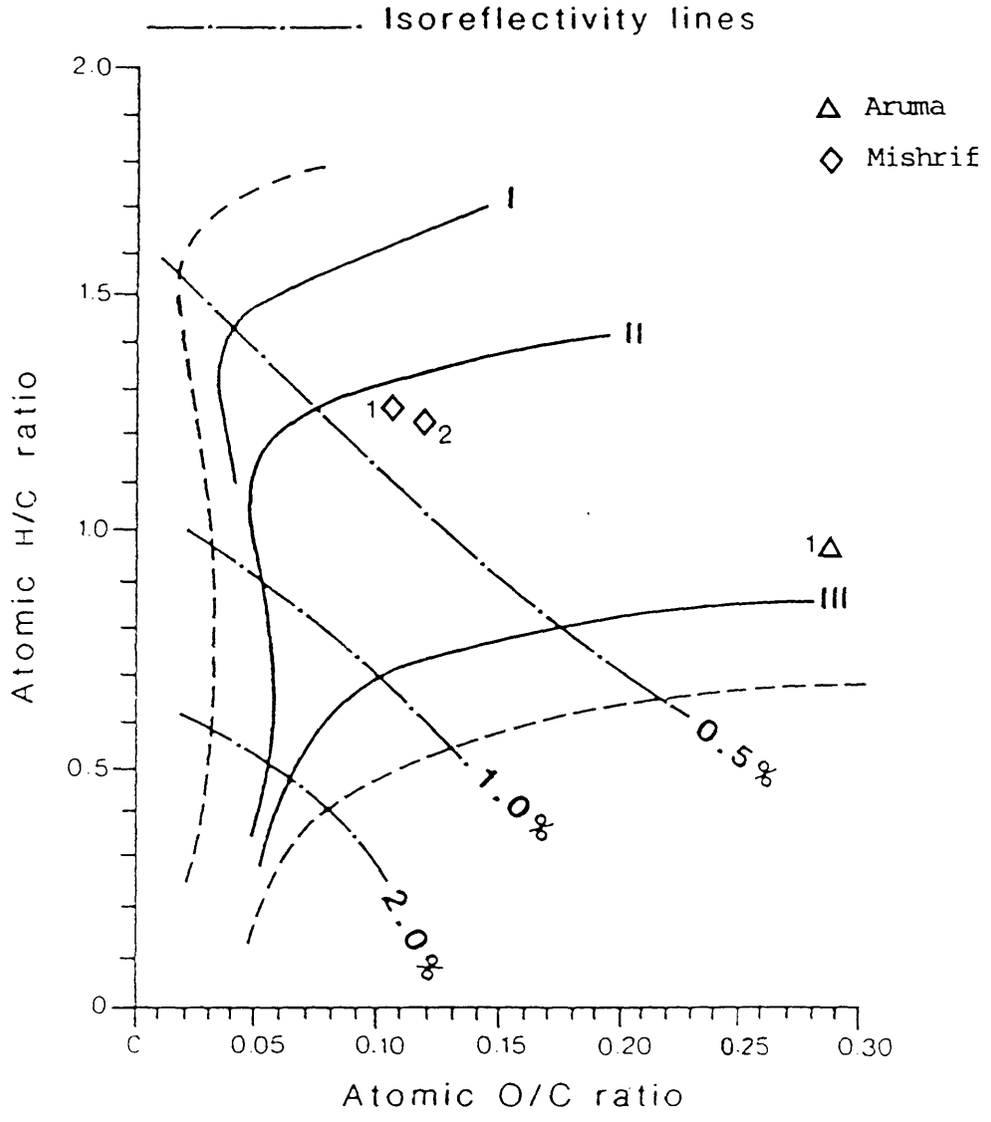


Figure 6.2(h) Van Krevelen diagram: Well. 12

(After Tissot & Welte, 1984)

content as can be seen in the elemental composition of the organic matter concentrates from wells 3 and 4 in Table 6.2. The hydrogen content of these samples ranges in value from 2.5 to 3.84 weight percent, while oxygen content is 10.79 to 18.26 weight percent. These kerogen types show relatively high O/C ratios and low H/C ratios.

To the east, i.e. basinward, the kerogen type varies considerably. This wide variation is most probably due to variations in contributing organisms including mixture of marine and terrestrial inputs and/or different conditions and degrees of preservation as can be demonstrated in the following discussion.

Vertically, type II kerogen has been identified in all samples from Lower Safaniya in the area of wells 5, 10, 11, and 14 and also from Lower Mishrif in the area of wells 5, 10, 11, 12, and 14 (see Figs. 6. 2c, e, f, g, and h). These samples are the same organic rich, lime mud samples identified in the previous chapter (chapter 5) as being associated with the development of an intrashelf basin during the deposition of Safaniya (Middle to Late Albian) and then with another intrashelf basin during the deposition of Mishrif (Late Cenomanian to Late Turonian).The geological development of these two intrashelf basins during the evolution of ALRub ALKhali has been interpreted in chapter 3 and their association with organic rich sediments has also been investigated in chapter 5. The presence of type II kerogen in Lower Safaniya and Lower Mishrif in these regional depression areas appears to be the result of accumulation and good preservation of lipid-rich marine phytoplankton material in anoxic

environments. The terrestrial input of both organic and inorganic material was negligible. The organic matter is oil-prone (hydrogen-rich) (see Table 6.2). The hydrogen content of the kerogen samples taken from Lower Safaniya and Lower Mishrif in the intrashelf basinal area ranges in value from 6.64 to 9.12 weight percent. The H/C ratios of these samples range from 1.20 to 1.41, while O/C ratios range from 0.08 to 0.12. The difference in preservation conditions between lower and upper parts of both Safaniya and Mishrif units can be clearly seen by comparing sample Sa/5-2 taken from Lower Safaniya with sample Sa/5-1 collected from Upper Safaniya (see Fig. 6.2c). Kerogen sample Sa/5-2 is of type II, oil-prone with a hydrogen content of 7.8 weight percent. On the other hand, kerogen sample Sa/5-1 is of type III, gas-prone with a hydrogen content of 2.97 weight percent. This difference in quality of organic matter between these two samples is most probably due to changes in preservation conditions from anoxic to oxic environments.

Apart from type II kerogen identified in these two organic rich units (i.e. Safaniya and Mishrif), only type III and mixed II/III kerogens have been recognized in kerogen samples taken from the remaining members/formations of the Cretaceous in the area of wells 5, 10, 11, and 14 (see Fig. 6.2c, e, f and g). This area is relatively far from the paleoshore line, hence the terrestrial input would be expected to be minimal. Thus, this variation in kerogen composition could be attributed to biochemical and chemical degradation of the marine organic matter prior to or during deposition. This would result in a decrease of H/C ratio and an increase of the O/C ratio. Therefore, it appears that the intensity of

biodegradation of type II kerogen precursors is probably the main factor for the formation of mixed type II/III and type III kerogens in the eastern part of the study area. However, terrestrial input from the west should not be ruled out as a contributing factor to the variability of kerogen types, particularly in the area with closer approximity to the paleoshore line. This is most probably the case in the organic matter of sample Mi/9-1 which is a mixed facies of types II and III (Fig. 6. 2d) and the organic matter of sample Ar/12-1 which is type III kerogen (Fig.6.2h).

Type IV kerogen has been occasionally identified in samples from Lower Aruma Formation in wells 4 and 9. These samples are Ar/4-4, Ar/9-3 and Ar/9-4 shown in Fig. 6.2 (b and d). As discussed in chapter 3, Lower Aruma shale was deposited following a major regional unconformity (Pre-Aruma Unconformity). Thus, it is quite possible that the formation of type IV kerogen in Lower Aruma shale was the result of residual type of kerogen composed mainly of organic matter derived from highly oxidized/altered material or high rank material recycled from older sediments. It is noted from these samples that this type of kerogen is characterized by abnormally low H/C ratios (0.57 to 0.64) associated with high O/C ratios (0.24 to 0.28).

The trend of lateral (horizontal) change in kerogen from type III to mixed type II and III and then to type II can be best demonstrated by following one stratigraphic unit across ALRub ALKhali Basin. This would help in understanding the progressive change in kerogen composition (type)with changes in the environment of deposition and facies variation in sediments.

An example is taken by tracing Mishrif kerogen samples in a section running from well 3 (close to the paleoshore line), through well 9 (on the edge of the intrashelf basin), to well 12 (in the intrashelf basinal area). Sample Mi/3-1 (Fig.6.2a) from well 3 is type III kerogen. This could be due to the effect of a massive influx of land derived material deposited in a high energy shallow marine (oxidizing) environment. Thus, the organic matter has a low H/C ratio and a high O/C ratio. Moving basinward, sample Mi/9-1 (Fig. 6.2d) from well 9 is a mixed type II/III kerogen. This is most likely due to a mixture of land derived and marine organic matter deposited in a relatively oxidizing environment. Finally, sample Mi/12-1 (Fig. 6.2h) from well 12, in the intrashelf basinal area, is type II kerogen. As discussed earlier, the formation of this organic rich lime mud sample is most probably attributed to the accumulation of lipid-rich marine phytoplankton material which were deposited in a reducing environment away from the influence of land derived debris. The organic matter in this situation would be highly preserved resulting in relatively high H/C ratio and a relatively low O/C ratio.

Kerogen samples normally become more mature with increased depth of burial. The elemental analysis of kerogen, i.e. H/C and O/C ratios, plotted on a van Krevelen diagram as shown in Fig. 6.2 can give a fairly good indication of the maturation stage of kerogen. As noted in these figures, all the Cretaceous kerogen samples in the study area appear to be immature and still in the diagenetic stage. However, in well 14 (see Fig. 6.2g) it is observed that samples from Lower Safaniya and Mishrif are approaching maturity. This finding is strengthened by the fact that this is the only well

in the study area with oil shows reported in its composite well log. This is most probably related to the fact that it is the deepest well encountered throughout the study area. It should be pointed out that, in general, the burial depth increases towards the east in ALRub ALKhali. This is related to the principle that thickness usually increases basinward. Also the Upper Cretaceous and Tertiary sediments in neighbouring Abu Dhabi and Oman are known to have a considerable thickness, probably due to the formation of a foredeep associated with the subduction zone and the development of Oman Mountains. This conclusion seems to be in line with the findings that the equivalent formations to these two units (i.e. Safaniya and Mishrif) identified further to the east in Abu Dhabi and Oman are mature and form major source for oil produced from several reservoirs in these countries (Hassan and Azer, 1985; Grantham *et al*, 1987; Videtich *et al*, 1988).

Thus, it appears that the depth of burial is probably the major factor which controls the level of maturation of organic matter in ALRub ALKhali. Therefore, it can be reasoned that the kerogens from Lower Safaniya and Lower Mishrif are about to enter the catagenetic stage in the area of well 14, whereas those from all the other wells in the study area are immature and still in the diagenetic stage.

6. 3. *CHARACTERIZATION OF KEROGENS BY DENSITY FRACTIONATION*

6. 3. 1. **Introduction**

Each maceral component of all different types of sedimentary organic matter has a characteristic density (Stach *et al*, 1975; Flenely, 1971). On the basis of this criterion, Kinghorn and Rahman (1980 and 1983) have developed a reliable and reproducible technique (described in Chapter 4) for separating the maceral components of the mineral free kerogen concentrate. The method consists of the sequential centrifuging of the various types of sedimentary organic matter in heavy liquid solutions (zinc bromide) which are of progressively higher specific gravities. The sedimentary organic matter is a mixture of different types of material, each with its own chemical composition and specific gravity. Thus, the specific gravity of each component will depend on its composition, which is related to its origin and level of maturation. Therefore, sedimentary organic matter can be split into groups according to density. Kinghorn and Rahman (1983) produced a plot of the specific gravity range within which the components of a kerogen occur versus the level of organic maturation. Such a plot is shown in Fig. 6.3. Three distinct bands, one for each kerogen type, have been identified from the range of the specific gravity of their components. As each type matures its density increases . At any given level of maturation, type I kerogen is lighter than type II which, in turn, is lighter than type III. Thus, the lightest kerogen is an immature type I, whereas the heaviest is a highly mature, terrestrially derived (type III)

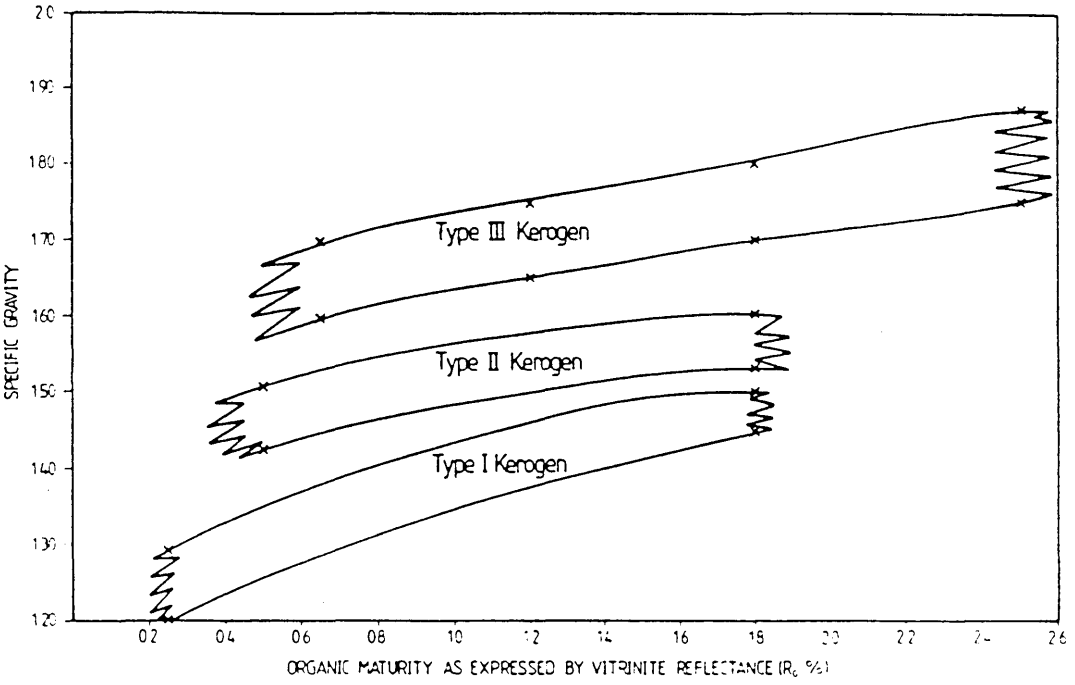


Figure 6.3 Variations of specific gravity of kerogen with maturation. (After Kinghorn, 1983)

kerogen.

One important advantage of this fractionation method is that it is possible to identify and differentiate the oil-prone and gas-prone types of amorphous organic matter (Kinghorn and Rahman, 1983). These two kerogens are difficult to distinguish by microscopic analysis (Tissot and Welte, 1984). Powell *et al* (1982) pointed out that the main disadvantage of optical assessment of kerogen is the inability of that method to differentiate between the hydrogen-lean and hydrogen-rich amorphous types. The two kerogens have different densities due to their different nature, with the gas-prone kerogens being deficient in hydrogen compared with the oil-prone material. The amorphous gas-prone organic matter has a higher specific gravity than the oil-prone amorphous kerogen. Kinghorn and Rahman (1983) have shown that the hydrogen-lean (gas-prone) amorphous kerogen is heavy with a specific gravity range of 1.53 to 2.2, whereas the hydrogen-rich amorphous kerogen is light with a specific gravity range less than 1.45 to 1.53. They have also associated the humic fragments (terrestrial materials) with the same specific gravity range of the gas-prone amorphous kerogen, i.e. 1.53 to 2.2.

6.3.2. *DENSITY FRACTIONATION OF THE CRETACEOUS KEROGENS*

The results of density fractionation of kerogen concentrates from the sampled intervals of the Cretaceous in ALRub ALKhali Basin are presented in Table 6. 3. The table shows the estimated volume percentage of each

Table 6.3 Estimated Volume Percentage of Kerogen Fractions

Locality Borehole	Sample Number	Density Range								Kerogen Type
		< 1.28	1.28-1.34	1.34-1.45	1.45-1.53	1.53-1.65	1.65-1.81	1.81-2.2	> 2.2	
Well 1	Mi/1-1	1	1	5	46	21	13	1	12	
	R-A-W/1-1	5	3	9	29	27	12	10	5	
	Su/1-1	3	5	46	21	11	3	2	9	
Well 2	Ya/2-1	1	1	5	51	25	9	3	5	
	Su/2-1	1	1	5	51	25	4	5	8	
Well 3	Ar/3-1	2	3	3	3	9	44	18	18	
	Ar/3-2	2	3	3	4	13	49	17	9	III
	Ar/3-3	2	3	3	5	17	46	12	12	III
	Mi/3-1	2	3	3	18	26	31	9	8	III
	R-A-W/3-1	2	3	3	5	17	42	15	13	III
	R-A-W/3-3	2	3	3	9	17	33	20	13	III
	R-A-W/3-4	2	2	3	9	17	30	19	18	III
	Sa/3-1	2	2	3	5	35	23	15	14	
Well 4	Ar/4-1	0	0	40	6	6	10	2	36	
	Ar/4-2	5	5	27	3	9	21	15	15	III
	Ar/4-3	1	1	2	10	4	57	10	15	III
	Ar/4-4	1	1	2	2	0	66	17	11	IV
	Ar/4-5	5	5	5	4	12	21	29	19	III
	R-A-W/4-1	5	5	23	3	10	16	11	27	III
	R-A-W/4-2	1	1	1	5	5	39	26	22	III
	R-A-W/4-4	1	1	1	2	2	47	28	18	
	R-A-W/4-5	1	1	1	0	1	1	33	62	
	Sa/4-1	2	1	5	23	21	14	19	15	III
	Kh/4-1	1	1	1	2	2	14	32	47	III
	Kh/4-2	5	5	27	9	5	17	13	19	
	Bu/4-1	1	1	1	2	43	29	14	9	III
	Su/4-1	1	1	5	9	46	19	13	6	III
	Su/4-2	2	2	5	41	25	16	6	3	III
Well 9	Ar/9-2	5	5	4	4	12	35	14	21	III
	Ar/9-3	5	5	5	4	8	33	18	22	IV
	Ar/9-4	5	5	4	4	4	31	26	21	IV
	Mi/9-1	10	5	13	36	16	10	5	5	II & III
	R-A-W/9-1	5	5	5	4	4	23	30	24	
	R-A-W/9-2	5	5	5	4	4	19	20	38	
	Sa/9-1	5	8	9	7	7	24	26	17	
	Kh/9-1	5	5	4	4	4	12	33	33	

Table 6.3 (Cont.)

Locality Borehole	Sample Number	Density Range								Kerogen Type
		<1.28	1.28-1.34	1.34-1.45	1.45-1.53	1.53-1.65	1.65-1.81	1.81-2.2	>2.2	
Well 12	Ar/12-1	5	9	9	4	7	26	20	20	III
	Mi/12-1	2	39	38	17	2	1	0	0	II
	Mi/12-2	5	29	43	20	2	1	0	0	II
	Kh/12-1	1	3	1	3	5	43	28	16	
Well 11	Mi/11-1	10	36	49	1	0	0	1	3	II
	Sa/11-1	5	24	57	5	3	1	2	3	II
	Kh/11-1	5	10	43	6	16	5	5	10	II & III
	Kh/11-2	1	1	5	3	4	13	22	51	
	Bi/11-1	5	5	40	25	10	7	3	5	
	Bi/11-2	5	5	9	8	29	22	7	15	
	Bu/11-1	5	5	13	8	21	24	13	11	II & III
	Ya/11-1	5	5	4	7	36	26	9	8	II & III
	Su/11-1	5	5	49	2	8	2	3	26	III
	Su/11-2	5	5	41	7	25	9	2	6	II & III
Well 14	Ar/14-1	65	21	8	1	1	0	0	4	
	Ar/14-2	65	22	8	1	1	0	0	3	
	Ar/14-3	10	9	24	28	14	6	1	8	
	Ar/14-4	20	40	20	8	5	3	2	2	II
	Ar/14-5	30	45	15	5	2	1	1	1	
	Ar/14-6	5	4	45	22	12	7	3	2	
	Mi/14-1	30	35	23	6	3	1	1	1	II
	Mi/14-2	70	18	7	3	1	1	0	0	II
	R-A-W/14-1	40	6	3	3	10	8	12	18	
	Sa/14-1	10	9	28	21	21	7	2	2	II
	Sa/14-2	30	21	22	18	6	2	1	0	II
	Kh/14-1	2	15	41	23	11	6	1	1	
	Kh/14-2	10	5	17	1	40	12	8	7	
	Bi/14-1	5	29	33	15	10	4	2	2	
	Bu/14-1	5	5	27	19	26	10	6	2	
	Ya/14-1	1	2	5	14	39	21	9	9	
	Su/14-2	5	29	23	15	14	7	4	3	II & III
Well 10	Ar/10-2	30	4	7	3	3	16	11	26	III
	Ar/10-3	1	1	2	2	38	28	20	8	
	Mi/10-2	50	35	14	1	0	0	0	0	II
	Mi/10-3	85	5	3	2	0	0	0	5	
	Sa/10-2	50	18	26	1	2	1	0	2	II
	Bu/10-1	15	17	37	18	7	3	2	1	
	Su/10-1	5	5	14	46	17	7	2	4	II & III
	Su/10-2	5	1	42	29	14	5	3	1	II & III

Table 6.3 (Cont.)

Locality Borehole	Sample Number	Density Range								Kerogen Type
		<1.28	1.28-1.34	1.34-1.45	1.45-1.53	1.53-1.65	1.65-1.81	1.81-2.2	>2.2	
Well 5	Ar/5-2	1	1	5	2	2	53	25	11	II
	Mi/5-1	30	60	6	2	1	0	0	1	II
	Mi/5-2	40	36	18	5	0	0	0	1	II
	R-A-W/5-1	2	5	5	5	8	45	21	9	III
	R-A-W/5-2	5	19	30	7	12	8	11		
	Sa/5-1	5	24	14	8	5	9	14	21	III
	Sa/5-2	50	30	12	2	1	1	1	3	II
	Kh/5-1	2	5	14	12	34	20	7	6	II & III
	Bu/5-1	20	12	34	19	10	3	1	1	II & III

specific gravity range for each fractionated sample. It should be pointed out that the volume percentage values have been estimated visually and can be considered subjective. However, the results of these fractionated kerogen samples indicate a good correlation with the kerogen types already identified by elemental analyses and have been inserted in the table for the purpose of comparison. It can be seen that type II kerogens are light in density with the majority having a specific gravity range of less than 1.45, while type III kerogens are heavy with a specific gravity range of 1.53 to 2.2, whereas the mixed type II and III kerogens are intermediate in density between the two types. Despite the wide density variation of the various kerogen components, there seems to be a general pattern which can be related to the different environments of deposition and the basin configuration of ALRub ALKhali.

In the area close to the shore line at the time of deposition, i.e. the area of wells 1, 2, 3, 4 and 9, it is noted from Table 6.3 that most of the samples are heavy in density (type III). They have a specific gravity range of 1.53 to 2.2 which is most probably due to a high influx of humic fragments (density range 1.53 to 2.2) deposited in a shallow marine environment. Thus, the organic matter is heavy in density and poor in hydrogen (gas-prone).

To the east, i.e. basinward, the sedimentary organic matter is noted to have a considerable variation in density throughout the Cretaceous section of ALRub ALKhali Basin. This is thought to be mainly the result of different environments of deposition. Being away from the paleoshore line, it seems

likely that different preservation conditions are the main factor that could influence the organic matter quality. As noted from Table 6.3, the Lower Safaniya and Lower Mishrif samples, all have a low density with a specific gravity range of less than 1.45 to 1.53, which is characteristic of hydrogen-rich kerogens. These samples, interpreted to have been deposited in a reducing environment (an intrashelf basinal area) away from the paleoshore line, show a good correlation between their organic matter quality and their inferred environment of deposition. If, on the other hand, the preservation conditions are poor, the organic matter in the sediment would be highly oxidized and poor in hydrogen content. Thus, the organic matter concentrate would be heavy with a high specific gravity range of 1.53 to 2.2 as seen in sample R-A-W/5-1 as an example. Oxidation and degradation can be intermediate leading to the formation of sedimentary organic matter which has a density range of 1.45 to 1.65 as seen in sample Su/10-2. This type of kerogen is a mixed type II and type III which was discussed earlier.

6. 4. *CHARACTERIZATION OF KEROGENS BY TRANSMITTED LIGHT MICROSCOPY*

6. 4. 1. **Introduction**

Microscopic examination of kerogen concentrates is a widely used technique for the assessment of source rock potential (Staplin, 1969; Correia, 1971; Bujak *et al*, 1977; Hunt, 1979; Rogers, 1980; Masran and Pocock, 1981; Kinghorn, 1983; Tissot and Welte, 1984). When viewed

under transmitted light microscope, the various organic components of kerogen can be recognized. The structure of the organic matter, its shape and colour can yield valuable information as to the kerogen type and its level of maturity. The components often being related to specific plant or animal tissues, e.g. spores, pollen, acritarch, filaments, etc. The relative abundance of each type of component present in the kerogen can be estimated, which allows an interpretation of the depositional environment. Thus, through visual observation and comparison of the organic matter, the hydrocarbon potential of a sedimentary basin and the types of hydrocarbons likely to be found can be evaluated. However, Powell *et al* (1982) consider that the main disadvantage of organic petrography is the inability to distinguish between hydrogen-rich (oil-prone) and hydrogen-poor (gas-prone) amorphous kerogens. This can be achieved by the use of elemental analysis described in the previous section. Also the density separation can give an indication as to the type of amorphous kerogen (Kinghorn and Rahman, 1983).

The main problem with organic petrography is the classification of kerogen. Several classifications have been proposed, each one is based upon the experience of its author(s). Staplin (1969), Correia (1971), and Burgess (1974) recognized four different types of organic matter based upon physical appearance. These are: amorphous - unorganised, structureless organic material which might be finely disseminated or coagulated into fluffy masses; herbaceous - membranes, vascular cuticular fragments, spores, pollen and transparent woody material; woody - elongate fibrous material of woody origin ranging in colour from pale yellow to brown;

and coaly - black , opaque and usually regular particles of woody origin. Bujak, Brass and Williams (1977) suggested the use of amorphogen - for unorganised structureless organic matter, which might be fine-grained or fluffy masses; phyrogen - comprising non-opaque recognisable plant material that was not of woody origin and included plant cuticles, spores, dinoflagellates; hylogen- non-opaque fibrous plant material of woody origin, and melanogen - comprising opaque organic matter. Masran and Pocock (1981) published an eight category system of plant derived particulate organic matter based on laboratory breakdown of tissues of identified extant plants.

It should be stated that the classification of the organic matter of sedimentary rocks has been made by three different scientific groups. These are : (i) palynologists, using microscopic examination of mineral-free organic material under transmitted light microscope; (ii) coal petrographers, applying microscopic examination of polished rock surfaces under reflected light microscope; and (iii) petroleum geochemists, using kerogen chemical analysis to determine its elemental composition (mainly C, H, and O).

Many authors in petroleum literature (e.g. Hunt, 1979; Kinghorn, 1983; Tissot and Welte, 1984; Brooks *et al*, 1987) have attempted a correlation of these three different classification systems. Figure 6.4 shows the approximate interrelationships of these three different classifications. As shown in the figure, the systems are similar in showing a division between the humic and sapropelic components of kerogen and coal. The term

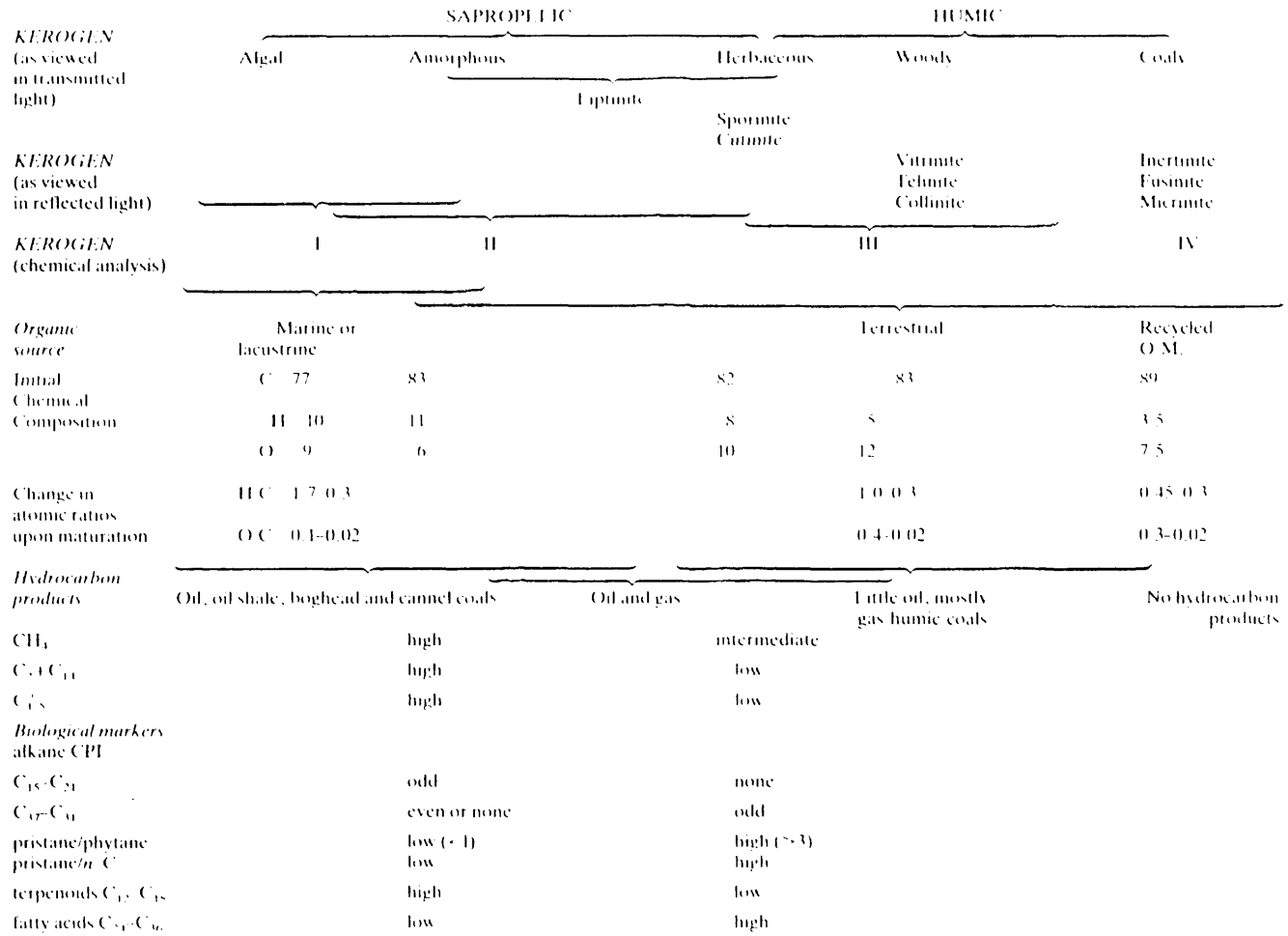


Figure 6.4 Comparison of kerogen classification

(After Kinghorn, 1983)

sapropelic refers to decomposition and polymerization products of fatty, lipid organic materials, e.g. planktonic algae deposited under oxygen restricted conditions. The term humic refers to products of peat formation, mostly the organic material of land origin deposited in oxygenated conditions, e.g. lignin, cellulose and aromatic tannins. This is important because most oil and gas are generated from sapropelic organic matter, whereas humic materials yield primarily gas.

Both the woody and coaly organic debris are grouped together as humic (see Fig. 6.4). The coaly material is regarded as inertinitic with very little or no hydrocarbon potential and corresponds to kerogen type IV in terms of chemical classification, whereas the woody fragments belong to the vitrinite coal maceral and correspond to the chemical kerogen type III.

The amorphous and herbaceous organic matter are regarded as lipid-rich materials (liptinites) and have been matched mainly with type II kerogen with some contribution to type I kerogen (see Fig. 6.4). However, not all amorphous organic matter can be classified as lipid-rich type I or II kerogens. Amorphous facies results from severe alteration of the original organic materials, which have lost their identity. Thus, if some amorphous kerogens belong to type I or II, others undoubtedly belong to type III. Powell *et al* (1982) and Kinghorn and Rahman (1983) have pointed out the existence of two types of amorphous organic matter. These are amorphous oil-prone and amorphous gas-prone kerogens. The amorphous oil-prone is hydrogen rich, believed to be derived from planktonic algal material deposited under anoxic conditions. Therefore, it is regarded as sapropelic

and commonly noted to occur as unorganized fluffy to semi-coherent masses when viewed under transmitted light microscope. Whilst the amorphous gas-prone is generally hydrogen lean and believed to be the result of microbial degradation of marine or terrestrially derived organic matter deposited under oxic conditions. It is chemically classified as type III kerogen and tends to be finely dispersed (fine-grained) in texture under transmitted light microscope.

Many authors (e.g. Gutjahr, 1966; Correia, 1967; Staplin, 1969; Peters *et al*, 1977) have shown that the thermal alteration of sedimentary organic matter as a result of increase in depth of burial (increased temperature) is reflected in the progressive darkening of colour and structural alteration of kerogen constituents, such as pollen, spores and sapropelic amorphous material. This observation is the basis for estimating kerogen maturity in transmitted light microscope. Correia (1967) and Staplin (1969) proposed two scales in which both colour and structure alteration were used. These are respectively named state of preservation of palynomorphs and thermal alteration index (TAI). Five stages are defined by colour and alteration of shape and ornamentation. Stage 1 refers to fresh yellow material, whereas stage 5 corrsesponds to barely identifiable remnants of the zone of metamorphism. Figure 6.5 shows a comparison of various maturation indicators based on kerogen analysis.

The use of colour indices for determining the approximate level of organic maturity is advantageous for its rapid and inexpensive interpretation. However, its primary disadvantage is the subjectivity of the colour

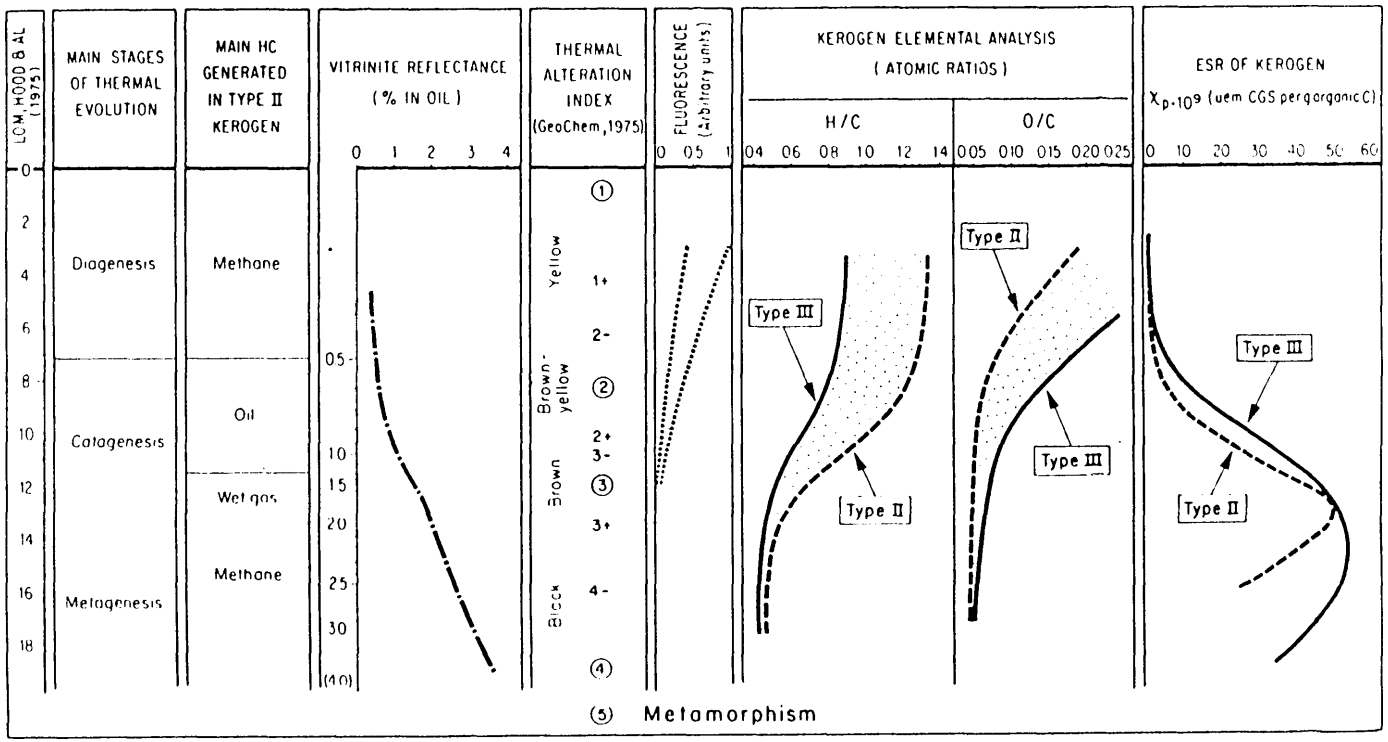


Figure 6.5 Comparison of various maturation indicators based on kerogen analysis (After Tissot and Welte, 1984)

determination. The examination of the colour of amorphous organic matter is carried out on a strewn slide by choosing the lightest coloured material as the maturation indicator. This is because thickness obviously can play a role in the observed colour and by choosing the thinnest part, a truer colour is obtained. Peters *et al* (1977) have used the colour of amorphous kerogen as a guide to its maturation. Their work is a study of laboratory-heated amorphous kerogen by transmitted light microscopy to determine the relations between organic maturation and colour changes over a range of time and temperature. They have shown that samples darken in colour from yellow through shades of brown to black with increasing thermal maturation and that the principal zone of oil generation occurs when the kerogen is between dark and very dark brown. Claypool *et al* (1978) have also indicated that thermally immature sediments are characterized by yellow to brown organic matter and thermally mature sediments have brown to dark brown kerogens, whilst incipiently metamorphosed sediments have very dark brown or black kerogens.

The organic constituents of the kerogen samples are classified in this project into five easily recognizable categories of sedimentary organic matter by transmitted-light microscopy. These are the sapropelic amorphous, the fine-grained amorphous, the structured plant remains (include pollen, spores, dinoflagellates, acritarchs and algal filaments), the humic (brown to opaque woody and coaly fragments), and the "cuticles" (any thin, translucent, tissue-like fragments of land plant origin). The relative abundance of these five organic groups is virtually estimated and expressed as "Dominant" (abbreviation D : > 75%), "Abundant"

(abbreviation A : 51-75%), "Very Common" (abbreviation VC : 26-50%), "Common" (abbreviation C : 5-25%), Minor (abbreviation M : 1-4%), and "Rare" (abbreviation R : < 1%).

In carbonate-type source rocks, the vitrinite reflectance and spore coloration techniques, which frequently determine source rock maturity, cannot be used because vitrinites and spores are scarce or absent in most carbonate sequences due to the lack of significant terrestrial input (Tissot and Welte, 1984). The same problem has been encountered in ALRub ALKhali potential carbonate source rocks. Consequently, the degree of maturation of the kerogen samples from Lower Safaniya and Mishrif have been estimated by examining the colour of their amorphous material. The problems of bleaching and false darkening by heavy-metal absorption are expected in the examination of amorphous organic matter (Kinghorn, 1983). Samples were standardized for colour interpretation from colour designations of Ridgway (1912) and Peters *et al* (1977) as in Fig. 6.6. The lightest kerogen of about the same thickness in any slide was used for colour determination. Subject to the fact that only contemporaneous kerogen constituents were considered in this optical maturity assessment, the levels of maturation reached for the kerogen samples from the Lower Safaniya and Lower Mishrif are considered to be indicative of the actual evolutionary stages attained by these Cretaceous organic matter.

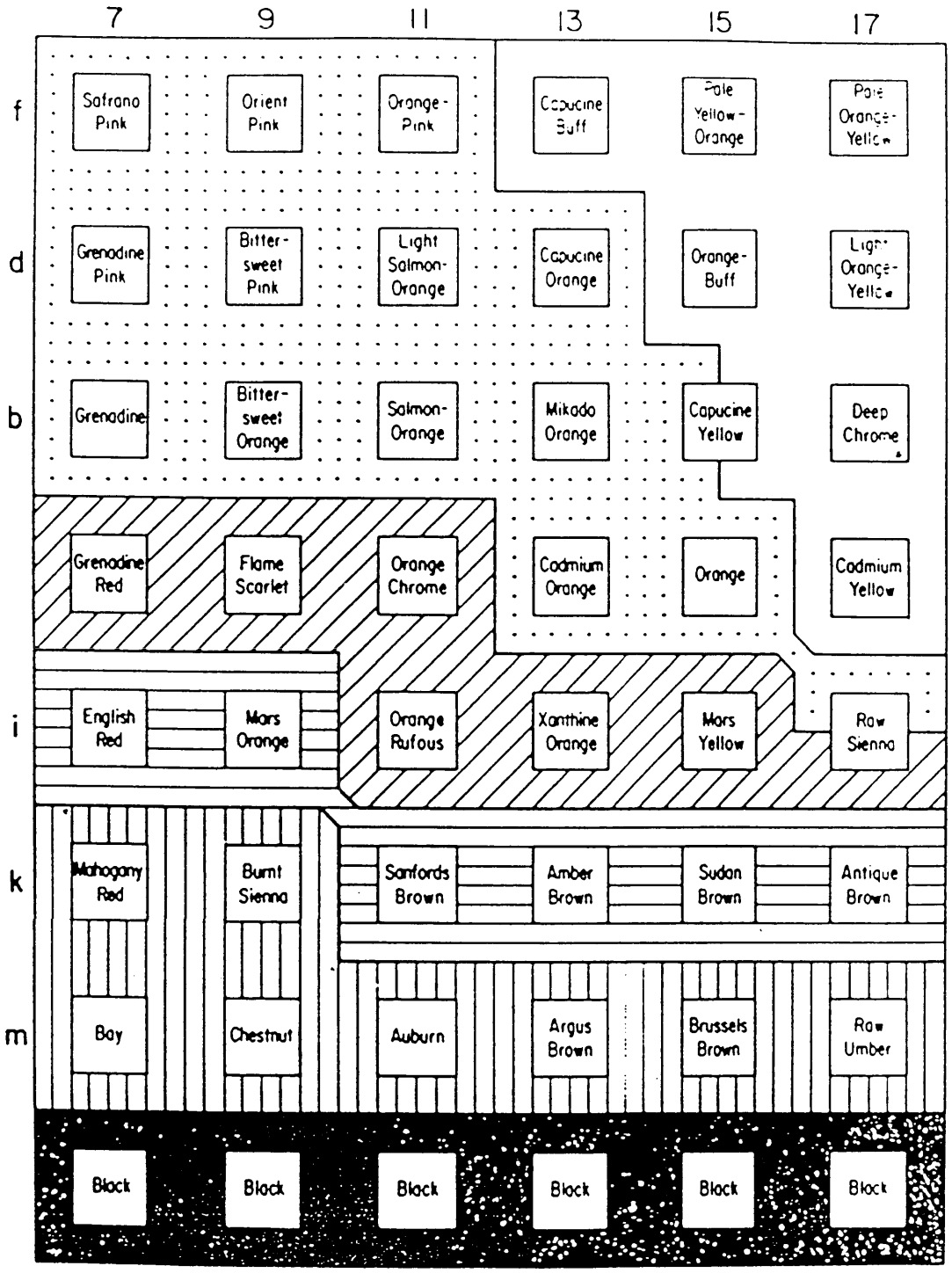


Figure 6.6 Colour designation of Ridgway (1912) and Peters et al (1977). Colour fields from upper right to lower left were termed yellow, light brown, brown, very dark brown, and black, respectively. (After Peters et al, 1977)

6.4.2. Assessment of Cretaceous Kerogens by Transmitted Light Microscopy

Table 6.4 shows the results of the transmitted-light microscopic assessment of kerogen concentrates from the sampled intervals of the Cretaceous in ALRub ALKhali Basin. The chemical kerogen type is indicated on the table for ease of compositional comparison between the various types. As with elemental analyses and density fractionation, variations are noted in the relative abundance of the five organic matter categories in samples within each kerogen type. These variations have been noted to be influenced by the distance from the paleoshore line and the different depositional environments which prevailed during the deposition of the Cretaceous sediments.

The visual examination of the organic matter indicates that kerogen type III in the study area can be divided into two groups. The first group, which is dominating the western part of ALRub ALKhali, i.e. the area of wells 1, 2, 3, 4 and 9 is noted to be influenced by terrestrial input from the continent deposited in a relatively oxidizing environment and will be referred to as "kerogen type III with terrestrial influence". This type of kerogen is noted to contain a mixture of humic fragments and fine-grained amorphous materials, each could reach up to 26-50% in most samples (see Plate 6.1). This mixture is heavy with a specific gravity range of 1.53 to 2.2. "Cuticular fragments" are rare (<1%) to common (5-25%), whereas the structured plant remains and the sapropelic amorphous materials constitute less than 4% in most of the samples.

Table 6.4 Transmitted-light Microscopic Assessment of the Cretaceous Kerogens

Locality Borehole	Sample Number	Kerogen Type	Composition of insoluble organic matter					Sapropelic Amorphous Colour of Lower Safaniya and Lower Mishrif Samples
			Sapropelic Amorphous	Fine-grained Amorphous	Structured Plant Remains	Humic	"Cuticles"	
Well 1	Mi/1-1	n.d.	M	C	R	UC	C	
	R-A-W/1-1	n.d.	R	V	R	UC	C	
	Ya/1-1	n.d.	R	C	R	VC	R	
	Su/1-1	n.d.	C	VC	R	C	R	
Well 2	Ar/2-1	n.d.	C	C	R	VC	M	
	Ya/2-1	n.d.	M	VC	R	VC	R	
	Su/2-1	n.d.	M	VC	R	VC	R	
	Su/2-2	n.d.	M	VC	R	VC	R	
Well 3	Ar/3-1	n.d.	M	VC	R	VC	M	
	Ar/3-2	III	M	VC	R	VC	M	
	Ar/3-3	III	M	VC	R	VC	M	
	Mi/3-1	III	C	VC	M	VC	M	
	R-A-W/3-1	III	M	VC	R	VC	M	
	R-A-W/3-3	III	M	VC	R	VC	M	
	R-A-W/3-4	III	R	VC	M	VC	M	
	Sa/3-1	n.d.	M	VC	R	VC	M	
Well 4	Ar/4-1	n.d.	C	VC	R	C	C	
	Ar/4-2	III	M	A	M	VC	C	
	Ar/4-3	III	R	VC	M	C	C	
	Ar/4-4	IV	R	VC	R	VC	M	
	Ar/4-5	III	R	A	R	VC	C	
	R-A-W/4-1	III	R	A	R	VC	C	
	R-A-W/4-2	III	M	C	R	VC	C	
	R-A-W/4-4	n.d.	C	A	M	C	M	
	R-A-W/4-5	n.d.	M	VC	C	C	R	
	Sa/4-1	III	M	C	M	A	C	
	Kh/4-1	III	M	VC	M	VC	C	
	Kh/4-2	n.d.	M	VC	C	VC	C	
	Bu/4-1	III	M	VC	R	A	R	
	Su/4-1	III	M	VC	R	VC	M	
	Su/4-2	III	M	A	R	C	R	

Table 6.4 (cont.)

Locality Borehole	Sample Number	Kerogen Type	Composition of insoluble organic matter					Sapropelic Amorphous Colour of Lower Safaniya and Lower Mishrif Samples
			Sapropelic Amorphous	Fine-grained Amorphous	Structured Plant Remains	Humic	"Cuticles"	
Well 5	Ar/5-1	n.d.	C	A	R	M	M	
	Ar/5-2	III	C	A	R	R	R	
	Mi/5-1	II	D	-	-	-	R	Light brown
	Mi/5-2	II	D	-	-	-	R	" "
	R-A-W/5-1	III	C	A	R	M	M	
	R-A-W/5-2	n.d.	VC	VC	R	-	-	
	Sa/5-1	III	C	A	R	R	M	
	Sa/5-2	II	D	-	-	-	R	Light brown
	Kh/5-1	II & III	VC	VC	R	R	R	
	Bu/5-1	II & III	VC	VC	R	R	R	
Well 10	Ar/10-1	n.d.	C	VC	R	R	R	
	Ar/10-2	III	C	A	R	R	M	
	Ar/10-3	n.d.	C	A	R	R	R	
	Mi/10-1	n.d.	D	-	R	-	-	Yellow
	Mi/10-2	II	D	-	-	-	R	"
	Mi/10-3	n.d.	D	-	-	-	-	"
	Sa/10-2	II	D	-	-	-	-	Light brown
	Kh/10-1	n.d.	M	A	-	R	-	
	Bu/10-1	n.d.	C	A	R	R	R	
	Su/10-1	II & III	VC	R	R	-		
	Su/10-2	II & III	VC	VC	R	R	-	
Well 11	Mi/11-1	II	D	-	R	R	R	Yellow
	R-A-W/11-1	n.d.	C	-	-	-	-	
	R-A-W/11-2	n.d.	M	-	-	-	-	
	Sa/11-1	II	D	-	-	R	-	Yellow
	Kh/11-1	II & III	VC	VC	R	R	R	
	Kh/11-2	n.d.	R	A	R	C	-	
	Bi/11-1	n.d.	C	R	R	-		
	Bi/11-2	n.d.	C	A	-	R	-	
	Bu/11-1	II & III	VC	VC	M	R	R	
	Ya/11-1	II & III	VC	VC	-	R	-	
	Su/11-1	III	M	A	-	M	-	
	Su/11-2	II & III	VC	VC	-	R	-	

Table 6.4 (cont.)

Locality Borehole	Sample Number	Kerogen Type	Composition of insoluble organic matter					Sapropelic Amorphous Colour of Lower Safaniya and Lower Mishrif Samples
			Sapropelic Amorphous	Fine-grained Amorphous	Structured Plant Remains	Humic	"Cuticles"	
Well 12	Ar/12-1	III	M	A	R	C	R	
	Mi/12-1	II	D	-	-	R	R	Yellow
	Mi/12-2	II	D	-	-	R	-	Yellow
	Kh/12-1	n.d.	M	A	-	C	R	
Well 9	Ar/9-1	n.d.	C	C	-	C	C	
	Ar/9-2	III	M	VC	R	VC	M	
	Ar/9-3	IV	M	VC	R	VC	M	
	Ar/9-4	IV	M	VC	R	VC	M	
	Mi/9-1	II & III	VC	M	R	VC	M	
	R-A-W/9-1	n.d.	M	VC	-	VC	R	
	R-A-W/9-2	n.d.	M	VC	R	UC	R	
	Sa/9-1	n.d.	C	VC	R	VC	R	
	Kh/9-1	n.d.	M	A	R	VC	R	
Well 14	Ar/14-1	n.d.	A	-	C	R	R	
	Ar/14-2	n.d.	A	-	-	R	M	
	Ar/14-3	n.d.	VC	VC	M	R	R	
	Ar/14-4	II	A	C	R	R	-	
	Ar/14-5	n.d.	A	C	-	R	-	
	Ar/14-6	n.d.	VC	VC	M	R	R	
	Ar/14-6	n.d.	VC	VC	M	R	R	
	Mi/14-1	II	D	-	-	R	R	Brown
	Mi/14-2	II	A	C	-	R	R	"
	R-A-W/14-1	n.d.	VC	VC	R	R	R	
	Sa/14-1	II	A	C	R	R	-	Brown
	Sa/14-2	II	A	C	-	-	-	"
	Kh/14-1	II & III	C	A	R	R	-	
	Kh/14-2	n.d.	C	A	-	R	-	
	Bi/14-1	n.d.	C	A	R	R	-	
	Bu/14-1	n.d.	C	A	R	R	-	
	Ya/14-1	n.d.	C	A	-	-	-	
	Su/14-1	n.d.	C	C	-	-	-	
	Su/14-2	II & III	VC	VC	-	R	-	

D = Dominant (>75%); A = Abundant (51-75%); VC = Very Common (26-50%); C = Common (5-25%); M = Minor (1-4%); R = Rare (<1%); n.d. = not determined

The second group of Kerogen type III has been identified in the eastern part of the study area (away from the paleoshore line) where the respective environment of deposition seems to be the dominating factor. This kerogen is referred to as "kerogen type III without terrestrial influence". In this type, the most abundant material is the fine-grained amorphous comprising 51 to 75% of the sample with specific gravity ranging from 1.53 to 2.2 (see Plate 6.2). This is the heavy, hydrogen-lean, fine-grained amorphous type described by Kinghorn and Rahman (1983). It is commonly greyish to greyish brown in colour. The sapropelic amorphous materials tend to be minor (1-4%) to common (5-25%) in this kerogen type. The humic fragments and the "cuticles" are minor (1 -4%) to rare (<1%).

The mixed type II/III kerogens in ALRub ALKhali Basin can be also divided into two groups, The first is noted to be more influenced by the humic input from the west in addition to the effect of the preservation conditions. This group of kerogens is referred to as "mixed type II/III kerogens with terrestrial influence". In this type, the sapropelic amorphous matter and the humic fragments constitute a mixture of 26-50% each (see Plate 6.3). Both the fine-grained amorphous material and the "cuticles" are minor (1-4), while the structured plant remains are less than 1%.

The second group of the mixed type II/III is referred to as "mixed type II/III kerogens without terrestrial influence". These samples are noted to contain a mixture of sapropelic and finely dispersed amorphous material, each in the range of 26-50% (see Plate 6.4). It should be pointed out that the fine-grained amorphous material in this type of kerogen is hydrogen-

lean and greyish brown in colour. In most of these samples, it is observed that the humic fragments, the "cuticles" and the structured plant ramains are rare (<1%).

In the type IV kerogen samples, each of the greyish fine-grained amorphous material and the humic fragments constitutes 26-50% of the total concentrate. These organic materials are the most abundant components (see Plate 6.5). The sapropelic amorphous and the "cuticles" are minor (1-4%) to rare (<1%). The structured plant remains are also rare (<1%) in these samples.

In the type II kerogen in ALRub ALKhali the dominant material (>75%) is the yellow to brown sapropelic amorphous material with specific gravity mostly in the range of <1.45, and therefore regarded as light and hydrogen-rich (see Plate 6.6). Also observed is the fact that the sapropelic amorphous matter in most of the samples have specific gravities ranging up to 2.2. The heaviness is most probably due to the unique abundance of opaque particles , interpreted here to be most likely pyrite, in these fluffy masses (see Plate 6.4G). The humic fragments, the "cuticles", and the structured plant remains are rare (<1%) in most of these type II kerogens, while the heavy fine-grained amorphous is absent. However, type II kerogens identified in well 14 are noted to contain 5-25% fine-grained amorphous. This material is yellow to brown in colour and light, with specific gravity range of <1.53. It is interpreted to be hydrogen-rich, unlike the grey, heavy, and hydrogen-poor fine-grained organic matter which has been discussed earlier and identified in kerogens type III, mixed

type II/III, and type IV.

Optical maturity assessment for Lower Safaniya and Lower Mishrif samples is shown in Table 6.4. These results indicate that, apart from well 14, the kerogen from all the sampled boreholes in the study area show colours ranging from yellow to light brown (see Plate 6.7). In well 14, kerogens are brown in colour. The colour interpretation of the organic matter suggests that the Lower Safaniya and Lower Mishrif potential source rocks are immature throughout the study area. Although these units appear to be relatively more mature in the area of well 14, they are not mature enough to reach the "principal phase of oil formation" of Peters *et al* (1977) corresponding to the boundary between dark-brown and very dark-brown colours. It should be stated that Peters *et al* work has been used in this project as a reference only without necessarily implying that their kerogen samples undergo a thermal evolution similar to that of the organic matter in ALRub ALKhali Basin.

These maturity findings are supported by the fact that despite an extensive hydrocarbon exploration program carried out by ARAMCO, only two oil fields have been discovered. This oil discovery is located further to the east of the study area, near the borders with Abu Dhabi, where the burial depth is higher. It can be stated that the maturity levels arrived at for the Lower Safaniya and Lower Mishrif kerogen samples based on colour determination are fairly consistent with the levels of maturation portrayed by these samples on the van Krevelen type-plots and discussed earlier in section 6.2.2.

Plate 6.1: Kerogen Type III "with terrestrial influence"

A. *The < 1.28 Density Fraction of Sample Ar/3-2:*

Most probably algal remains (magnification x 250). This fraction accounts for about 2 volume % of the total organic concentrate.

B. *The 1.28-1.34 Density Fraction of Sample Ar/3-2:*

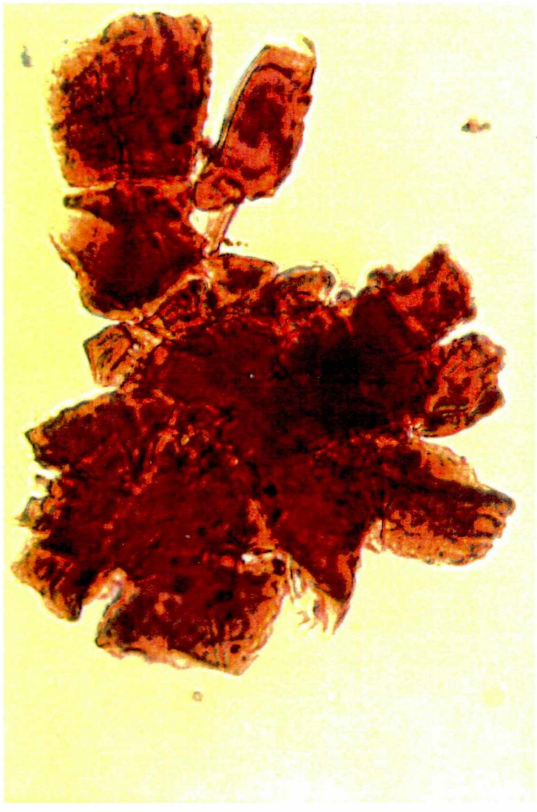
A spore, most probably an algal spore (magnification x 400). This fraction forms about 3 volume % of the total organic concentrate. Structured plant remains are rare in this sample.

C. *The 1.34-1.45 Density Fraction of Sample Ar/3-2:*

Most probably algal remains (magnification x 250). The sapropelic amorphous is minor in this sample. This fraction accounts for about 3 volume % of the total organic concentrate.

D. *The 1.45-1.53 Density Fraction of Sample Ar/3-2:*

A "cuticle" probably phloem cells (Masran and Pocock, 1981). Their affinities are frequently difficult to determine. "cuticles" are minor in this sample (magnification x 160). This fraction accounts for about 4 volume % of the total organic concentrate.



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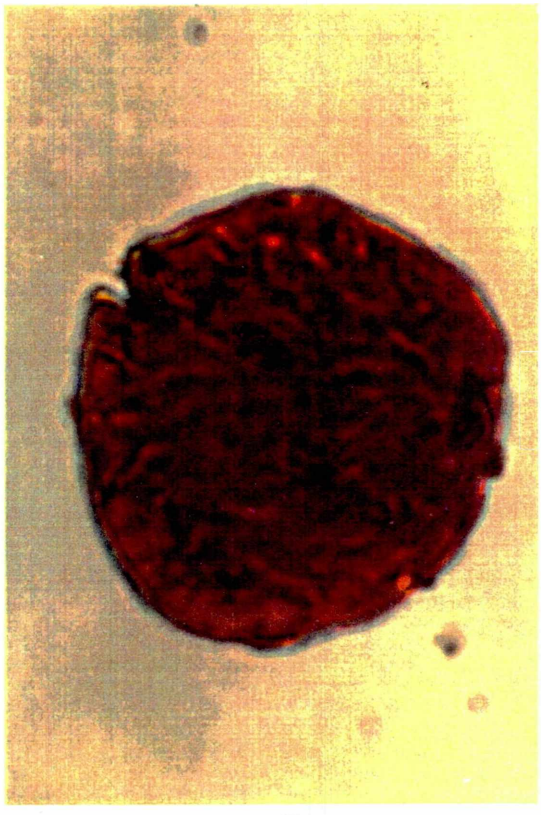
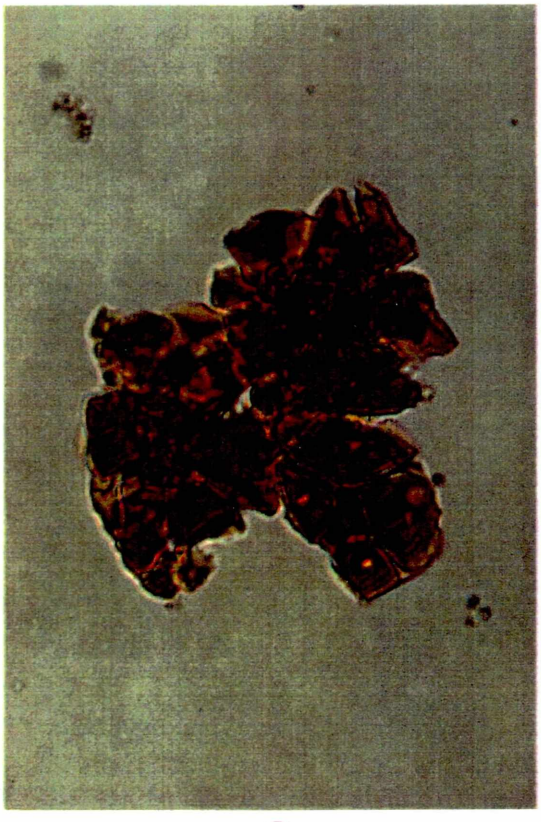


B



C

D

Place 6.1: Kerogen Type III "with terrestrial influence" (contd.)

E. *The 1.53-1.65 Density Fraction of Sample Ar/3-2:*

An acritarch (magnification x 250). These are indicators of open marine environments. Structured plant remains are rare in this sample. This fraction forms about 13 volume % of the total organic concentrate.

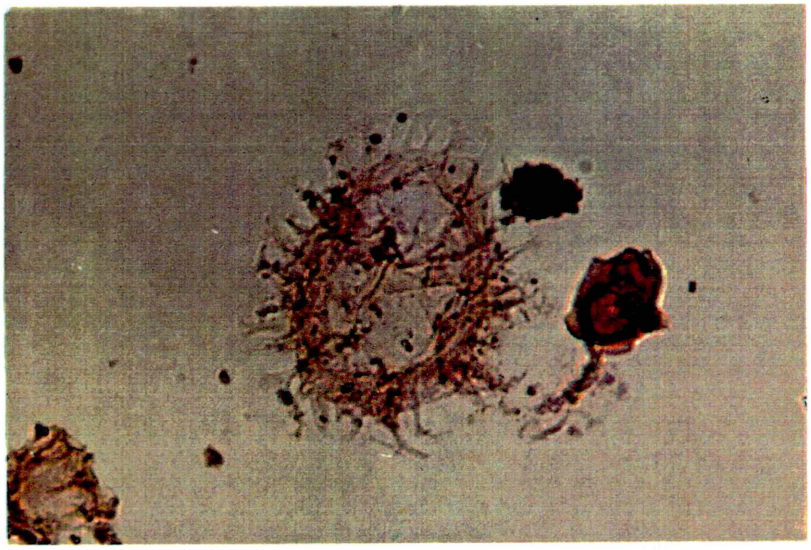
F. *The 1.65-1.81 Density Fraction of Sample Ar/3-2:*

This fraction accounts for about 49 volume % of the total organic concentrate, and consists dominantly of fine-grained amorphous and humic fragments which are very common in this sample (magnification x 63).

G. *The 1.81-2.2 Density Fraction of Sample Ar/3-2:*

This fraction forms about 17 volume % of the total organic concentrate. Fine-grained amorphous and humic fragments are very common in this sample. Sapropelic amorphous and "cuticles" are minor and structured plant remains are rare (magnification x 63).

E



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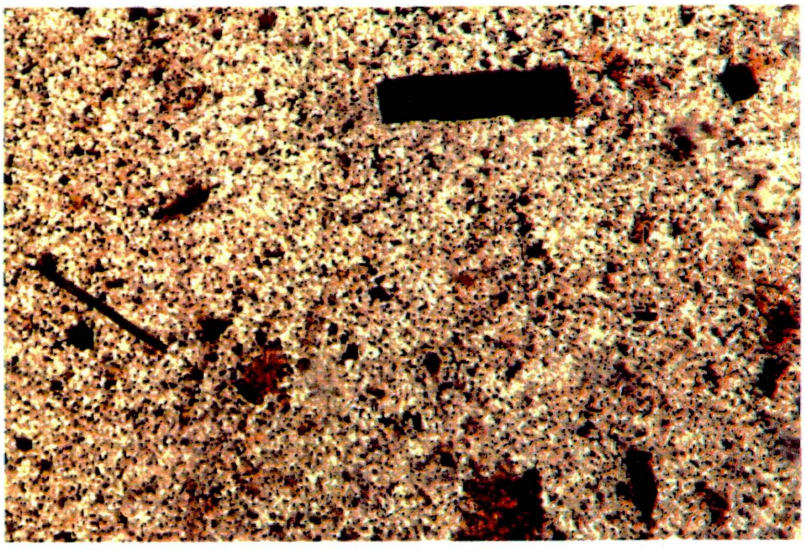

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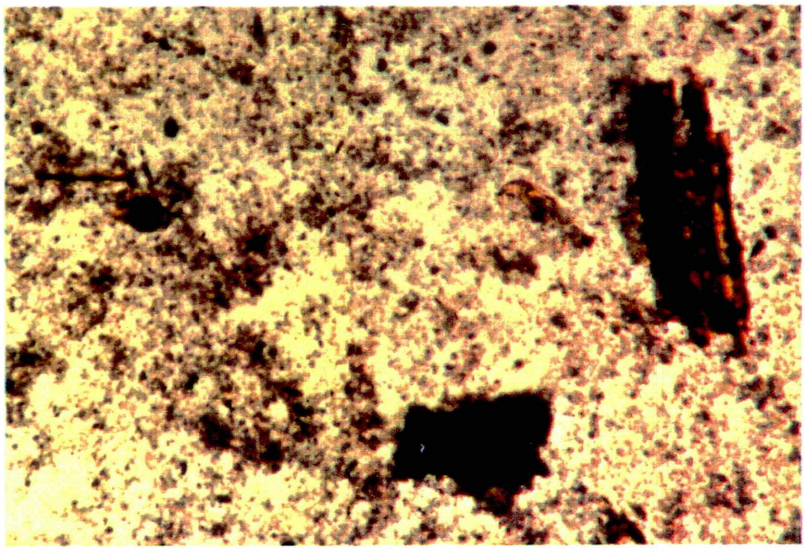


Plate 6.2: Kerogen Type III "without terrestrial influence"

A. *The < 1.28 Density Fraction of Sample Ar/52:*

Most probably algal remains (magnification x 250). This fraction accounts for about 1 volume % of the total organic concentrate.

B. *The 1.28-1.34 Density Fraction of Sample Ar/5-2:*

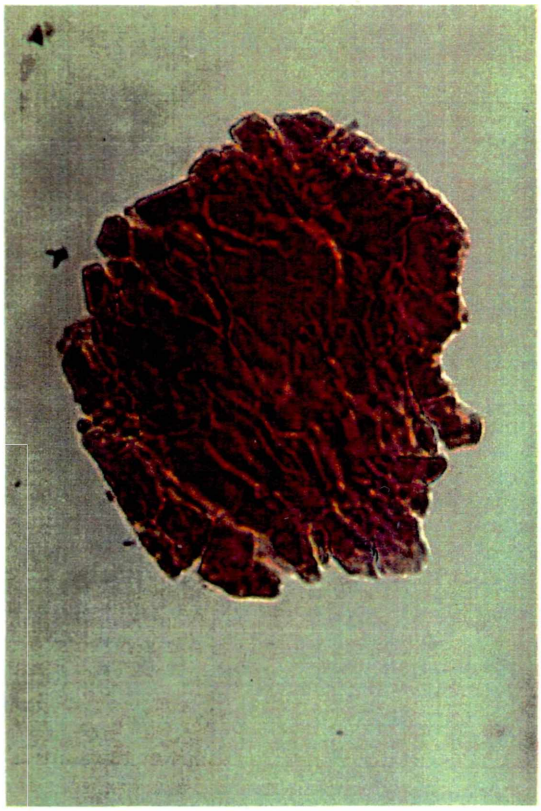
Most probably algal remains (magnification x 250). This fraction forms about 1 volume % of the total organic concentrate.

C. *The 1.34-1.45 Density Fraction of Sample Ar/5-2:*

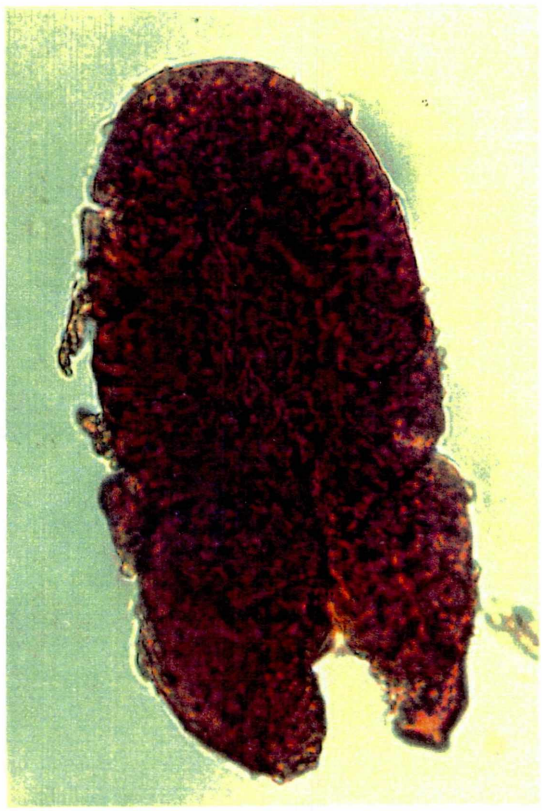
Most probably algal remains (magnification x 160). The sapropelic amorphous is common in this sample while "cuticles" are rare. This fraction accounts for about 5 volume % of the total organic concentrate.

D. *The 1.45-1.53 Density Fraction of Sample Ar/5-2:*

Spiral vessels derived from the xylem, or water conducting tissue of the plant (Masran and Pocock, 1981). In the right side of the plate, most probably a filamentous algal remain (Venkatachala, 1981). The structured plant remains are rare in this sample. This fraction accounts for about 2 volume % of the total organic concentrate (magnification x 250).

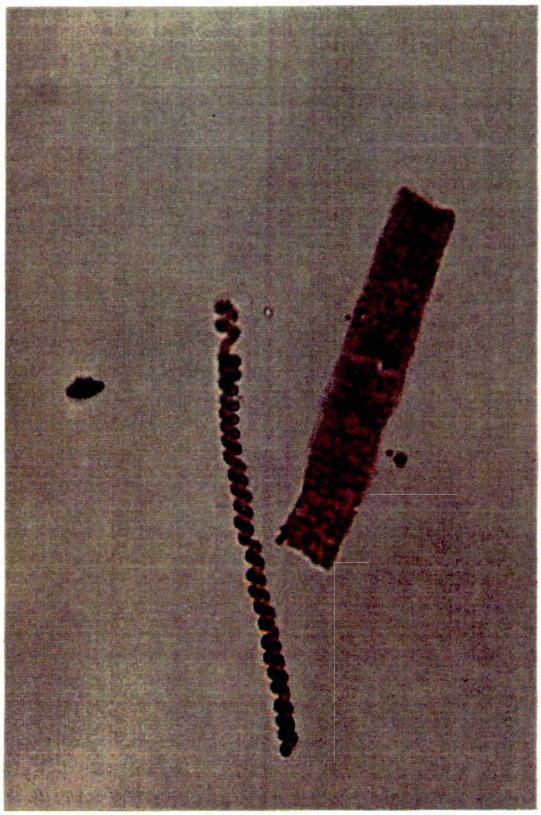


A



B

C



D

Plate 6.2: Kerogen Type III "without terrestrial influence" (contd.)

E. *The 1.53-1.65 Density Fraction of Sample Ar/5-2:*

A humic fragment (magnification x 160). Humic is rare in this sample. This fraction forms about 2 volume % of the total organic concentrate.

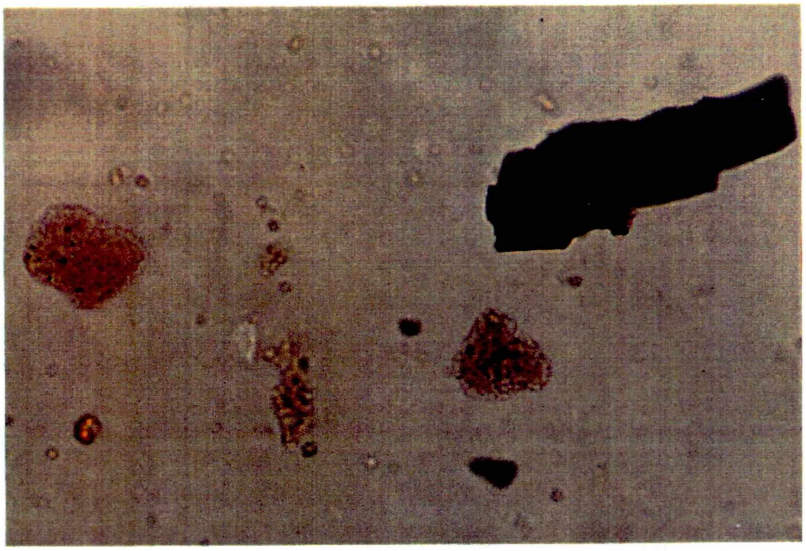
F. *The 1.65-1.81 Density Fraction of Sample Ar.5-2:*

This fraction accounts for about 53 volume % of the total organic concentrate, and consists dominantly of fine-grained amorphous. Sapropelic amorphous is common in this sample (magnification x 63).

G. *The 1.81-2.2 Density Fraction of Sample Ar/5-2:*

This fraction forms about 25 volume % of the total organic concentrate, consisting mainly of fine-grained amorphous. "cuticles", structured plant remains, and humic are rare in this sample (magnification x 63).

E



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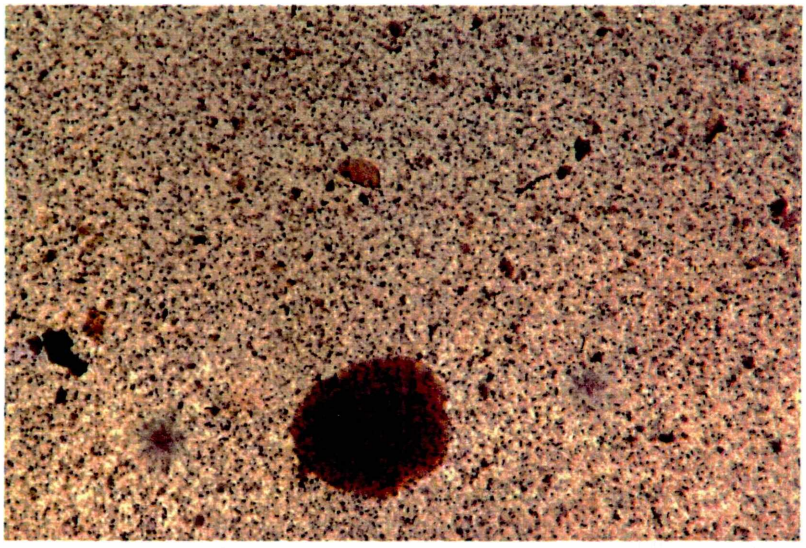

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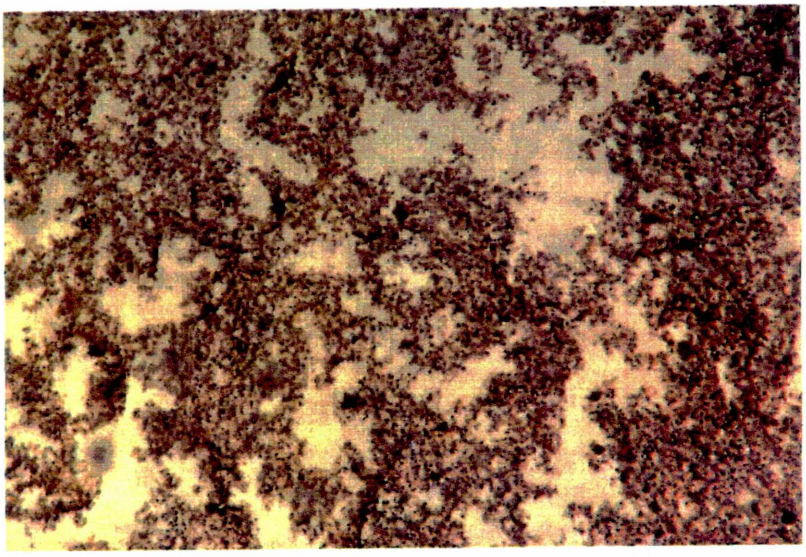


Plate 6.3: Mixed Type II/III Kerogens "with terrestrial influence"

A. *The < 1.28 Density Fraction of Sample Mi/9-1:*

Sapropelic amorphous (magnification x 160). This fraction accounts for about 10 volume % of the total organic concentrate.

B. *The 1.28-1.34 Density Fraction of Sample Mi/9-1:*

Sapropelic amorphous (magnification x 40). The sapropelic amorphous is very common in this sample. This fraction forms about 5 volume % of the total organic concentrate.

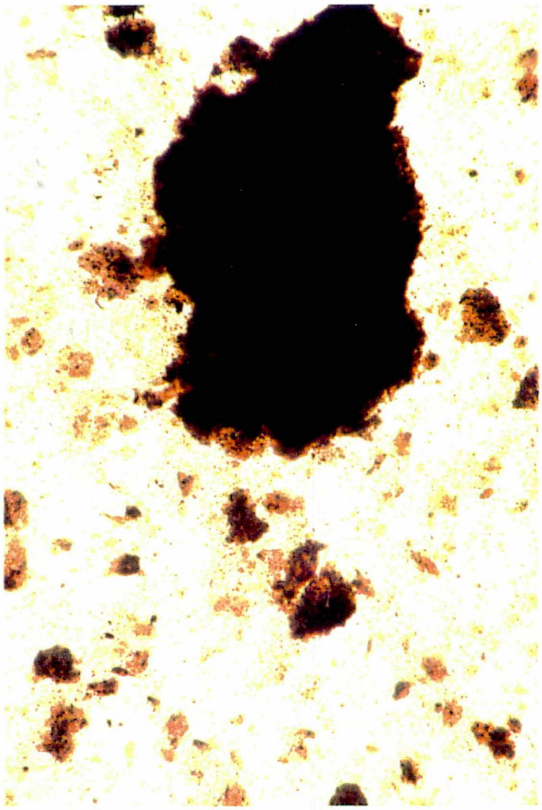
C. *The 1.34-1.45 Density Fraction of Sample Mi/9-1:*

Sapropelic amorphous and a "cuticle" which is most probably a woody tissue (Masran and Pocock, 1981). This fraction accounts for about 13 volume % of the total organic concentrate. "cuticles" are minor in this sample (magnification x 40).

D. *The 1.45-1.53 Density Fraction of Sample Mi/9-1:*

Sapropelic amorphous and a humic fragment (magnification x 160). This fraction accounts for about 36 volume % of the total organic concentrate. The humic is very common in this sample.

A



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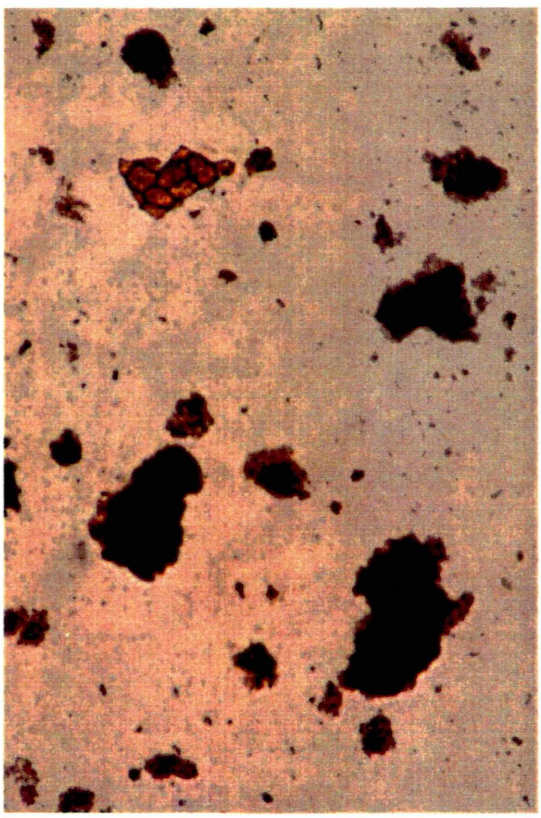


C

D

Plate 6.3: Mixed Type II/III Kerogens "with terrestrial influence" (contd.)

E. *The 1.53-1.65 Density Fraction of Sample Mi/9-1:*

Sapropelic amorphous and humic fragments (magnification x 40). This fraction forms about 16 volume % of the total organic concentrate. Structured plant remains are rare in this sample.

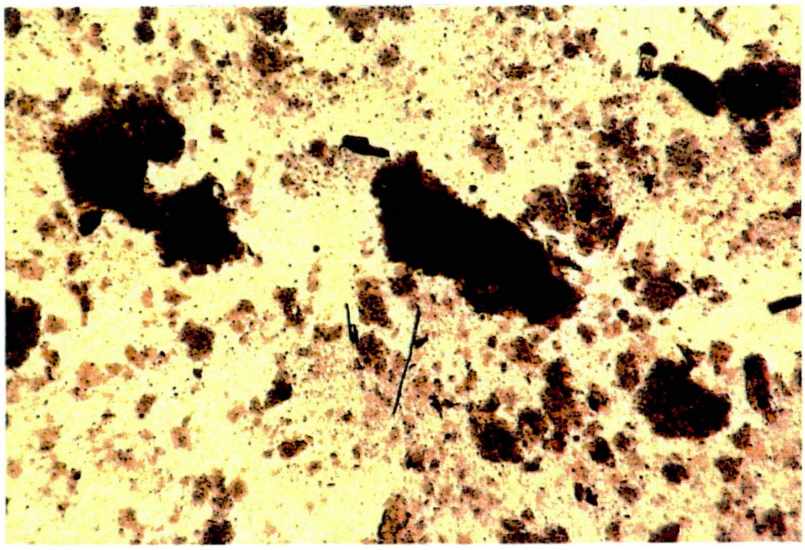
F. *The 1.65-1.81 Density Fraction of Sample Mi/9-1:*

Sapropelic amorphous, humic fragments are fine-grained amorphous (magnification x 40). This fraction accounts for about 10 volume % of the total organic concentrate.

G. *The 1.81-2.2 Density Fraction of Sample Mi/9-1:*

Fine-grained amorphous, humic fragments, and sapropelic amorphous (magnification x 63). This fraction accounts for about 5 volume % of the total organic concentrate. The fine-grained amorphous is minor in this sample.

E



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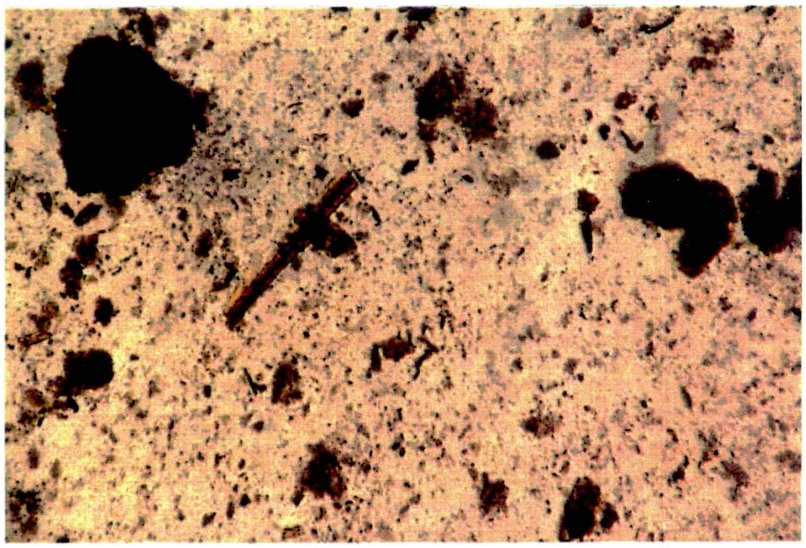

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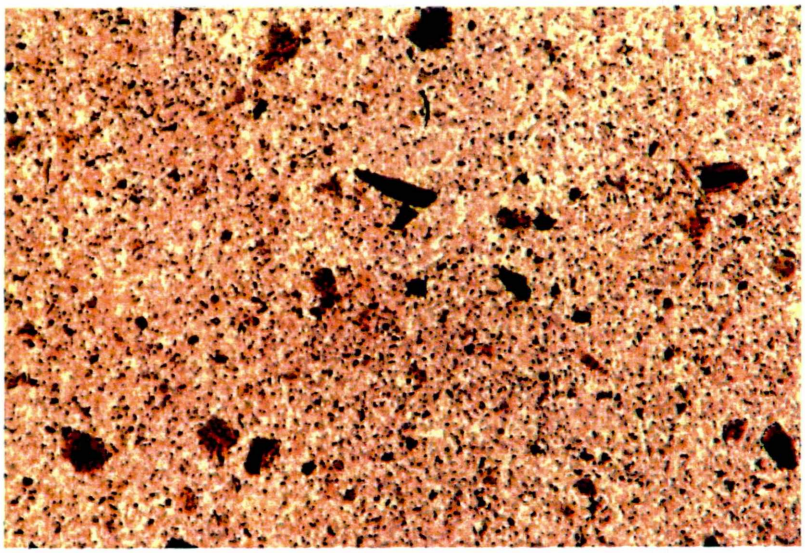


Plate 6.4: Mixed Type II/III Kerogens "without terrestrial influence"

A. *The < 1.28 Density Fraction of Sample Kh/11-1:*

A spore with sapropelic amorphous (magnification x 250). This fraction accounts for about 5 volume % of the total organic concentrate. Structured plant remains are rare in this sample.

B. *The 1.28-1.34 Density Fraction of Sample Kh/11-1:*

Sapropelic amorphous (magnification x 63). This fraction forms about 10 volume % of the total organic concentrate.

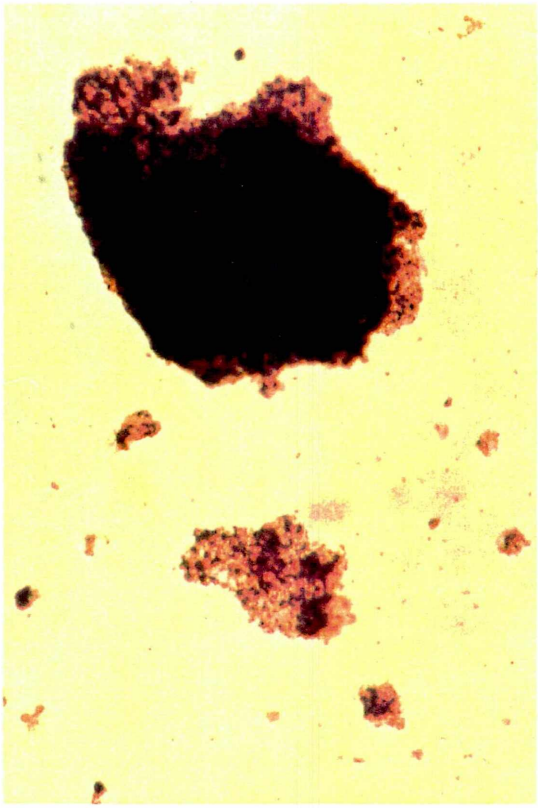
C. *The 1.34-1.45 Density Fraction of Sample Kh/11-1:*

Sapropelic amorphous (magnification x 63). This fraction accounts for about 43 volume % of the total organic concentrate. Sapropelic amorphous is very common in this sample.

D. *The 1.45-1.53 Density Fraction of Sample Kh/11-1:*

Sapropelic amorphous (magnification x 63). This fraction forms about 6 volume % of the total organic concentrate. "cuticle" are rare in this sample.

A



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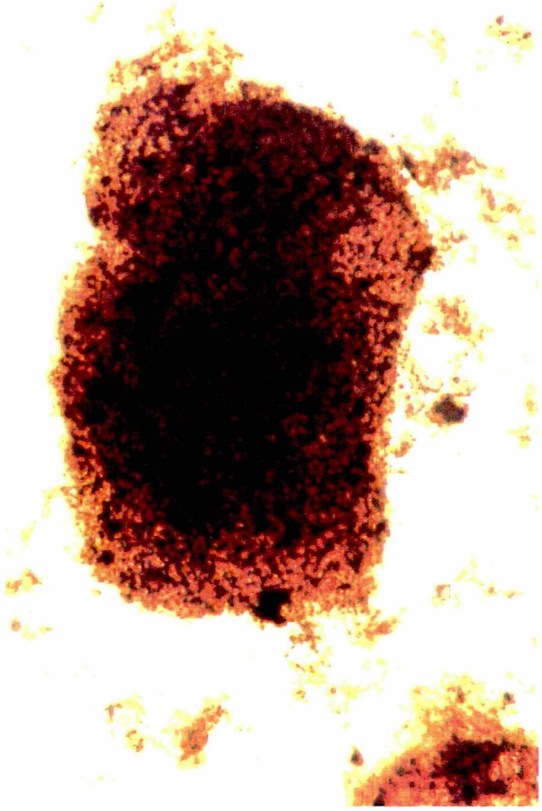

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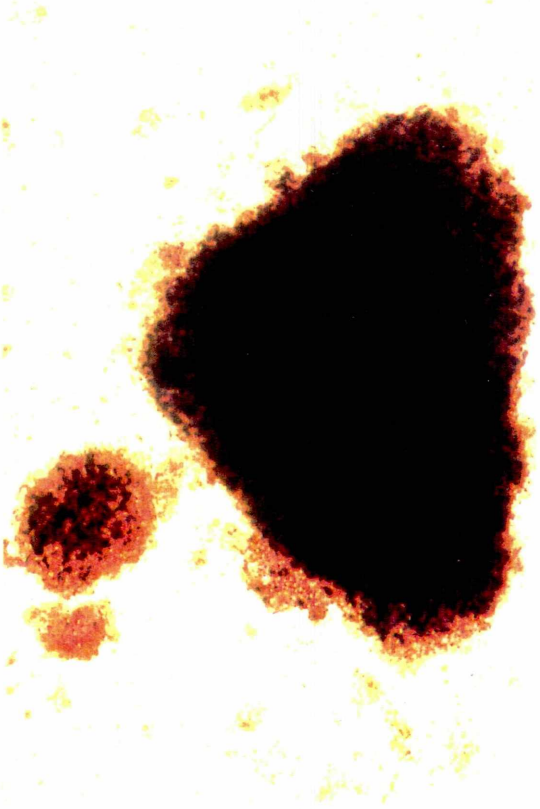


D

Plate 6.4: Mixed Type II/III Kerogens "without terrestrial influence" (contd.)

E. *The 1.53-1.65 Density Fraction of Sample Kh/11-1:*

Sapropelic amorphous and fine-grained amorphous (magnification x 63). This fraction accounts for about 16 volume % of the total organic concentrate. The fine-grained amorphous is very common in this sample.

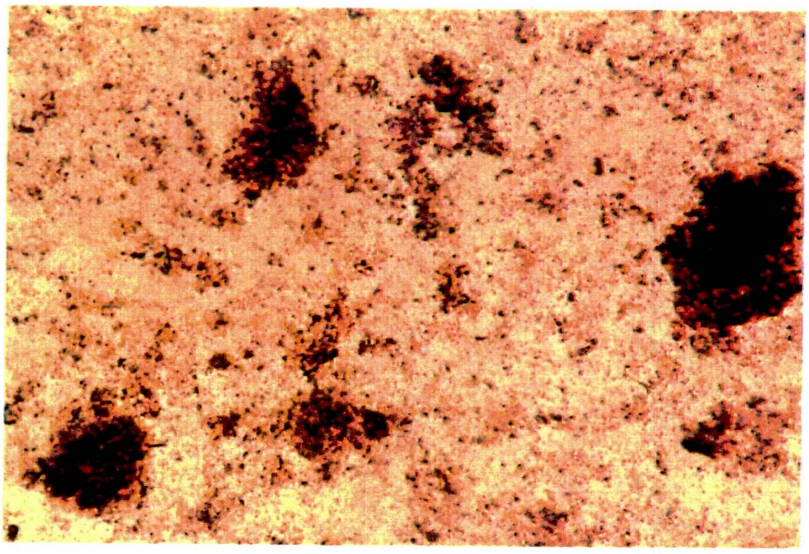
F. *The 1.65-1.81 Density Fraction of Sample Kh/11-1:*

Fine-grained amorphous and a humic fragment (magnification x 63). This fraction forms about 5 volume % of the total organic concentrate. The humic is rare in this sample.

G. *The 1.81-2.2 Density Fraction of Sample Kh/11-1:*

Fine-grained amorphous and sapropelic amorphous (magnification x 63). This fraction accounts for about 5 volume % of the total organic concentrate. The sapropelic amorphous masses are heavily infested with opaque, ? heavy mineral grains - most probably pyrite.

E



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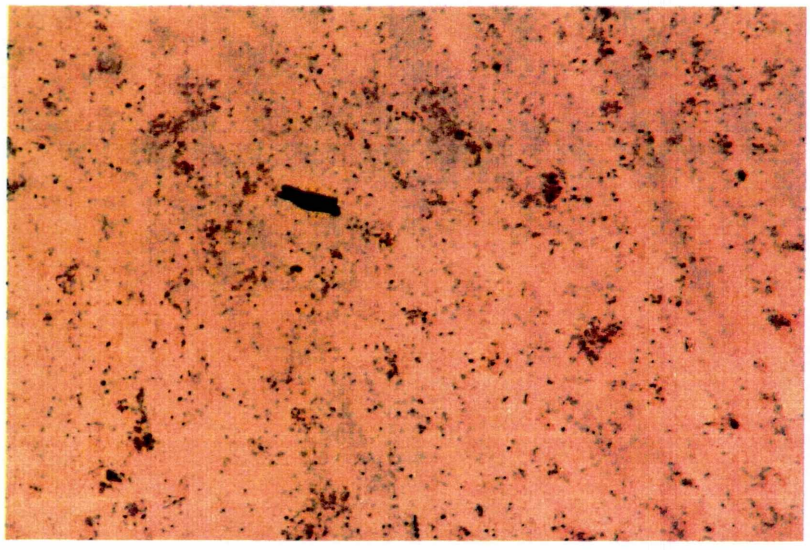

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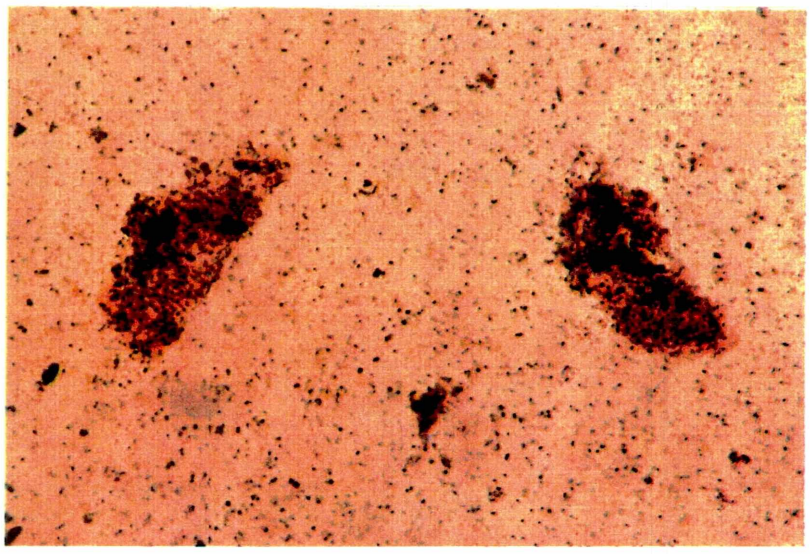


Plate 6.5: Kerogen Type IV

A. *The < 1.28 Density Fraction of Sample Ar/9-3:*

A "cuticle", most probably a woody tissue (Masran and Pocock, 1981). This fraction accounts for about 5 volume % of the total organic concentrate. The "cuticles" are minor in this sample (magnification x 63).

B. *The 1.28-1.34 Density Fraction of Sample Ar/9-3:*

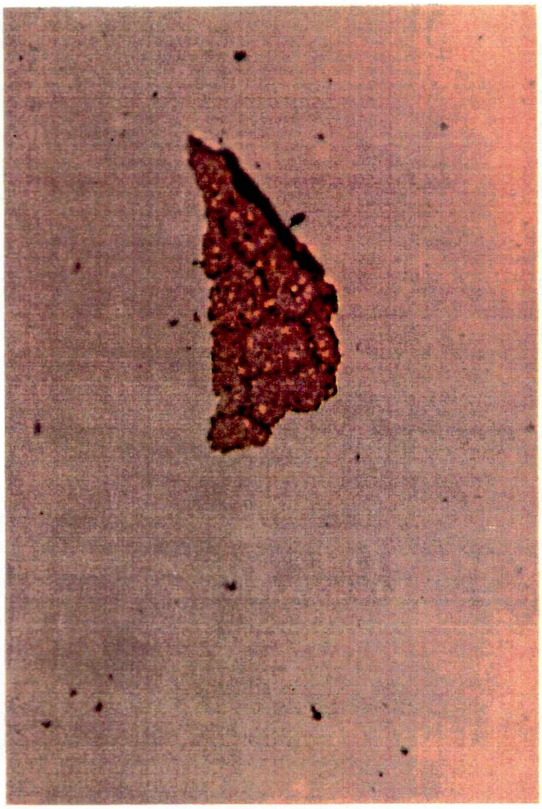
A broken spore (magnification x 630). This fraction forms about 5 volume % of the total organic concentrate. The structured plant remains are rare in this sample.

C. *The 1.34-1.45 Density Fraction of Sample Ar/9-3:*

Most probably algal remains (magnification x 250). This fraction forms about 5 volume % of the total organic concentrate. The sapropelic amorphous is minor in this sample.

D. *The 1.45-1.53 Density Fraction of Sample Ar/9-3:*

Sieve plate, derived from sieve tube of the pholem, the food carrying structures of vascular tissue (Masran and Pocock, 1981). This fraction accounts for about 4 volume % of the total organic concentrate (magnification x 630).



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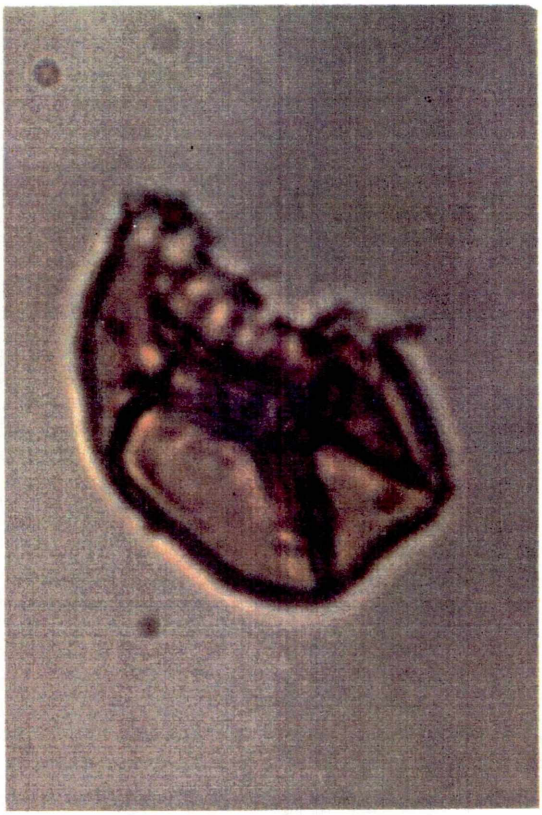

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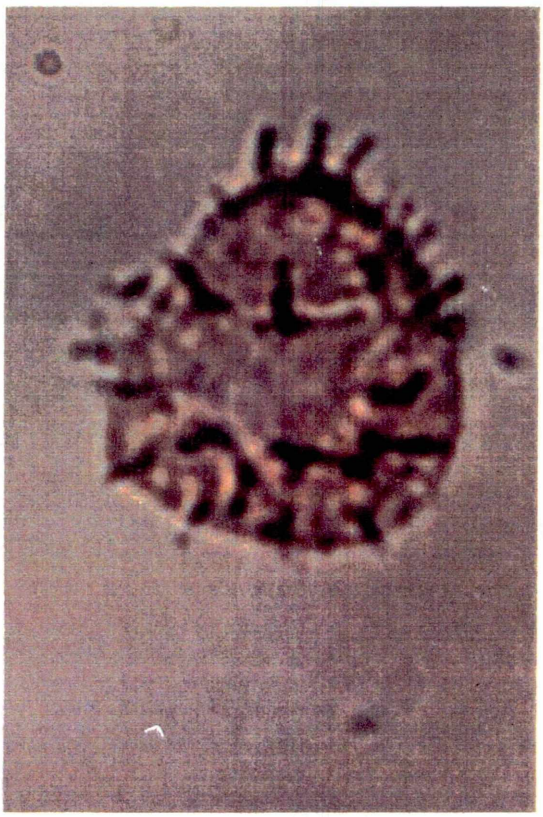
C



D

Plate 6.5: Kerogen Type IV (contd.)

E. *The 1.53-1.65 Density Fraction of Sample Ar/9-3:*

Humic fragments (magnification x 63). This fraction accounts for about 8 volume % of the total organic concentrate. The humic is very common in this sample.

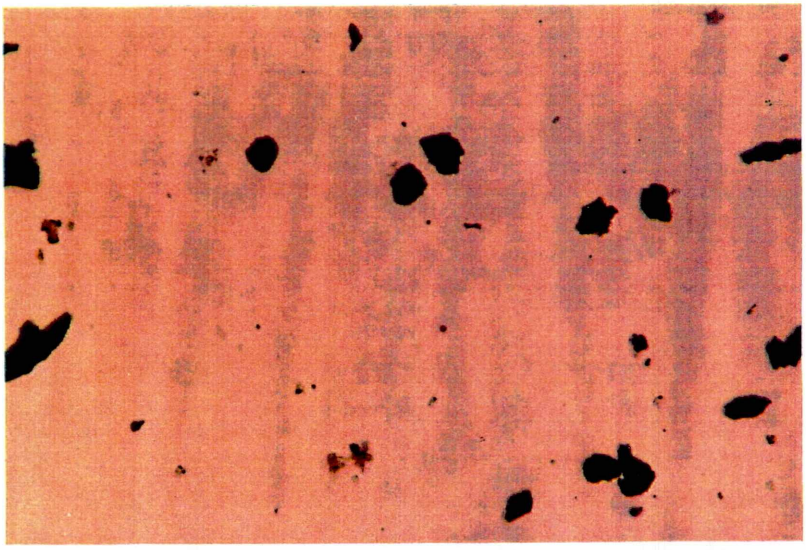
F. *The 1.65-1.81 Density Fraction of Sample Ar/9-3:*

Humic fragments (magnification x 63). This fraction forms about 33 volume % of the total organic concentrate.

G. *The 1.81-2.2 Density Fraction of Sample Ar/9-3:*

Fine-grained amorphous with humic fragments (magnification x 63). this fraction forms about 18 volume % of the total organic concentrate. The fine-grained amorphous is very common in this sample.

E



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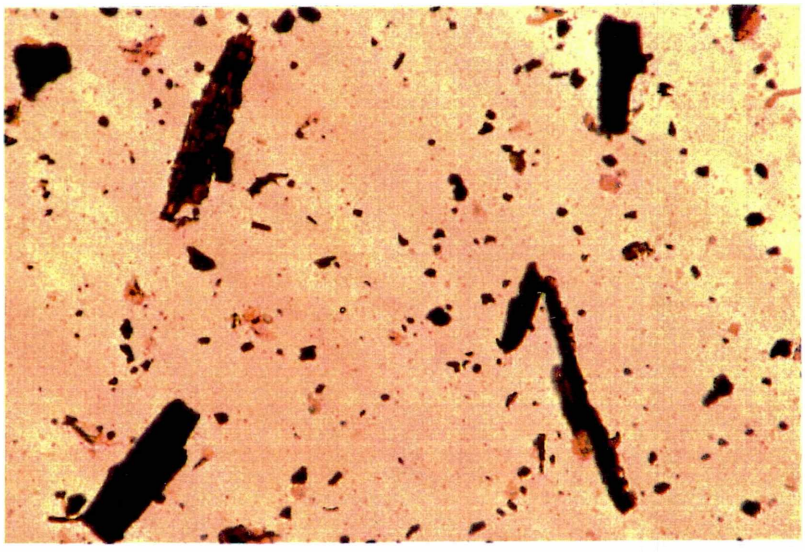

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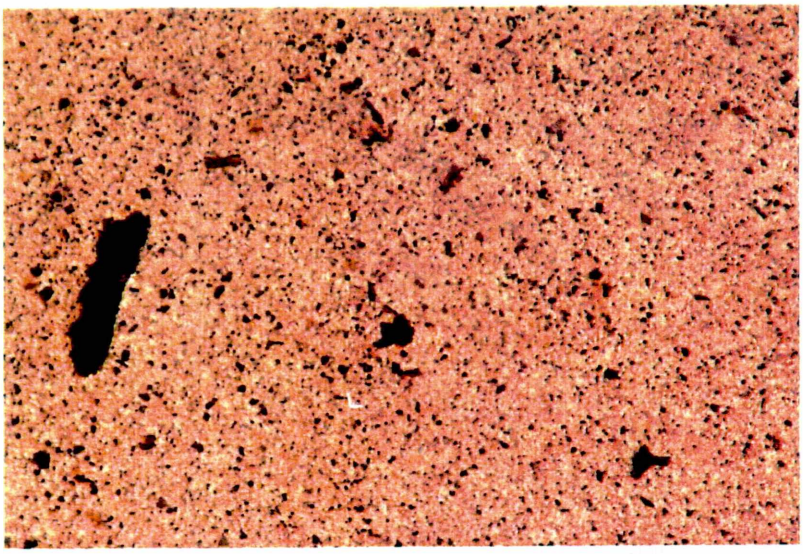


Plate 6.6: Kerogen Type II

A. *The < 1.28 Density Fraction of Sample Mi/14-1:*

Fluffy masses of sapropelic amorphous (magnification x 63). This fraction forms about 30 volume % of the total organic concentrate, dominantly sapropelic amorphous organic matter.

B. *The 1.28-1.34 Density Fraction of Sample Mi/14-1:*

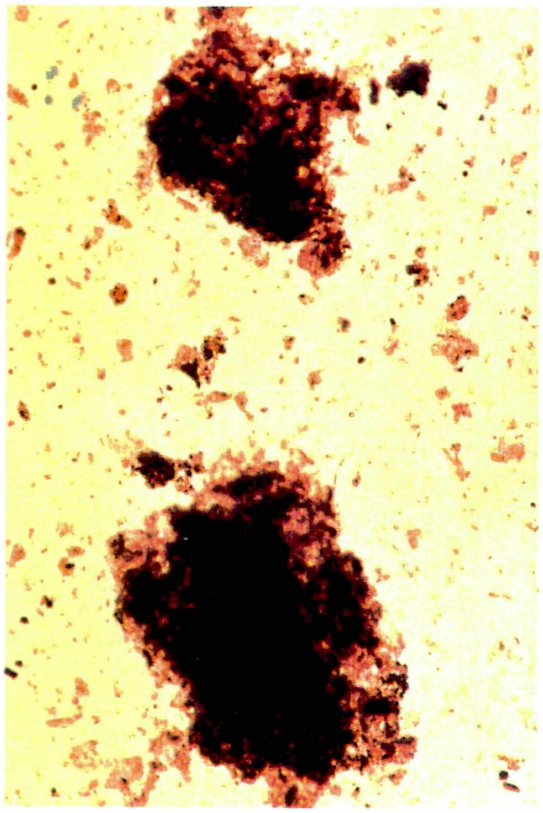
A fluffy mass of sapropelic amorphous (magnification x 63). This fraction accounts for about 35 % of the total organic concentrate.

C. *The 1.34-1.45 Density Fraction of Sample Mi/14-1:*

Fluffy masses of sapropelic amorphous with a "cuticle" (magnification x 40). This fraction accounts for about 23 volume % of the total organic concentrate. The "cuticles" are rare in this sample.

D. *The 1.45-1.53 Density Fraction of Sample Mi/14-1:*

Fluffy masses of sapropelic amorphous (magnification x 50). This fraction forms about 6 volume % of the total organic concentrate.



A

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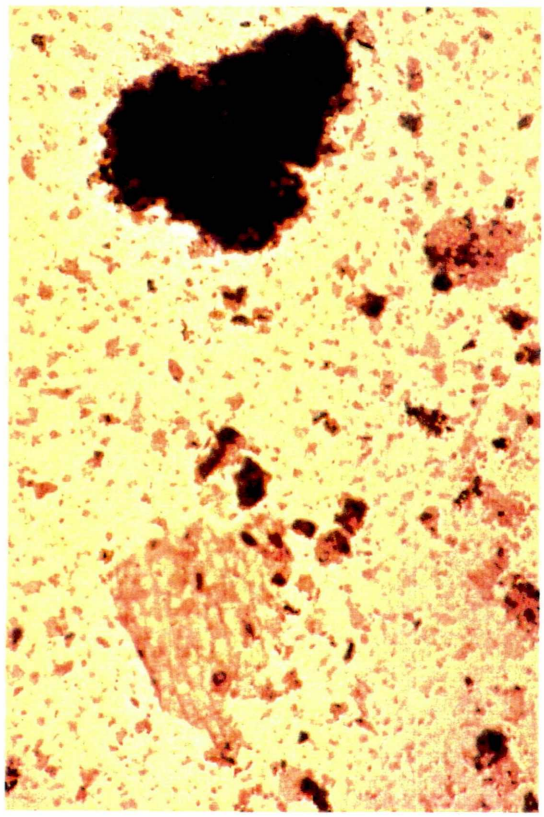

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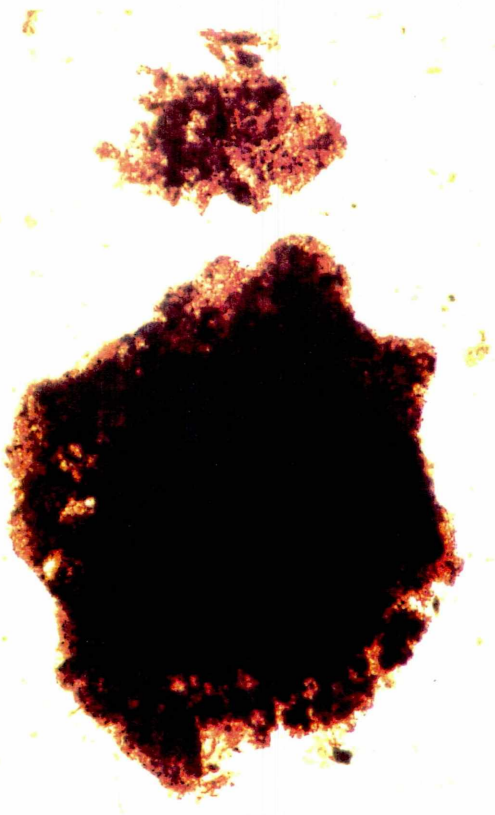


D

Plate 6.6: Kerogen Type II (contd.)

E. *The 1.53-1.65 Density Fraction of Sample Mi/14-1:*

A fluffy mass of sapropelic amorphous with a humic fragment, most probably a moss tissue (Masran and Pocock, 1981). This fraction accounts for about 3 volume % of the total organic concentrate. The humic is rare in this sample (magnification x 50).

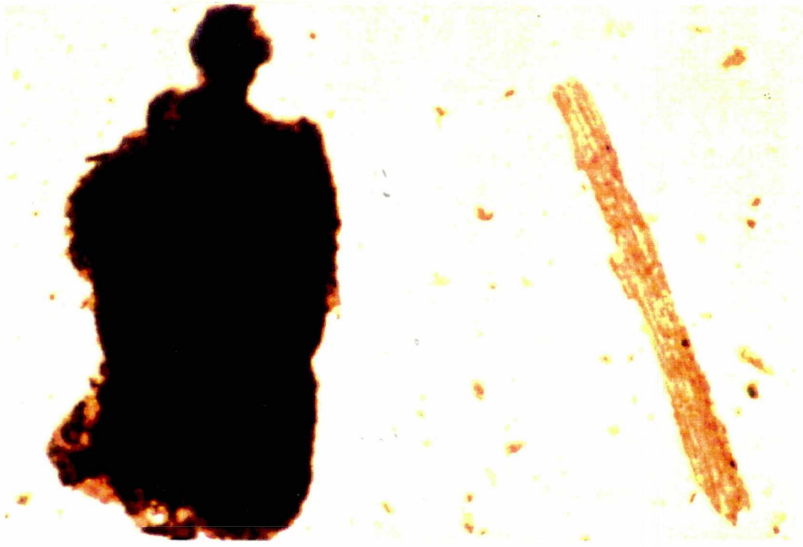
F. *The 1.65-1.81 Density Fraction of Sample Mi/14-1:*

Sapropelic amorphous (magnification x 200). This fraction accounts for about 1 volume % of the total organic concentrate.

G. *The 1.81-2.2 Density Fraction of Sample Mi/14-1:*

Sapropelic amorphous (magnification x 160). This fraction forms about 1 volume % of the total organic concentrate.

E



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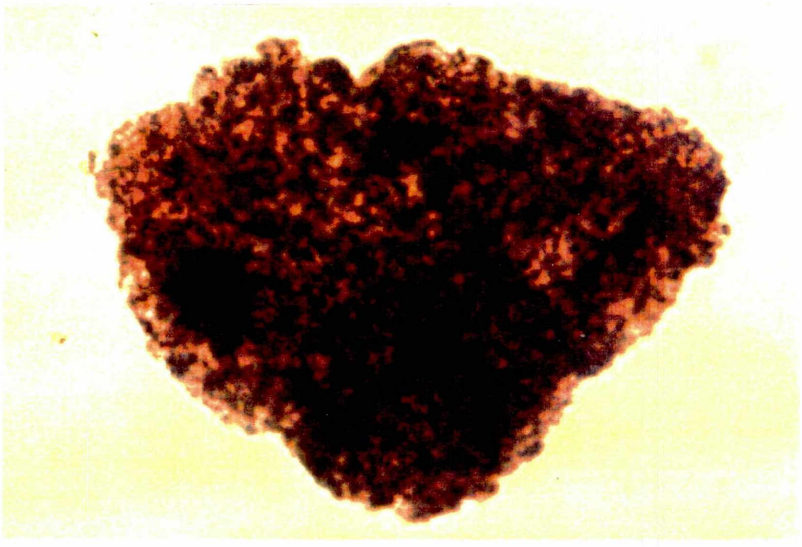

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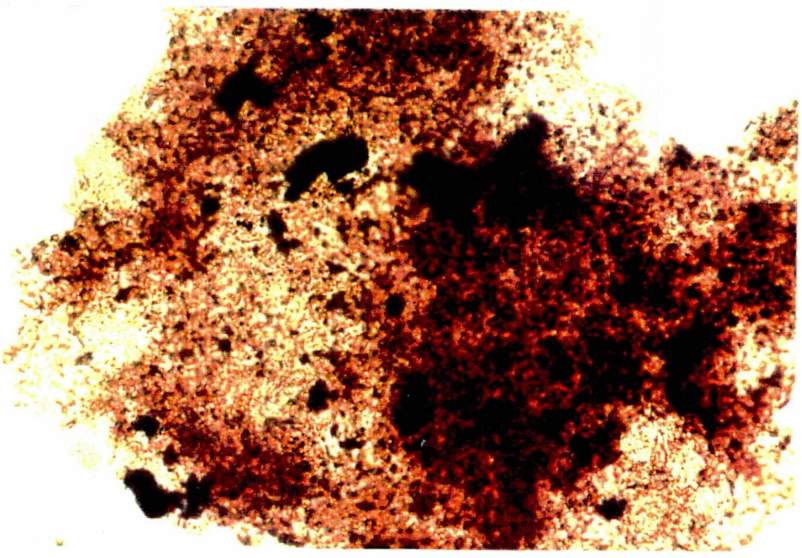


Plate 6.7: Maturation Assessment using Sapropelic Amorphous Colour

A. *Sample Mi/12-1 (magnification x 50)*

Colour is yellow-immature.

B. *Sample Mi/11-1 (magnification x 50)*

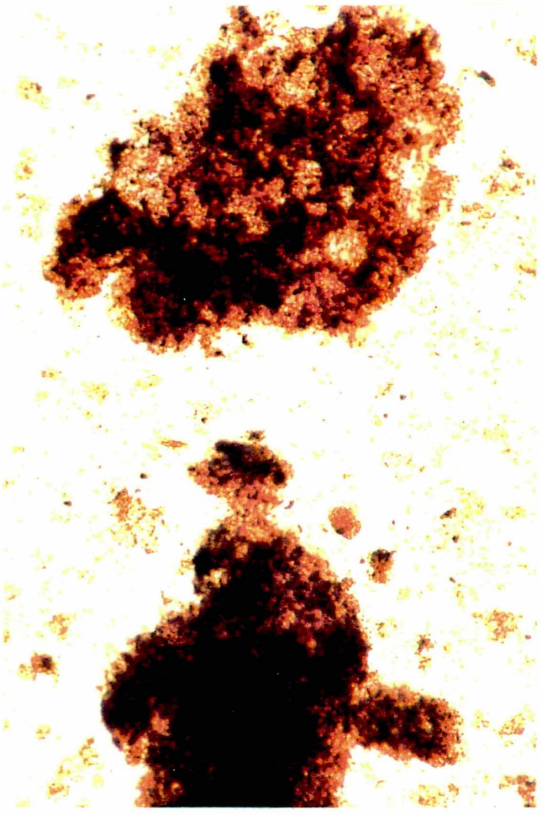
Colour is yellow-immature.

C. *Sample Sa/11-1 (magnification x 50)*

Colour is light brown-immature.

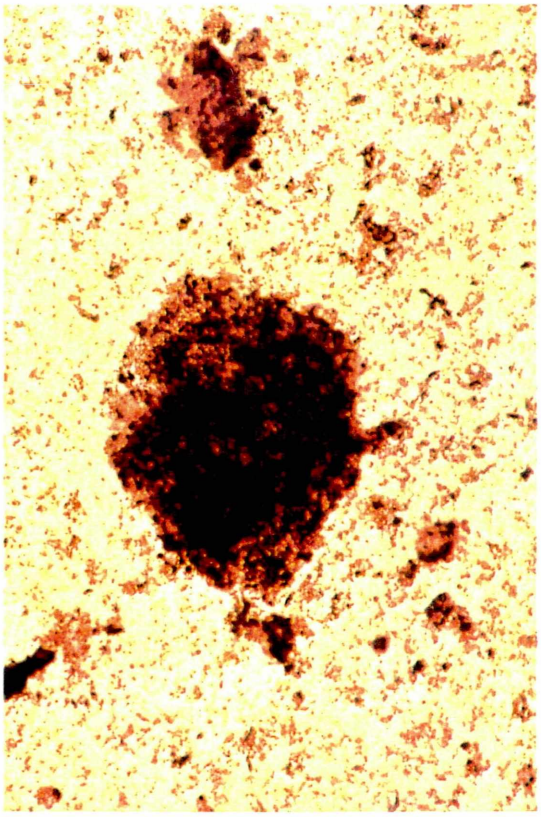
D. *Sample Sa/14-2 (magnification x 50)*

Colour is brown-approaching maturity.



A

B



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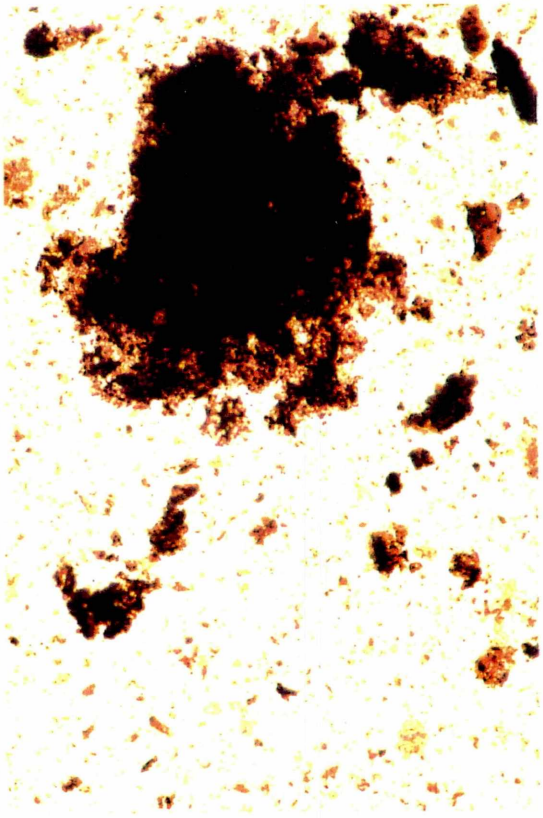


D

6. 5. *PROGRAMMED PYROLYSIS OF WHOLE - ROCK SAMPLES*

6. 5. 1. **Introduction**

Pyrolysis has become a common analytical method in geochemical research. Its principles and applications were outlined in Chapter 4. The technique is widely accepted among exploration geologists as a rapid and effective means of characterizing the quality and thermal maturity of prospective source rocks (Barker, 1974; Espitalié et al., 1977; Clementz, 1979; Espitalié *et al,* 1980; Dembicki *et al,* 1983; Peters *et al,* 1983; Peters, 1986; Espitalié and Joubert, 1987).

The two detector peak responses commonly produced in the course of programmed pyrolysis of a potential hydrocarbon source-rock sample are : P_1 - due to thermal distillation of already generated bitumen in the rock, and P_2 - due to hydrocarbons generated by the pyrolytic degradation of the contained kerogen. In other publications, P_1 and P_2 are respectively referred to as S_1 and S_2. The T_{max} is the pyrolysis temperature at which the second peak (P2) reaches maximum detector response. This is the temperature at which the maximum generation of hydrocarbons from kerogen cracking of the sample occurs. Linked directly to the cracking kinetics of organic matter, T_{max} varies with the type of organic matter.

A quantitative evaluation of the genetic potential of prospective source rocks can be obtained using pyrolysis. The quantity P_1 is the part of the original genetic potential which has been effectively transformed into

hydrocarbons. The quantity P_2 is the other part of the genetic potential which has not yet been converted to hydrocarbons. Therefore, P_1+P_2 expressed in kg hydrocarbons per ton of rock can be used as an evaluation of the genetic potential in terms of abundance and type of organic matter. Tissot and Welte (1984) suggested the following classification of the source rocks based on their genetic potential :

- lower than 2 kg/tone : no oil source rock, some potential for gas
- from 2 to 6 kg/tone : moderate source rock
- above 6 kg/tone : good source rock

The transformation ratio (sometimes called the production index) is defined as the ratio $P_1/(P_1+ P_2)$. The level of thermal maturation of potential source rocks can be roughly estimated from the transformation ratio and T_{max}. Peters (1986) pointed out that in general, transformation ratio and T_{max} values less than about 0.1 and 435-445°C, respectively, indicate immature organic matter. A T_{max} greater than 470°C represents the wet-gas zone, while the transformation ratio reaches about 0.4 at the bottom of the oil window (beginning of the wet-gas zone) and increases to 1.0 when the hydrocarbon-generative capacity of the kerogen has been exhausted.

In spite of the extensive work which has been done on pyrolysis, a number of problems require further work. Kerogen-concentrate and whole rock samples can produce very different pyrolysates, different in composition as well as in quantity. Espitalié *et al* (1980) reported that rocks and their

corresponding kerogen concentrates did not always yield the same amount of hydrocarbons per gram of organic carbon, and that certain minerals caused catalytic cracking of hydrocarbons when pyrolyzed with kerogen concentrates. Katz (1983) found that the pyrolysates of type I kerogens were less affected by minerals than were the pyrolysates of type III kerogens, and suggested that type I kerogens may be able to oversaturate the retention capacity of a mineral matrix. According to Dembicki *et al* (1983), when organic carbon content in a rock (TOC) exceeds 10% retention and /or cracking effects are unimportant.

Variations in type of organic matter affect the T_{max} vs. depth trend, especially in rocks that have not entered the oil-generative window (Tissot and Welte, 1984; Espitalié and Joubert, 1987). Peters (1986) has indicated variations in T_{max} up to about 20°C in samples of equivalent low maturity (R_o < 0.6%) where the kerogen is composed of essentially one maceral. He stated that the Rock-Eval FID does not measure hydrogen or water, which are important pyrolysis products of immature samples. Oil-based and water-based drilling mud additives and lubricants can contribute to P_1, P_2, and T_{max} of the indigenous organic matter. Similar problems can result from migrated oil or large amounts of bitumen (Clementz, 1979). These types of contaminants generally lower T_{max}. Oil-based mud contamination or migrated oil is likely for immature rocks, with T_{max} less than about 435°C, where the transformation ratio is greater than 0.2 (Clementz, 1979; Peters, 1986). Barker (1974) have studied the effect of drying out on the transformation ratio in sample cuttings. His findings show that any drying of the sample reduces the amount of generated hydrocarbons remaining

and leads to spurious values for the transformation ratio. He recommended that all samples used to be stored under water from the instant they are brought to the surface to ensure sample quality. Peters (1986) indicated that all samples should be approximately the same weight because results for P_2, T_{max}, and other parameters can be affected by sample size. In addition, he pointed out that the most reliable geochemical interpretations are based on wells for which large amounts of pyrolysis data are available. The proper interpretation of pyrolysis data also requires information on lithologies, the relative abundances of organic matter and mineral matrix, well conditions, and the presence or lack of generated hydrocarbons.

6.5.2. **Results and Interpretation**

The main objective of employing this study technique is to assess further the quality and thermal maturity of the organic matter in both the Lower Safaniya and the Lower Mishrif potential hydrocarbon source units.

The results of the programmed -temperature pyrolysis of the selected whole-rock samples are presented in Table 6.5. As discussed earlier, P_1+P_2 expressed in kg hydrocarbon per tone of rock can be used as an evaluation of the genetic potential in terms of abundance and type of organic matter.
It can be noted from the results that most of the samples have genetic potentials in excess of 6 Kg/tone. This indicates that they are good source rock samples according to the classification suggested by Tissot and Welte (1984). This provides a further evidence that Lower Safaniya and Lower Mishrif are good potential source rock units. Also noted is the fact that

Table 6.5 Results of Programmed Temperature Pyrolysis of Selected Whole Rock Samples

Locality Borehole	Sample Number	Depth (m)	TOC (Wt.%)	$P_1 + P_2$ genetic potential (Kg/tonne)	$P_1/P_1 + P_2$ Transformation Ratio	T_{max} (°C)
Well 5	Mi/5-1	1405	5.61	27.82	0.05	420
	Mi/5-2	1425	4.99	28.89	0.03	413
	Sa/5-2	1658	5.03	20.65	0.03	424
Well 9	Mi/9-1	1417	1.8	2.92	0.01	425
Well 10	Mi/10-1	1314	1.27	5.28	0.05	421
	Mi/10-2	1341	3.46	14.79	0.04	422
	Mi/10-3	1376	2.01	8.29	0.05	431
	Sa/10-1	1676	2.74	12.17	0.05	425
	Sa/10-2	1693	4.07	18.31	0.05	418
Well 11	Sa/11-1	1282	2.82	7.66	0.09	428
Well 12	Mi/12-1	1200	4.48	20.46	0.03	413
	Mi/12-2	1216	7.21	35.41	0.03	403
Well 14	Mi/14-1	2207	1.37	4.53	0.24	457
	Mi/14-2	2237	1.34	4.95	0.38	445
	Sa/14-2	2588	2.92	8.23	0.25	445

there is a general trend which suggests that high TOC values are associated with high genetic potentials. It should be pointed out that few samples have relatively low genetic potentials. This is probably due to either a difference in kerogen type which seems to be the case in sample Mi/9-1 (kerogen type II/III) or a relatively low organic carbon content which appears to be the case in samples Mi/10-1, Mi/14-1 and Mi/14-2.

As discussed earlier, the level of thermal maturity of potential source rocks can be roughly estimated from the transformation ratio and T_{max}. The results in Table 6.5 indicate that apart from well 14, all the analysed samples from Lower Safaniya and Lower Mishrif potential source rocks in the study area are immature. These samples have transformation ratios and T_{max} values less than 0.1 and 445°C, respectively, indicating immature organic matter (Peters, 1986). As noted from the results, some relative variations in the T_{max} as well as in the transformation ratios do occur with the depth trend. This is most probably due to the fact that these samples are immature and the Rock-Eval FID does not measure hydrogen or water, which are important pyrolysis products of immature samples (Peters, 1986). In addition, some effect on the transformation ratio and T_{max} due to mineralogic variations in the samples may not be entirely ruled out despite the fact that organic carbon content is in excess of 1.0% in all samples (Espitalié *et al*, 1980; Dembicki *et al.*, 1983).

Many oil shows in well 14 have been reported in the composite well log at different depths. This migrated oil is most likely to influence the transformation ratio and T_{max} values. As noted in Table 6.5, samples from

well 14 show abnormally high transformation ratio values most probably due to this oil migration. Nevertheless, T_{max} values are still showing that samples in well 14 are relatively more mature than elsewhere in the study area. This is in complete agreement with the fact that these samples have the highest burial depth compared with all other samples.

It can be concluded that the high genetic potential of the Lower Safaniya and Lower Mishrif samples is an indication that these units contain rich and good quality organic matter to be qualified as good potential source rock sequences. Furthermore, the transformation ratio and T_{max} values recorded for these samples are relatively low. This indicates that the degree of maturation attained by their organic matter content in the area of study (except the area of well 14) is relatively low. On a broad consideration, the results of this programmed whole-rock pyrolysis further support the quality and level of maturation already arrived at for analysed samples from Lower Safaniya and Lower Mishrif based on elemental analyses and transmitted light microscopic examination of the kerogen concentrates.

6. 6. *RELATIONSHIP BETWEEN ORGANIC RICHNESS, KEROGEN TYPE, LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE CRETACEOUS SECTION*

The depositional history of the study area was revealed in Chapter 3 by constructing interval facies layer maps and thickness maps for each interval of the Cretaceous section. The study indicates that marine conditions dominated the area. This is further supported by the transmitted

light study of the organic matter through the recognition of microfossils such as Acritarchs and Microforaminifera, an example is shown in Plate 6.8. These fossils are good indicators of open marine environments. It should be pointed out that these Microforaminifera have been identified despite a statement by Durand (1980, p.16) indicating that microfossils such as Foraminifera whose tests are destroyed by acids, cannot be identified. Their identification is possible through the preservation of the organic linings of their tests as can be seen in Plate 6.8.

Two intrashelf basins developed away from the paleoshore line in the eastern part of ALRub ALKhali. The first, during the deposition of Safaniya, and the second during the deposition of Mishrif. The occurrence of organic rich, oil-prone potential source rocks seems to be controlled and influenced by the development of such intrashelf depressions. These large restricted basins (anoxic) , located in forereef areas (oceanward) of a high bioproductive shallow-water platform, produced good potential source rock sequences. These are Lower Safaniya and Lower Mishrif organic rich units with total organic carbon up to 7%. They are composed of laminated lime mud (84% carbonate) which is most probably derived organically through the accumulation of marine phytoplankton. It may be suggested that it was these unfavourable conditions for the benthic fauna that resulted in the increased preservation of the deposited organic matter. This is confirmed by the analysis of their organic matter. It is light in density, hydrogen-rich, sapropelic, and chemically type II kerogen. There is a very good relationship between the existence of these regional depression areas and the deposition of organic rich, lime-mud, kerogen type II source rocks.

Plate 6.8 Indicators of Open Marine Environments

A, B, and C:

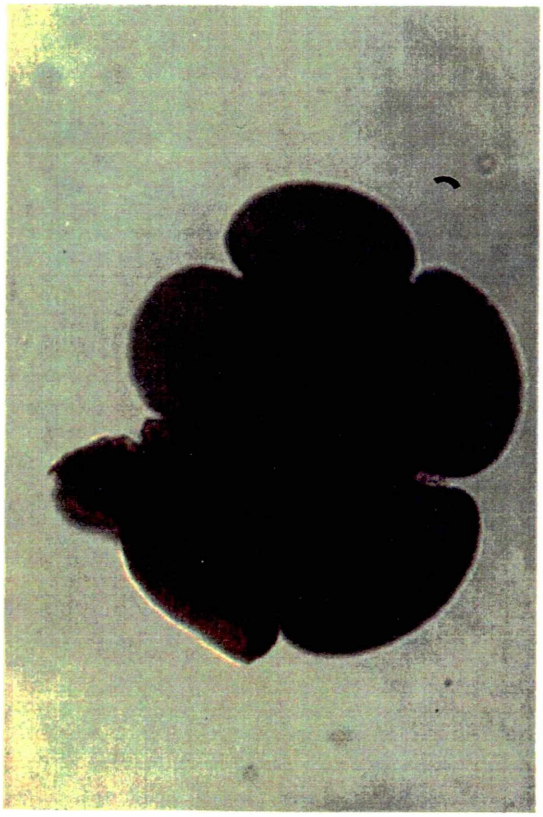
Microforaminifera (magnification x 250). These microfossils have been identified through their organic linings after the removal of their tests by acid treatment (Stancliffe, 1989).

D:

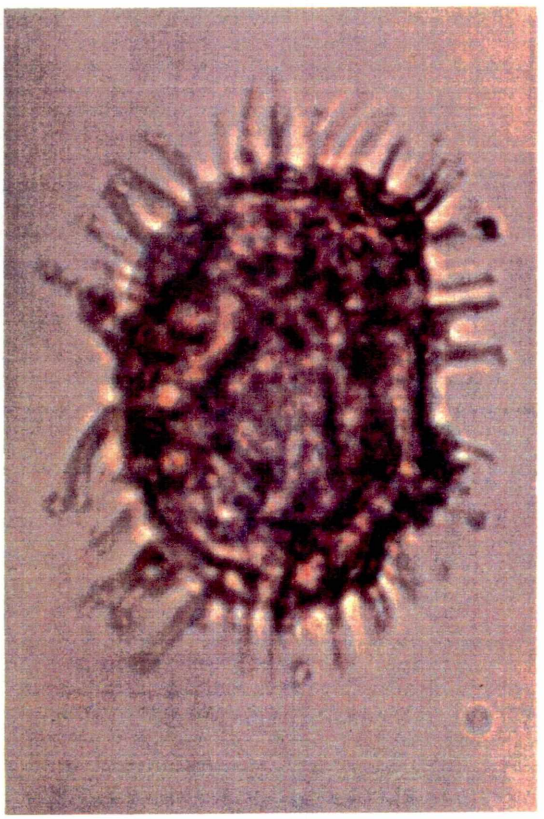
An Acritarch (magnification x 400). These microfossils are good indicators of open marine environments.

A

B



C



D

The association of the two is so defined that it is possible to map these source rock areas geographically, thus determining their lateral extent by simply mapping the intrashelf basins. Their vertical thickness can be estimated by calculating the thickness of the lime mud strata. Thus, a volumetric estimate of these rocks can be obtained.

By contrast, the remainder of the Cretaceous intervals are relatively poor in organic richness. The chemical type of their associated organic matter varies considerably depending on the extent of the degree of oxidation and the distance from the palaeoshore line. It thus seems that the nature or composition of the mixed type II/III and type III kerogen as well as the relatively low TOC values of their associated lithologies are due to the oxidising nature of their depositional environments. Oxic bottom conditions would have favoured significant destruction of the deposited organic matter and in particular the preferential degradation of the lipid-rich marine phytoplankton. The result is an increase in the relative content of the heavy, fine-grained degraded amorphous material. Thus, the formation of mixed type II/III or type III kerogens will depend to a certain extent on the intensity of such degradation. The area close to the shore line during deposition appears to have been influenced by terrestrial input from the continent. The Humic influx decreases basinward to a minimal. This line of reasoning seems to correlate fairly well with the observations on the nature and composition of the identified kerogen types in the study area.Type III kerogens with terrestrial influence are noted to occur in the area closer to the palaeoshore line, while mixed type II/III and type III kerogens without significant terrestrial influence have been identified

basinward (away from the palaeoshore line).

Lower Aruma shale has been deposited on top of a major regional unconformity throughout the Arabian Platform (Pre-Aruma unconformity). Kerogen type IV hase been identified with the lower part of this formation. It should be pointed out that the Upper Aruma Formation is composed of limestone. The association of kerogen type IV with the Lower Aruma shale could be the result of the extensive erosion, reworking, and redeposition of such sediments that usually accompany such a major regional unconformity. Thus, their organic matter would most likely be derived from highly oxidized altered material or high rank material recycled from older sediments.

It can be concluded that the fluctuating anoxic-oxic depositional conditions during the Cretaceous through the development of intrashelf basins and ALRub ALKhali basinal configuration appear to have been the major factors controlling the distribution of the kerogen type as well as the organic matter richness of the associated lithologies in the various Cretaceous intervals. Figure 6.7 is a source bed depositional model for the Lower Safaniya and Lower Mishrif potential source units in ALRub ALKhali Basin summarizing the above discussion.

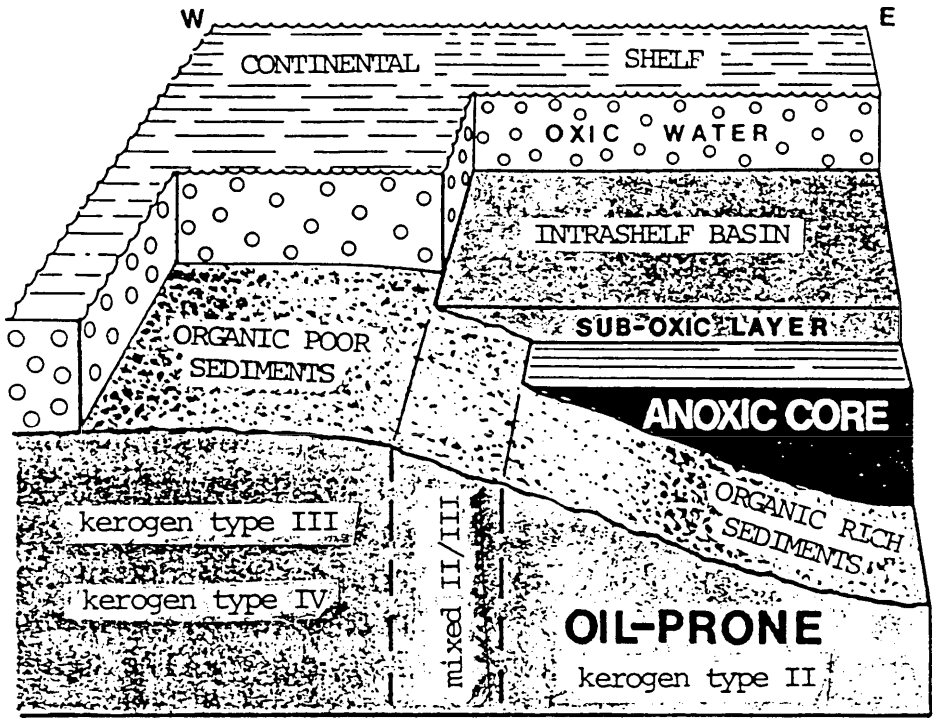


Figure 6.7 Lower Safaniya and Lower Mishrif source bed depositional model in AlRub AlKhali. Paleoshore line is to the west, while the shelf margin is to the east. (This block diagram is adapted from Demaison et al, 1983)

7.1. *INTRODUCTION*

Petroleum geochemistry is a relatively new discipline to the oil industry. However, it plays an important role in exploration programmes for hydrocarbons. Organic geochemistry has advanced rapidly in the last ten years and has increasingly and successfully been applied in petroleum exploration. It seems that a new strategy or concept is emerging, where the search for hydrocarbon traps is combined with a careful integration of the information given by geology and organic geochemistry in what is called basin analysis. The target is to concentrate the exploration means on the areas where the traps have the best chance to be filled with hydrocarbons.

It is important and essential to establish the presence of source beds to a high level of certainty, in the subsurface of the area under exploration for a better basin assessment. This involves locating their precise stratigraphic placement as well as their geographical extent. Today, this requirement is usually met by analysing a large number of rock samples obtained from all available drilled wells. The information obtained from different analytical techniques is then used to identify and locate any possible source rock sequences. In relying almost exclusively on analytical data, organic geochemists constrain themselves far too much by sample availability. In theory, in order for an analytical approach to be valid, organic geochemists should have data coverage of the area of interest to allow interpolation between points rather than extrapolation beyond control. In many

exploratory regions, frontier areas in particular, adequate data are not available. As a result, in using an analytical approach, organic geochemists maybe forced to extrapolate what data they do have across large unsampled areas.

Thus, the fundamental problem in basic geochemistry is to be able to integrate these source rock data into a mapping system which would be capable of predicting regional hydrocarbon source bed occurrence and quality. This problem is in concept similar to that of stratigraphic mapping of reservoir trends. An exercise which has been achieved and made possible by long standing research into clastic and carbonate sedimentation. The need for predicting the distribution of potential source rocks in sedimentary basins has been expressed by many authors (e.g. Demaison et al, 1983; Waples, 1984; Jones, 1987). Durand (1987) stated the following: "no general theory of the accumulation and preservation of organic matter in sediments is available for the moment, with the consequence that no one is able to predict accurately the location and quality of source rocks in a sedimentary basin. This is a great obstacle to the appraisal of the petroleum potentialities of basins and therefore, increasing research has now to be devoted to this aspect".

Some good pioneering work has already been accomplished upon which to build. For example, Demaison and Moore's study (1980) on the significance and role played on the preservation of organic matter through the development of anoxic conditions during sedimentation. This work was

based mainly on concepts and contained little analytical data. Nevertheless, Demaison and Moore's research can be seen as the first guideline for the successful application of organic geochemistry in hydrocarbon exploration. It was the first time that attention was drawn to the concept that explorationists could use sedimentological principles to understand and predict the occurrence of organic rich rocks. Since then, other researchers (e.g. Degens and Ittekkot, 1987; Tyson, 1987) have accumulated a more detailed knowledge of the most important factors influencing the hydrocarbon source capacity of sedimentary rocks. The factors that might have influenced the organic richness of the Safaniya and Mishrif potential hydrocarbon source units in ALRub ALKhali have been discussed in chapter 5 - section 5.3. However, most of the debate has centred on the question of the relative importance of preservation and productivity.

Productivity is highly affected by the availability of "mineral nutrients" in solution. Upwelling of deep ocean water can introduce large quantities of nutrients into the water surface, thus promoting high productivity. This high organic productivity often results in high organic carbon contents in the underlying sediments. Therefore, it is logical both to look in the geological record for evidence of ancient upwelling regimes as possible indicators of the presence of hydrocarbon source rocks, and to attempt to predict the location of such upwellings from basic principles. These approaches have been promoted by Parrish (1982) who superimposed climate patterns on plate tectonics reconstruction of the relative location of continental and oceanic masses in Paleozoic in an effort to predict where

upwellings would have occurred.

While Parrish (1982, 1987) and some other workers (e.g. Miller, 1989; Pedersen and Calvert, 1990) consider upwelling and consequent high productivity to be the most important element in the deposition of many organic rich sediments, still others prefer to attribute most cases of organic richness to unusually favourable conditions for preservation. As Demaison and Moore (1980), Tyson (1987), and others have noted, anoxia or near anoxia in bottom waters can strongly influence preservation of organic matter. Demaison and Moore (1980) described environments in which anoxia can occur. One of these involve restricting movement of bottom waters, so that oxygen replenishment cannot occur easily. It should be stated here, that the results of this project are in line with such views (see chapter 5 - sec. 5.3.1 for more details). The development of depressions, i.e., intrashelf basins, in the study area helped to create the sort of environment where anoxic or near anoxic conditions could develop, and these conditions are thought to be responsible for the excellent preservation of the organic matter in the Lower Safaniya and Mishrif Members of ALRub ALKhali basin. It is necessary to point out that this conclusion would not have been reached without establishing the stratigraphic evolution of the basin which is described in chapter 3. Identifying the mechanism which might be the cause of the anoxia can be rather difficult, because it requires a detailed sedimentologic and paleontologic (and sometimes tectonic) study of the surrounding area. This emphasizes the importance and need of understanding the geology of the

region under investigation. Thus, the approach in this chapter is basically geological. This approach is supported by the work of Pelet and Deroo (1983) who have stated that in addition to detailed microscopic and organic geochemical studies, no global interpretation is possible without a detailed geologic framework. As can be noted in this chapter, the application of fundamental stratigraphic principles to the distribution of organic matter types and organic richness in carbonate rocks has made it feasible for the first time to predict and map the occurrence and variability of hydrocarbon source beds in sedimentary basins. This hopefully would represent a crucial turning point for the successful application of organic geochemistry in hydrocarbon exploration.

7.2 *ORGANIC FACIES CONCEPT*

The term facies was first introduced by Gressly in 1938 and defined by Reading (1986, p.4) as "a body of rock with specified characteristics" with respect to sedimentary facies, he notes that features to recognize facies may derive from content, process, or be a function of sedimentary or tectonic environment. Thus, it appears to be acceptable in sedimentological terminology to refer to a lime mud facies (content); a pelagic limestone facies (process); a shallow marine limestone facies (environment); or a stable platform facies (tectonics), where all four types of "facies" potentially relate to the same volume of sediment.

The phrase "organic facies" appears in the literature frequently (Cornford

et al, 1980; Jones, 1984; Waples, 1985; Jones, 1987; Miles, 1989). However, it is ill-defined and the selection of features to recognize it and the weight attached to each of them are dependent on a subjective personal evaluation. For example, Miles (1989, p. 92) has defined organic facies as "a distinctive assemblage of kerogen components which can be visually identified, or has a characteristic chemical composition". This definition is synonymous with earlier definitions which equate organic facies with the terms "palynofacies" of Combaz (1980), "kerogen facies" of Barnard et al. (1981) and "organic facies" of Waples (1985). On the other hand, Cornford et al. (1980) recognized the association of the organics with a specific volume of sediment and related specific (combinations of) geochemical indicators to particular depositional environments and tectonic settings. They defined "organofacies" as "the organic petrographic and geochemical parameters that characterise a given association of sediments". Their concept has been taken up by subsequent workers (e.g. McKindy et al., 1984; Knudsen et al., 1988) and used as a basis for correlating the source rock properties of lithostratigraphic units between wells and for relating oil families to source rocks. Jones (1984) specifically compares the organic facies concept in clastics and carbonates. Furthermore, Jones (1984, 1987), based on a published paper by Jones and Demaison in 1982, defined organic facies as "a mappable subdivision of a designated stratigraphic unit distinguished from adjacent subdivisions on the basis of the character of its organic constituents, without regard to the inorganic aspects of the sediment". Huc (1988) discusses the process-related approach to organic facies using both recent and ancient sediments from

different parts of the world. Considering only clastic source rocks, he emphasizes the control of the depositional processes on the distribution of sedimentary organic matter and stresses the overall concentric zonation of organic facies in most situations.

In consideration of the evolution of the organic facies concept, the idea that the term organic facies relates solely to the type of organic matter in the sediment (i.e. is synonymous with kerogen type) is rejected here. Jones's (1987) definition of organic facies is preferred in this project as compared to Cornford et al's (1980) definition since the term facies describes a specific body of rock (irrespective of its inorganic character) with lateral and vertical extent which would make it particularly useful for predictive source rock evaluation in frontier areas (as illustrated in the next section). However, the defining parameters proposed by Jones (1987) are not accepted in this study (see below). Jones's work is discussed and extended with particular reference to organic-rich carbonates prediction in the following paragraph.

The organic facies concept is adapted in this research as the most useful tool which can be applied to petroleum source bed prediction and mapping. Its application can be seen as the best way to integrate microscopic observations and geochemical results and theory with geological and geophysical knowledge and concepts. This would allow prediction of sedimentary organic matter type and quantity away from analysed locations, since there is a predictable lateral and vertical progression of

organic facies in a given depositional environment (e.g. as in the Lower Safaniya and Mishrif units in this study: from type III to type II/III to type II kerogen, from coastal plain through the margin of the intrashelf basin to the intrashelf basinal area as shown in Figure 6.7, p. 231).

In his publication, Jones (1987) defines seven organic facies types using H/C ratios and Rock Eval H and O Indices combined with transmitted light microscopy as primary defining parameters. He discusses TOC, vitrinite reflectance, stable (carbon) isotopes, sulphur, and the molecular analysis of extracts as secondary defining parameters. Thus, the practical limitations of the organic facies approach as proposed by Jones (1987) focus on what analytical technique or techniques are used to define "the character of its organic constituents". In this sense "organic facies" cannot be separated from "kerogen type" or "palynofacies", as the latter are used to define the former. It is clear that an organic facies (a body of rock or "mappable subdivision") defined solely on the basis of a common H/C ratio could overlap with an organic facies defined by, for example, common values of pristane/phytane ratios. This narrowness of definition, ignoring process or environment, produces a classification which is very difficult to maintain, as he demonstrates in Section IV of his article.

For instance, the classification proposed by Jones (1987, P. 44) lumps together kerogens deposited in lacustrine, shallow marine, and lagoonal depositional environments (both clastics and carbonates) as Facies A/B on the basis of one common bulk property (H/C ratio). This is misleading,

since if by chance these three depositional facies were juxtaposed, they would constitute a single organic facies by his definition (Facies A/B). However, kerogens deposited in these three different depositional environments can be easily distinguished on the basis of specific microscopic, molecular or isotopic characteristics. Thus, concentrating on a single defining parameter (H/C ratio), and ignoring the processes controlling organic facies effectively prevents it from being of predictive use.

To discuss an example local to the study area, Ayres et al (1982) have identified the Callovian-Oxfordian organic rich carbonates to be the primary source for the main Saudi producing region (for more details, see chapter 2). However, Barker and Dickey (1984) stated that mass balance calculations do not show these rocks to be the primary source and suggested other source rocks had a major role in producing the Saudi petroleum reserves. In a reply to Barker and Dickey's discussion, Jones (1985) argued this point and stated that through suitable modification of a few numbers in the data used, mass balance consideration do permit the Callovian-Oxfordian source rocks to be the primary source of the Saudi oil reserves. It should be mentioned here that both Barker and Dickey (1984) and Jones (1985) calculations are based on Ayers et al. (1982) paper. In their work (page 3), Ayers et al. have indicated the use of logs to estimate and map source-rock richness. This would lead to inaccurate data input in terms of organic matter content and volume which would in turn prevent any realistic quantitative petroleum evaluation. In addition, their work is

lacking discussion on fundamental factors concerning the actual distribution of organic matter in the sediment itself (such as stratigraphic variations, sequences, organic distribution pattern, etc.) These factors control oil saturation and subsequently the efficiency and timing of oil expulsion out of these source rocks.

Relating the above (the Callovian/Oxfordian source rocks of the main Saudi producing areas) to organic facies, Jones (1987, page 45) defines these sediments as his organic facies A/B on the basis of an H/C of ca. 1.4 when immature (see Jones, 1985 for discussion of data). Palacas (1984, p.36) indicated these rocks to be extremely rich in carbonate content (> 90%) and almost devoid of clay. In the 1987 paper, Jones suggests the slightly lower H/C ratio than expected for a kerogen accumulating in a carbonate shelf basin to be attributable to "a less hydrogen rich algal/bacterial input", rather than a small influence of terrestrial organic matter. It is evident that if two possible combinations of organic matter types give the same bulk properties and if Jones's approach is applied, then the resulting rock would be interpreted to constitute one instead of two organic facies.

Thus if the term "organic facies" is to be of use in predictive studies of source rocks it must include in its definition details of the indigenous organic content of the sediment at a bulk molecular and isotopic level, together with a recognition of the processes influencing the abundance and type of sedimentary organic matter (sedimentation rate, water oxicity, organic input etc.).

In this thesis, it is possible to define a rich organic facies which can be of useful application in carbonate source rock prediction. This significant contribution has been achieved using the H/C ratios as bulk parameters, and the density separated fraction composition and transmitted light microscopy results (chapters 5 and 6) to provide a breakdown of the detailed composition seen in the context of the paleogreographic reconstructions developed in chapter 3.

The Cretaceous depositional environments in ALRub ALKhali were established in chapter 3 by the construction of facies layer maps and thickness maps for each interval of the Cretaceous section. This study made it possible to identify and locate two intrashelf basins that developed during the deposition of two intervals of the Cretaceous. Anoxic conditions have been shown in chapter 5 and 6 to prevail in the basinal areas of these embyments. Detailed source rock evaluations of the Cretaceous sediments in the study area have shown the existence of a rich organic facies associated with these two large depressions as can be illustrated below.

Figure 7.1 and Figure 7.2 demonstrate this relationship, showing the changes in total organic carbon values across ALRub ALKhali for the Safaniya and Mishrif intervals (TOC data from Table 5.1, p. 122). As shown the association of these intrashelf basins with such organic facies seems strong enough that by mapping these regional depressions, it is

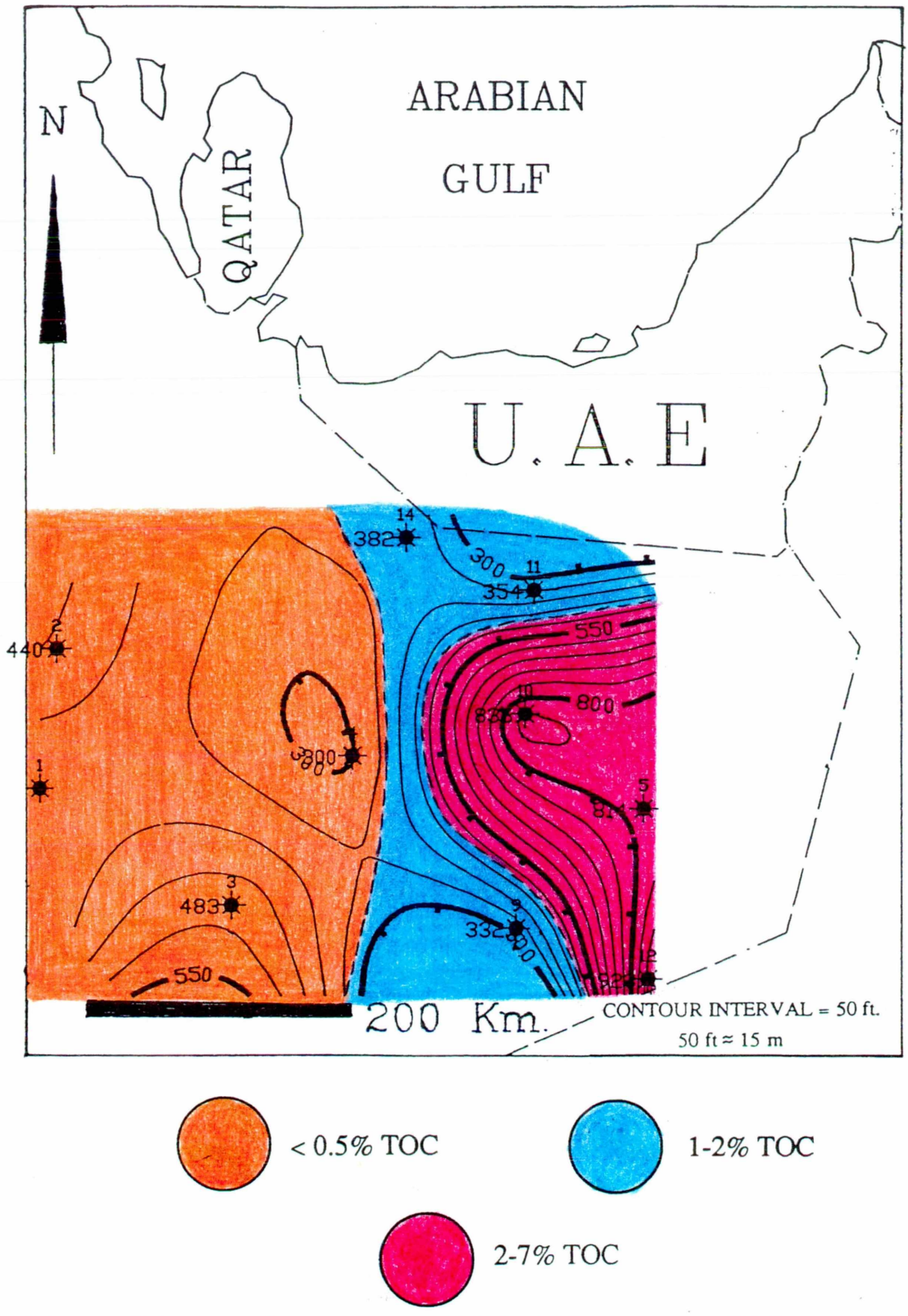
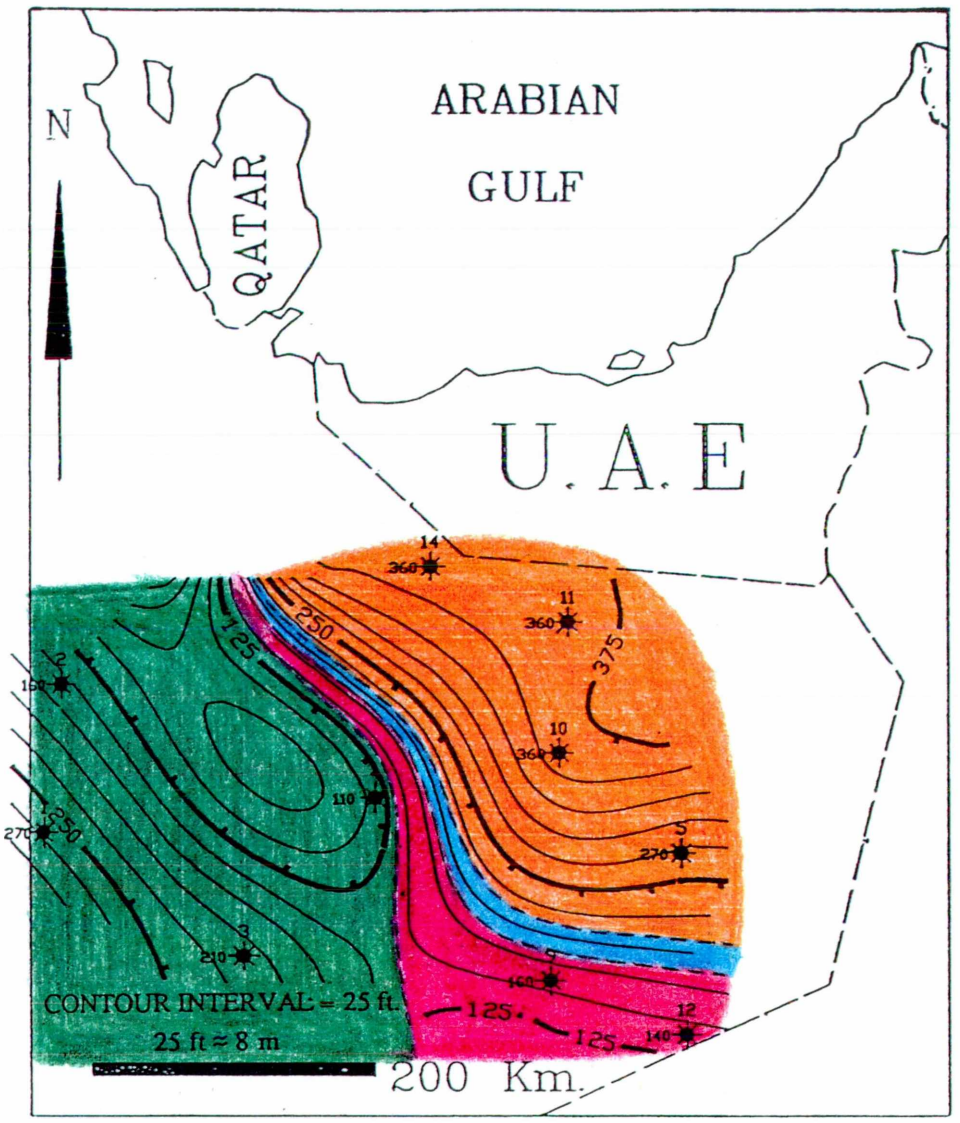


Figure 7.1 Isopach map of Mishrif Member, with TOC distribution across the study area.



< 0.5% TOC

0.5-1% TOC

1-2% TOC

2-5% TOC

Figure 7.2 Isopach map of Safaniya Member, with TOC distribution across the study area.

possible to map the geographical extent of these source rocks. This rich organic facies is concentrated in the Lower Safaniya and Lower Mishrif units in their respective intrashelf basinal areas. The processes incluencing the organic richness of this organic facies such as bottom water oxygenation, sedimentation rate, bioproductivity, etc. have been discussed in detail in chapter 5, page 126.

It can be seen in Figure 7.3 to 7.7 (data from Table 6.2 p. 154, Table 6.3 p. 172, Table 6.4 p. 187) how the organic constituents of such organic facies vary across the study area. Near the paleoshore line, i.e. wells 1, 2, 3, 4, and 9, the organic matter is heavy in density with low H/C ratio and composed mostly of fine grained amorphous material with significant terrestial influence. On the other hand basinward, in the carbonate intrashelf basinal areas (wells 5, 10, 11, and 14 for Safaniya and wells 12, 5, 10, 11, and 14 for Mishrif), the sedimentary organic matter changes in quality and composition and becomes lighter in density with high H/C ratio and composed mostly of sapropelic amorphous with minimum terrestial influence from the land (see chapters 5 and 6 for more details). These plots show how the organic matter quality of the Safaniya and Mishrif changes across the study area and clearly illustrate the strong relationship between the development of an organic rich facies and the existence of these regional intrashelf depressions in ALRub ALKhali basin.

Thus, in line with the previous discussion on the organic facies concept and in view of the results of the combination of geological and geochemical

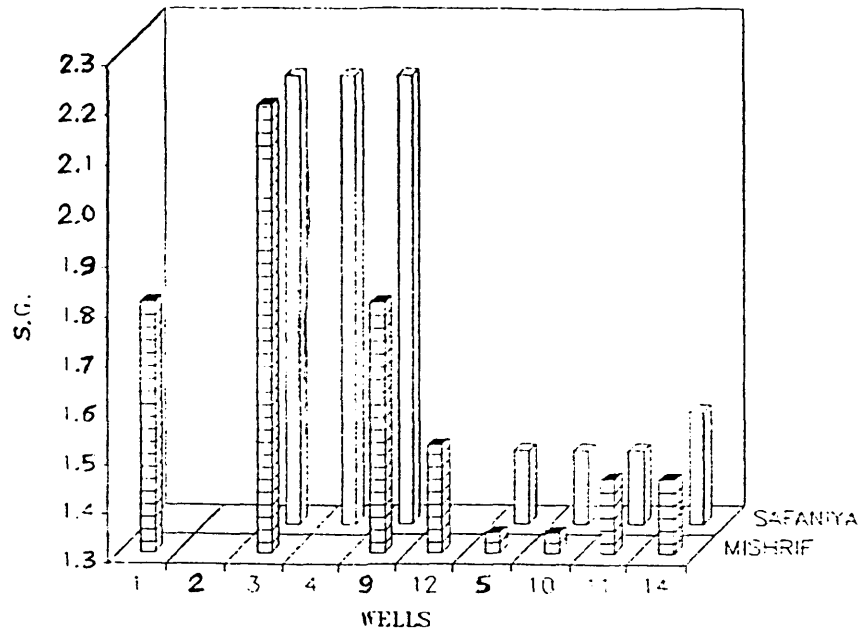


Figure 7.3 Variations of specific gravity of the Safaniya and Mishrif kerogens throughout all the sampled boreholes.

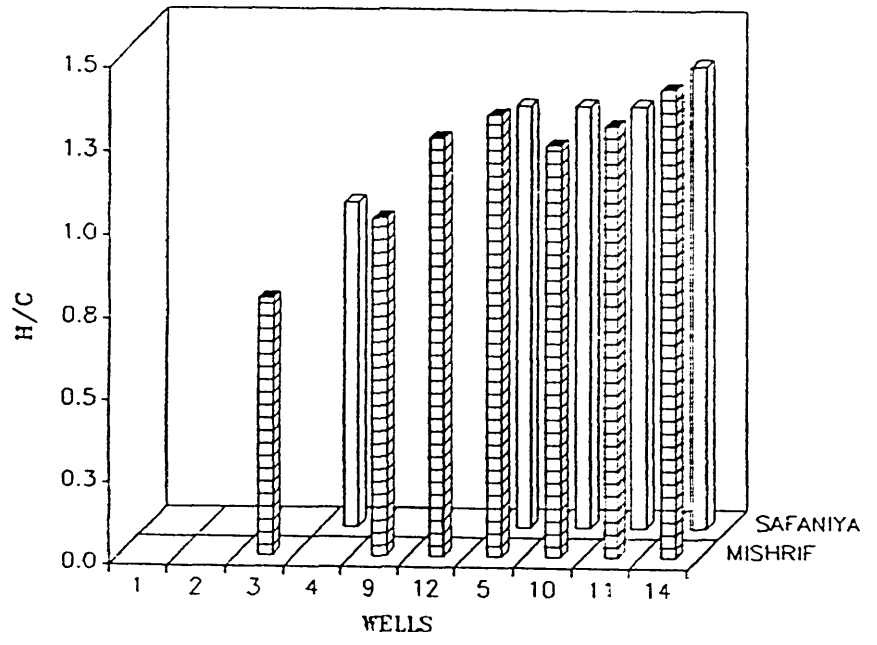


Figure 7.4 Variations of H/C ratio of the Safaniya and Mishrif kerogens throughout all the sampled boreholes.

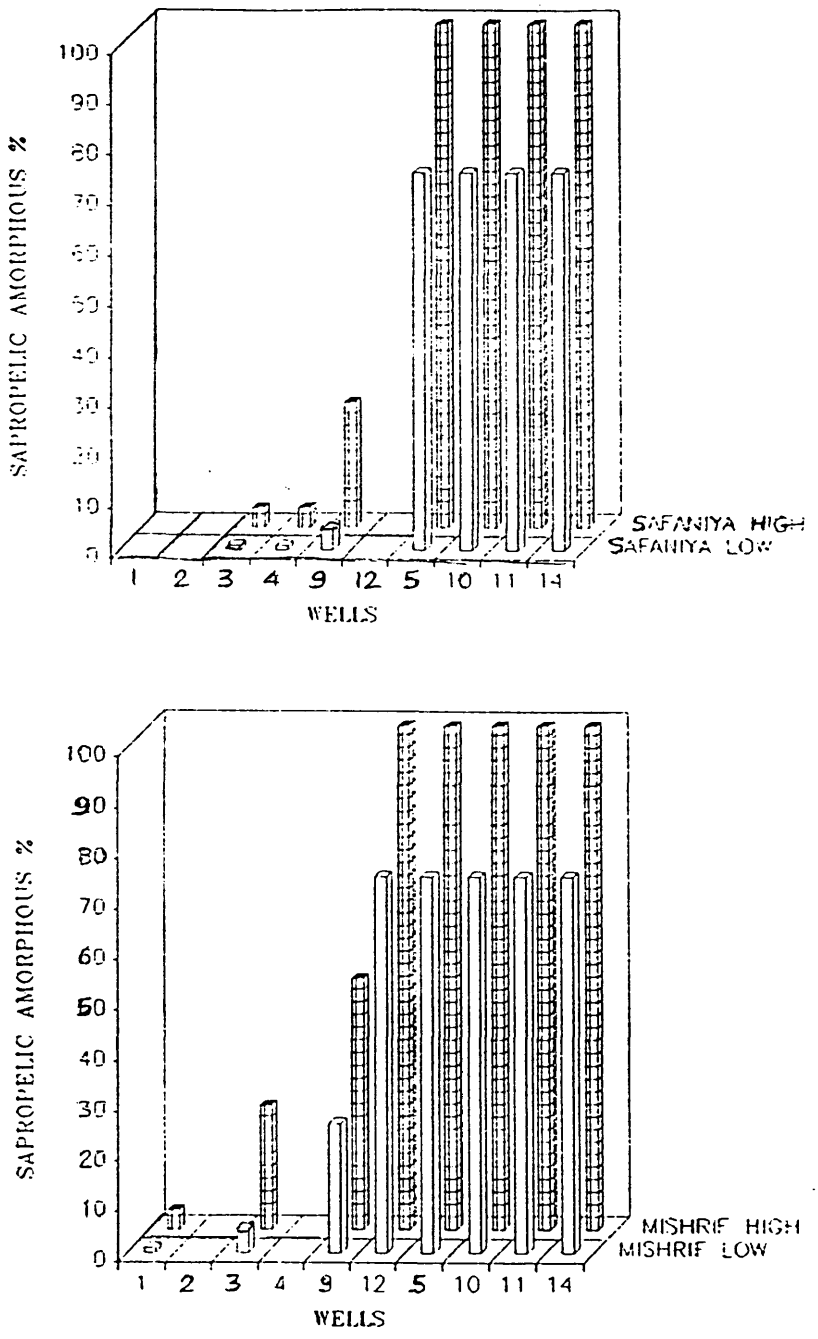


Figure 7.5 Variations of sapropelic amorphous fraction of the Safaniya and Mishrif kerogens throughout all the sampled boreholes.

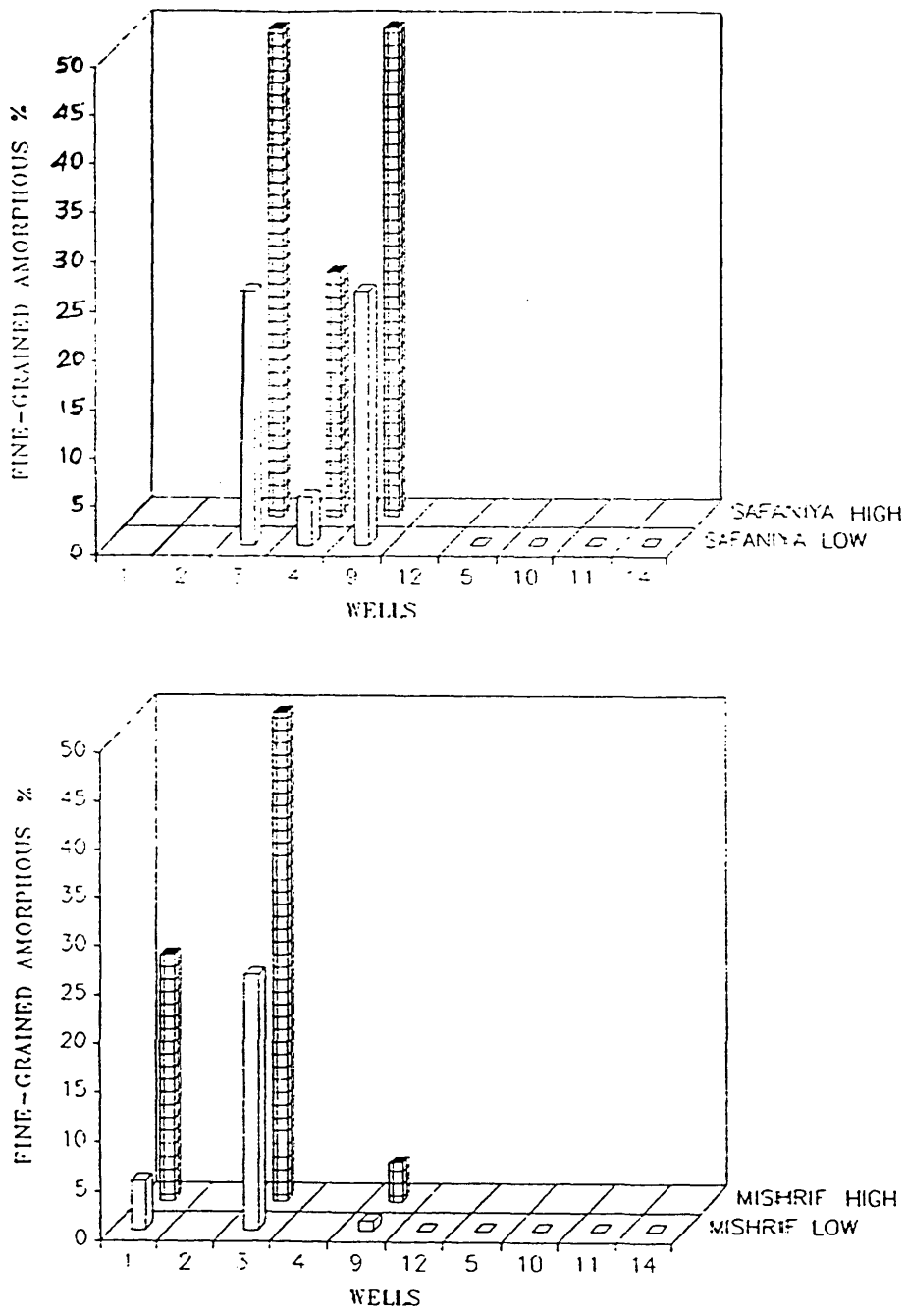


Figure 7.6 Variations of fine-grained amorphous fraction of the Safaniya and Mishrif kerogens throughout all the sampled boreholes.

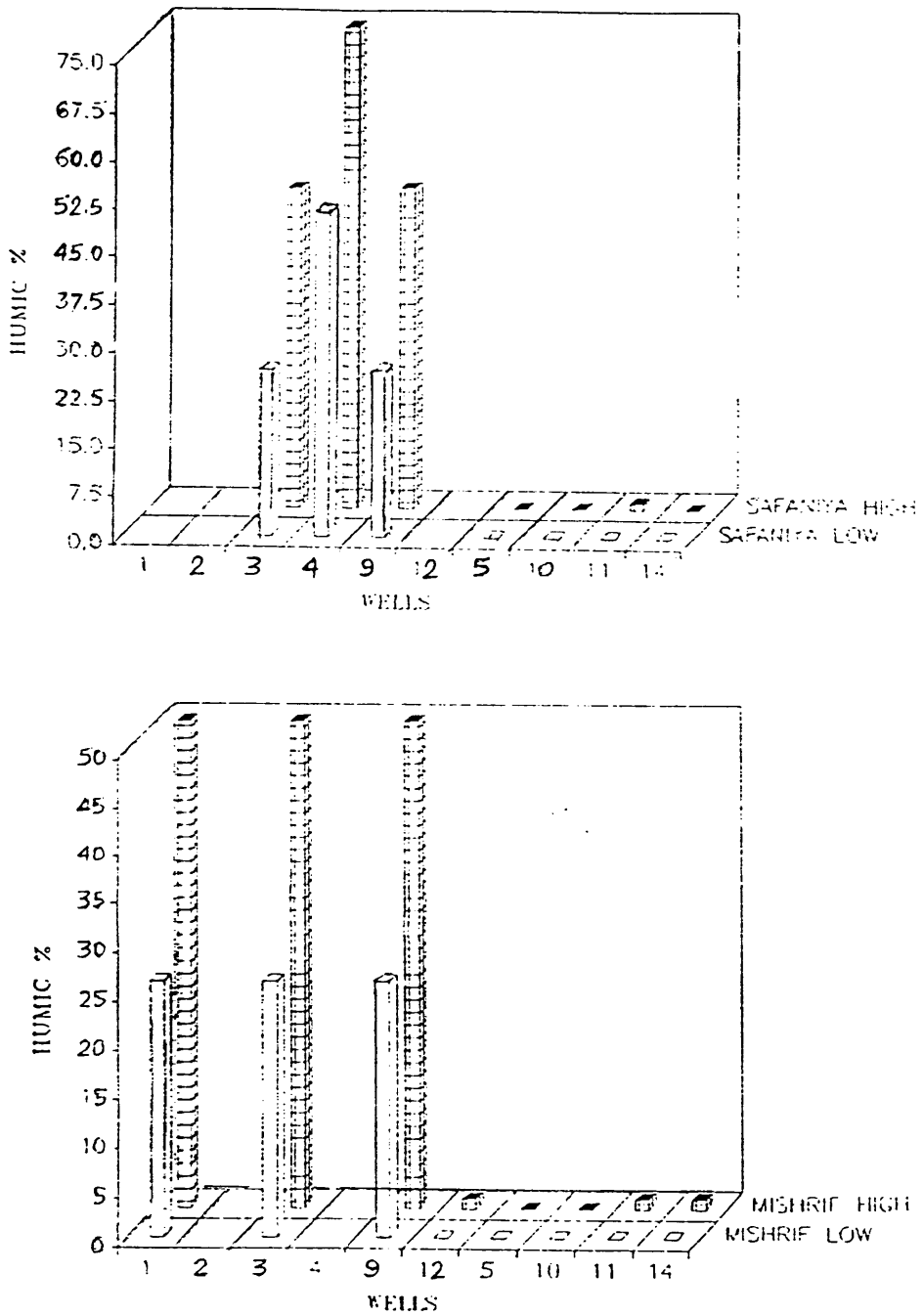


Figure 7.7 Variations of humic fraction of the Safaniya and Mishrif kerogens throughout all the sampled boreholes.

studies (considering only carbonate source rocks) in this project, it is possible to define a rich organic facies that is associated with carbonate intrashelf basins. Such definition does include the processes influencing the abundance and type of the sedimentary organic matter as well as the detailed character of the organic constituents of this organic facies. This makes it possible for the first time to apply the organic facies concept in carbonate source rock prediction studies as discussed in the following section.

7.3 *INTRASHELF BASINS AND ORGANIC FACIES PREDICTION*

This study demonstrates that the existence or development of a large depression (intrashelf basin) located away from the shore line in shallow-water stable carbonate platforms can produce a lime mud oil source rock type organic facies. The geographical extent of such facies is mostly the same as that of the depression. The organic content of this potential source rock averages 5% and the organic matter is light in density with high H/C ratio and composed of sapropelic amorphous organic matter with minimum terrestial influence. This is a very good potential source rock which can be mapped by simply mapping the intrashelf basin.

Seismic stratigraphy has developed to the point where thickness interval maps for a sedimentary basin can be produced (Vail et al, 1977; Badley, 1985). Any depression or intrashelf basin within such a sedimentary basin can be deduced, thereby the most likely occurrence of a potential source

rock interval can be inferred. This would make it feasible for the first time to predict the presence of carbonate source beds, their quantity as well as their quality, in the subsurface of the area under exploration. It involves locating their precise stratigraphic placement as well as their geographical extent.

The prediction of potential source units can be combined with an investigation into their maturity. This can be achieved by applying the Time-Temperature Index (TTI) concept (Lopatin, 1971; Waples, 1980) to estimate thermal maturation.

It should be pointed out that the findings of this chapter seem to hold for the Middle East basin or any other sedimentary basin with a similar geological setting. Such findings would not have been possible without establishing the detailed geologic framework of the study area. The successful application of this prediction method would make it possible to identify and locate any possible source rock sequences without relying almost exclusively on sample availability. This would be very useful in many exploratory regions, especially in frontier areas.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS 249

8.2 RECOMMENDATIONS FOR FURTHER STUDY 253

8.1 CONCLUSIONS

A. The reconstruction and modelling of the Cretaceous depositional history of ALRub ALKhali basin indicate the following:

1. The basin was undefined and it remained as part of the Arabian Platform sedimentation pattern up to the Middle Cretaceous.

2. The depositional history is dominated by carbonate sedimentation on the broad and stable Arabian Shelf which was flanked on the east by the open Tethys ocean. To the west, the carbonates were replaced by clastics. The source for these clastics was the uplifted highlands of the Arab-African continent.

3. A significant change in the depositional system occurred in ALRub ALKhali during the deposition of Safaniya Member, Middle to Late Albian time. The area became more differentiated with an intrashelf basin breaking up the shallow carbonate platform in the north-east of the study area. This is considered to be the start of ALRub ALKhali basin evolution during which the basin geometry changed throughout the Middle Cretaceous.

4. Another intrashelf regional depression developed in the eastern part of the study area during the deposition of Mishrif Member, Late Cenomanian to Late Turonian time.

5. These intrashelf basins are thought to be the site for the accumulation and preservation of high quality organic rich sediments.

6. ALRub ALKhali started to mould up into a gentle downward basinal shape during the Middle Cretaceous, receiving the thickest sedimentary deposit in the well 4 and well 14 area. The basin is trending north-east and continued to subside during Upper Cretaceous and Tertiary receiving more sediments in the central part of the basin. Past-Neogene deposition was merely the filling up of the basin.

B. Results of the regional geochemical study point out the following:

1. The Safaniya, Middle to Late Albian and Mishrif, Late Cenomanian to Late Turonian are the only organically rich units of the Cretaceous section to qualify as regional potential petroleum source rocks in the study area. Their organic richness varies from 1.8 to 7.21 weight percent and concentrated in the lower part of these two units. These organic rich intervals are composed mostly of dark coloured and laminated lime mudstone, deposited in relatively quiet anoxic waters of large intraplatform depressions with thickness ranging from 15m to 76m. Their dispersed sedimentary organic matter is sapropelic amorphous, hydrogen rich, and of chemical type II kerogen.

2. Several factors might have influenced the accumulation and preservation of organic matter during the deposition of Safaniya and

Mishrif organic rich units. These are: bottom water oxygen deficiency - high primary biologic productivity - rate of sediment accumulation - sediment's particle size - paleobathymetry (water depth) - a credible time correlation between these two organic rich units and worldwide oceanic anoxic events.

3. Maturity assessments indicate the Safaniya and Mishrif potential hydrocarbon source sequences to be immature throughout the study area. However, they seem to be approaching maturity with a few oil shows in well 14 which is the deepest well in the area.

4. There is a strong association between the development of intrashelf basins in the study area and the occurrence of organic rich sediments. These intraplatform embayments seem to play an important role in establishing anoxic conditions which help to enhance preservation of organic matter and produce an organic facies such as the Lower Safaniya and Lower Mishrif. This relationship is so defined that it is possible to determine the geographical distribution of this organic facies by simply mapping these regional depressional areas. The vertical distribution of the Lower Safaniya and Lower Mishrif organic facies can be obtained by estimating the thickness of their lime mud strata.

5. Regional intrashelf depressions located away from the paleoshore line of high bioproductive shallow-water platforms can be deduced using seismic stratigraphy. Thus, the most likely occurrence of potential

hydrocarbon source sequences can be inferred. This makes it possible for the first time to predict the presence and location of hydrocarbon source beds in the subsurface of the area under exploration. It also involves locating their precise stratigraphic placement as well as their geographical extent without relying almost exclusively on sample availability.

6. Apart from the Safaniya and Mishrif units, the remainder of the sampled Cretaceous intervals in the study area are too poor in organic matter to qualify as potential petroleum source rocks. The chemical type of their dispersed sedimentary organic matter ranges from mixed type II/III and type III to type IV kerogens.

7. The wide variation in the composition of the identified kerogen types is related to the intensity of oxidising nature of their depositional environments and the distance from the paleoshore line.

8. Type III kerogens with terrestial influence are noted to occur in the area closer to the paleoshore line while mixed type II/III and type III without significant terrestial influence have been identified basinward with an appearant domination of biodegraded fine-grained amorphous material.

9. Kerogen type IV has been identified with samples from the Lower Aruma Shale which has been deposited on top of the Pre-Aruma Unconformity. The association of kerogen type IV with this unit

could be the result of the extensive erosion, reworking, and redeposition of these sediments that usually accompany such a major regional unconformity.

8.2 RECOMMENDATIONS FOR FURTHER STUDY

1. Additional data are needed from boreholes located further east of the study area and if possible from United Arab Emirates and Oman. These additional data might help to locate the eastern limit of the two intrashelf basins identified in this work. This in turn, would help tracing the eastern limit of the Safaniya and Mishrif organic rich units where maturity is expected to increase due to increase in depth of burial.

2. Additional data are also needed for hydrocarbon source-rock evaluation from wells penetrating deeper formations (Jurassic and Paleozoic) in ALRub ALKhali, Saudi Arabia. Maturity assessments in this project have indicated the Cretaceous organic rich sequences to be immature in the study area.

REFERENCES AND BIBLIOGRAPHY

ALA, M. A., 1982: Chronology of Trap Formation and Migration of Hydrocarbons in the Zagros Sector of Southwest Iran: AAPG Bull., V. 66, p. 1535-1541.

ALA, M. A., 1990: Seventy-Five Years of Petroleum Exploration and Production in the Zagros Basin of Southwest Iran. In: Seventy Five Years of Progress in Oil Field Science and Technology, 1990, Balkema, Rotterdam, p. 61-76.

ALSHARHAN, A. S. & NAIRN, A. E. M., 1986: A review of the Cretaceous Formations in the Arabian Peninsula and Gulf: Part I: Journal of Petroleum Geology, 9(4), p. 365-392.

ALSHARHAN, A. S. & NAIRN, A. E. M., 1988: A Review of the Cretaceous Formations in the Arabian Peninsula and Gulf: Part II: Jour. of Petrol. Geol., 11(1), p. 89-112.

ARABIAN AMERICAN OIL COMPANY STAFF (ARAMCO), 1959: Ghawar Oilfield, Saudi Arabia: AAPG Bull., V. 43, p. 434-454.

ARAMCO, 1962: Public Relations Department, Aramco, Dhahran, Saudi Arabia, 29 p. (Unnumbered).

ARAMCO, 1975: Eastern Arabia and Adjacent Areas - Geological Sketch in: Schlumberger Well Evaluation Conference: Arabia p. 9-25.

ARAMCO, 1978: Public Relations Department, Aramco, Dhahran, Saudi Arabia, 36 p. (Unnumbered).

ARAMCO, 1980: Public Relations Department, Aramco, Dhahran, Saudi Arabia, 33 p. (Unnumbered).

ARTHER, M. A. & SCHLANGER, S. O., 1979: Cretaceous "oceanic anoxic events" as Causal Factors in Development of Reef-Reserviored Giant Oilfield: AAPG Bull., V. 63, p. 870-885.

AYRES, M. G., BILAL, M., JONES, R. W., STENTZ, L. W., TARTIR, M., AND WILSON, A. O., 1982: Hydrocarbon Habitat in the Main Producing Areas, Saudi Arabia: AAPG Bull., V. 66, p. 1-9.

BADLEY, M. E., 1985: Practical Seismic Interpretation, D., Reidel Publishing Company.

BARKER, C., 1974: Pyrolysis Techniques for Source Rock Evaluation: AAPG Bull., V. 58, p. 2349-2361.

BARNARD, P. C., COLLINS, A. G., AND COOPER, B. S., 1981: Identification and Distribution of Kerogen Facies in a Source Rock Horizon - Examples from the North Sea Basin. In: Organic Maturation Studies and Fossils Fuel Exploration (Ed. Brooks, J.), Academic Press, London etc., p. 271-282.

BORDOVSKY, O. K., 1965: Accumulation and Transformation of Organic Substance in Marine Sediments: Marine Geology, V. 3, p. 3-114.

BOSTICK, N. H. & ALPERN, B., 1977: Principles of Sampling, Preparation and Constituent Selection of Microphotometry in Measurement of Maturation of Sedimentary Organic Matter: Journal Microscopy, V. 109, pt. 1, p. 41-47.

BRALOWER, T. J. & THIERSTEIN, H. R., 1987: Organic Carbon and Metal Accumulation Rates in Holocene and Mid-Cretaceous Sediments: Palaeoceanographic Significance, In: Marine Petroleum Source Rocks (Eds. J. Brooks and A. J. Fleet), Geol. Soc. Lon. Spec. Publ. 26, p. 345-369.

BRAMKAMP, R. A. & POWERS, R. W., 1958: Classification of Arabian Carbonate Rocks: Geological Society of America Bull., V. 69, p. 1305-1318.

BROOKS, J., 1981: Organic Maturation of Sedimentary Organic Matter and Petroleum Exploration - A review. In: Organic Maturation Studies and Fossils Fuel Exploration (Ed. Brooks, J.), Academic Press, London etc., p. 1-38.

BROOKS, J. & CORNFORD, C. & ARCHER, R., 1987: The Role of Hydrocarbon Source Rocks in Petroleum Exploration, In: Marine Petroleum Source Rocks (Eds. J. Brooks and A. J. Fleet), Geol. Soc. Lond. Spec. Publ. 26, p. 17-46.

BROWN, G. F., 1972: Tectonic Map of the Arabian Peninsula: Ministry of Petroleum & Mineral Resources - Directorate General of Mineral Resources, Kingdom of Saudi Arabia, Arabian Peninsula Series Map, AP-2.

BRUMSACK, H. J., 1980: Geochemistry of Cretaceous Black Shales from the Atlantic Ocean (D. S. D. P. Legs 11, 14, 36 and 41).

BUJAK, J. P., BARS, M. S. & WILLIAM, G. L., 1977: Off-shore East Canada's Organic Type and Colour and Hydrocarbon Potential: Oil and Gas Jour., V. 75, No. 14, p. 198- 202.

BURCHETTE, T. P & BRITTON, S. R., 1985: Carbonate Facies Analysis in the Exploration for Hydrocarbons: A Case-Study for the Cretaceous of the Middle East, In: Sedimentology: Recent Development and Applied Aspects (Eds. P. J. Brenchley and B. P. J. Williams), Blackwell Scientific Publications, Geo. Soc. Spec. Publ. No. 18, p. 311-338.

BURGESS, J. D., 1974: Microscopic Examination of Kerogen (dispersed Organic Matter) in Petroleum Exploration: Geol. Soc. America Spec. paper. 153, p. 19-30.

CALVERT, S. E., 1987: Oceanographic Control on the Accumulation of Organic Matter in Marine Sediments, In: Marine Petroleum Source Rocks (Eds. J. Brooks and A. J. Fleet), Geol. soc. Lond. Spec. Publ. 26, p. 137-151.

CLAYPOOL, G. E., LOVE, A. H., & MAUGHAN, E. K., 1978: Organic Geochemistry, Incipient Metamorphism and Oil Generation in Black Shale Members of the Phosphoris Formation of Western Interior USA: AAPG Bull., V. 62, p. 98-120.

CLEMENTZ, D. M., 1979: Effect of Oil and Bitumen Saturation, source-Rock Pyrolysis: AAPG Bull., V. 63, p. 2227-2232.

COMPAZ, A., 1980: Les Kerogenes Vus au Microscope, In: Kerogen-Insoluable Organic matter from Sedimentary Rocks. (Ed. Durand, B.), Editions Technip, Paris, p. 55-1111.

COOPER, B. S. & CORNFORD, C., 1984: Geochemistry in Petroleum Exploration: Notes for Japec Course No. 26, Imperial College.

CORREIA, M., 1967: Relations Possible Entre L'etat De Conservation Des Elements Figures De La Matiere Organicque (Microfossiles, Palynoplantologiques) et L'existence de Gisements d'Hydrocarbures. Rev. Inst. Franc. Du Petrole, Vol. 22, p. 1285-1306.

CORREIA, M., 1971: Diagenesis of sporopollenin and other Comparable Organic Substances; Application to Hydrocarbon Exploration, In: Sporopollenin (Eds. J. Brooks et al), London and New York, Academic Press, p. 569-620.

DEGENS, E. T. & LITTEKKOT, V., 1987: The Carbon Cycle - Tracking the Path of Organic Particles from Sea to Sediment, In: Marine Petroleum Source Rocks (Eds. J. Brooks and A. J. Fleet), Geol. Soc. Lond. Spec. Publ., 26, p. 121-135.

DEGENS, E. T. & MOPPER, K. 1976: Factors Controlling the Distribution and Early Diagenesis of Organic Material in Marine Sediments, in J. P. Riley et al, eds., Chemical Oceanography, V. 6, 2nd ed.: New York, Academic Press, p. 59-113.

DEMAISON, G., HOLCK, A.J. J., JONES, R. W. & MOORE, G. T., 1983: Predictive Source Bed Stratigraphy; A Guide to Regional Petroleum Occurrence. In: Origin Migration and Accumulation of Hydrocarbons. Eleventh World Petroleum Congress, London, John Wiley, p. 1-13.

DEMAISON, G. & MOORE, G. T., 1980: Anoxic Environments and Oil Source Bed Genesis: AAPG Bull., V. 64, p. 1179-1209.

DEMBICKI, H., HORSFIELD, Jr., B., & Ho, T.T.Y., 1983: Source Rock Evaluation by Pyrolysis - Gas Chromatography: AAPG Bull., V. 67, p. 1094-1103.

DIETZ, S. D. & HOLDEN, J. C., 1970: Reconstruction of Pangaea: Breakup and Dispersion of Continents, Permian to Present. J. Geophys. Res., 75: p. 4939-4956.

DIXON, C. J., 1982: A Contribution to the Economic Potential of the Phanerozoic Cover Rocks, Kingdom of Saudi Arabia: Deputy Ministry for Mineral Resources, Open-File Report, IC-OF-02-4.

DOW, W. G., 1977: Kerogen Studies and Geological Interpretations: Jour. Geochm. Exploration, V. 7, p. 79-99.

DUNNINGTON, H. V., 1967: Stratigraphic Distribution of Oil fields in the Iraq-Iran-Arabianbasin: Journal of the Institute of Petroleum, V. 53, No. 520, p. 129-153.

DURAND, B., 1980: Sedimentary Organic Matter and Kerogene, Definition and Quantitative Importance of Kerogene. In: Kerogene - Insoluable Organic Matter from Sedimentary Rocks (Ed. Durand, B.), Editions Technip, Paris, p. 13-34.

DURAND, B., 1987: Organic Geochemistry for Petroleum Exploration: Recent Advances in Concepts and Applications. In: petroleum Geochemistry and Exploration in the Alpo-Asian Region, (Eds. Kumar et al.), Balkema, Rotterdam, p. 37-49.

DURAND, B. & MONIN, J. C., 1980: Elemental Analysis of Kerogens (C, H, O, N, S, Fe). In: Kerogen-Insoluable Organic Matter from Sedimentary Rocks (Ed. Durand, B.), Editions Technip, Paris, p. 113-142.

DURAND, B & NICAISE, G., 1980: Procedures for Kerogen Isolation. In: Kerogen-Insoluable Organic Matter from Sedimentary Rocks (Ed. Durand, B.), Editions Technip, Paris, p. 35-53.

EL-AQUAR, M. A., 1960: Reservoir Performance Under Gas and Water Injection, Abqaiq Field, Saudi Arabia: Second Arab Petroleum Congr., The League of Arab States, p. 5-25.

ENTSMINGER, L. D., 1981: Sedimentary Response to Tectonic and Eustatic Changes: An Example from the Mid-Cretaceous Wasia Formation, Saudi Arabia: Soc. of Petrol. Engn., March 1981, Manama, p. 159-169.

ESPITALIE, J. & JOUBERT, L., 1987: Use of Tmax as a maturation Index in Petroleum Exploration, In: Petroleum Geochemistry and Exploration in Alpo-Asian Region, (Eds. Kumar et al), Balkema, Rotterdam, p. 67-73.

ESPITALIE, J., MADEC, M., AND TISSOT, B., 1980: Role of Mineral Matrix in Kerogen Pyrolysis: Influence on Petroleum Generation and Migration: AAPG Bull., V. 64, p. 59-66.

ESPITALIE, J., MADEC, M., TISSOT, B., MENNING, J. J. & LEPLAT, P., 1977: Source Rock Characterization Method for Petroleum Exploration: Proceedings of the 9th Annual Offshore Technology Conference, V. 3, p. 439-448.

FIENELY, J. R., 1971: Specific Gravity of Pollen Exine. Pollen Spores, XIII, (1), p. 179-186.

GARFIELD, L., 1985: Evolution of the Sedimentary Environments of the Cover Rocks of the Arabian Peninsula: Deputy Ministry for Mineral Resources, Open-File Report RF-OF-05-5.

GAUCHER, L. P., 1972: Origin of Petroleum (Abstract): AAPG Bull., V. 56, p. 619.

GEALEY, W. K., 1977: Ophiolite Obduction and Geologic Evolution of the Oman Mountains and Adjacent Areas: Geol. Soc. America Bull., V. 88, p. 1183-1191.

GLENNIE, K. W., BOEUF, M. G. A., CLARKE, M. W. H., MOODY-STUART, M., PILAAR, W. F. H., & REINHARDT, B. M., 1973: Late Cretaceous Nappes in Oman Mountains and their Geologic Evolution: AAPG Bull., V. 57, p. 5-27.

GLINTZBOECKEL, C., 1981: A Tentative Synopsis of the Geology of the Saudi Arabian Sedimentary basin in Relation to Phospate Prospecting: Deputy Ministry for Mineral Resources, Open-File Report, BRGM-OF-01-23.

GOLD, T., 1979: Terrestrial Sources of Carbon and Earthquake Outgassing, Jour. of Petroleum Geol., I(3), p. 3-19.

GORIN, G. E., RAEZ, L. G., & WELLER, M. R., 1982: Late Precambrian-Cambrian Sediments of Hugf Group, Sultanate of Oman; AAPG Bull., V. 66, p. 2609-2627.

GRANTHAM, P. J., LIJMBACK, G. W. M., POSTHUMA, J., HUGHES, CLARKE, M. W., & WILLINK, R. J., 1987: Origin of Crude Oils in Oman: Jour. of Petroleum Geol. II(1), p. 61-80.

GUTJAHR, C. C. M., 1966: Carbonization Measurements of Pollen Grains and Spores and their Application. Leidse Geologische Mededelinen, V. 38, p. 1-29.

HALBOUTY, M. T., et al 1970: World's Giant Oil and Gas Fields, Geologic Factors Affecting their Formation and Basin Classification, in Geology of Giant Petroleum Field, A Symposium, (Ed. Halbouty, M. T.), AAPG memoir 14, p. 502-555.

HARLAND, W. B., COX, A. U., LLEWELLYN, P. G., PICKTON, C. A. G., SMITH, A. G., & WALTERS, R. 1982: A Geologic Time Scale, Cambridge University Press, Cambridge, 131 p.

HARRIS, P. M., FROST, S. H., KENDALL, C. G., SHAFFER, B. L., & SCHNEIDERMANN, N., 1980: Cretaceous Sea Level and Stratigraphy, Eastern Arabian Peninsula (Abstract) AAPG Bull., V. 64, p. 719.

HARRIS, P. M., FROST, S. H., SEIGLIE, G. A., & SHNEIDERMANN, N., 1984: Regional Unconformities and Depositional Cycles, Cretaceous of the Arabian Peninsula, (Ed. Schlle, J. S.), Interregional Unconformities and Hydrocarbon Accumulation: AAPG Memoir 36, p. 67-80.

HARWOOD, R. J., 1977: Oil and Gas Generation by the Laboratory Pyrolysis of Kerogen: AAPG Bull., V. 61, p. 2082-2101.

HASSAN, T. H. & AZER, 1985: The Occurrence and Origin of Oil in Offshore Abu Dhabi, Proc. SPE 1985, Middle East Oil Technical Conference, Bahrain, March 1985, p. 143-149.

HEATH, G. R., Moore, T. C., Jr., and Dauphin, J. P., 1977: Organic Carbon in Deep-Sea Sediments, In (Ed. Andersen, R. N.), The Fate of Fossil Fuel CO_2 in the Oceans: New York, Plenum Press, p. 627-639.

HOSOI, H. 7 MURAKAMI, R., 1971: Radiated Supture Faults on the Arabian Type Oilfield: Jour. of the Japanese Petroleum Technologists, V. 36, p. 10-17.

HUNT, J. M., 1979: Petroleum Geochemistry and Geology: W. H. Freeman and Co., San Francisco., 617 p.

HUSSEINI, M. I. & HUSSEINI, S. I., 1990: Origin of the InfraCambrian Salt Basins of the Middle East: In Classic Petroleum Provinces, (Ed. Brooks, J.), Geol. Soc. Spec. Publ., No. 50, p. 279-292.

IBACH, L. E. J., 1982: Relationship between Sedimentation Rate and Total Organic Carbon content in Ancient Marine Sediments: AAPG Bull., V. 66, p. 170-188.

IBRAHIM, M. W., KHAN, M. S., & KHATIB, H., 1981: Structural Evolution of Harmaliyah Oilfield, Eastern Saudi Arabia: AAPG Bull., V. 65, p. 2403-2416.

IRVING, E., NORTH, F. K. & COUILLARD, R., 1974: Oil Climate and Tectonics: Canadian Journ. of Earth Sciences, V. 11, p. 1-17.

JONES, R. W., 1987: Organic Facies, in Advances in Petroleum Geochemistry, V. 2, (Ed. Brooks, J., Welte, D.), Academic Press, London, p. 1-90.

KATZ, B. J., 1983: Limitations of "Rock-Eval" Pyrolysis for Typing Organic Matter: Organic Geochemistry, V. 4, p. 195-199.

KINGHORN, R. R. F., 1983: An introduction to the Physics and Chemistry of Petroleum. John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore, 420 p.

KINGHORN, R. R. F. & RAHMAN, M., 1980: The Density Separation of Different Maceral Groups of Organic Matter Dispersed in Rocks: Jour. Petrol. Geol., 3(4), p. 449-454.

KINGHORN, R. R. F. & RAHMAN, M., 1983: Specific Gravity as a Kerogen Type and Maturation Indicator with Special Reference to Amorphous Kerogens: Jour. Petrol. Geol., V. 6, (2), p. 179-194.

LAPLANTE, R. E., 1974: Hydrocarbon Generation in Gulf Coast Tertiary Sediments: AAPG Bull., V. 58, p. 1281-1289.

LOPATIN, N. V., 1971: Temperature and Geologic Time as Factor in Coalification, Akad Nauk SSSR, Izv. Ser. Geol. 3: p. 95-106.

MASRAN, Th. C. & Pocock, S. A. J., 1981: The Classification of Plant Derived Particulate Organic Matter in Sedimentary Rocks. In: Organic Maturation Studies and Fossil Fuel Exploration. (Ed. Brooks, J.), Academic Press, London, etc. p. 145-175.

MCLVER, R. D., 1967: Composition of Kerogen_Clue to its Role in Origin of Petroleum. Proc. 7th World Petrol. Congr., 2: p. 25-36.

MILLER, R. G., 1989: Prediction of Ancient Coastal Upwelling and Related Source Rocks from Palaco-Atmospheric Pressure Maps, Marine and Petroleum Geology, V. 6, p. 277-285.

MORRIS, R. J., 1987: The Formation of Organic-Rich Deposits in Two Deep-Water Marine Environments, In: Marine Petroleum Source Rocks, (Eds. Brook, J., and Fleet, A. J.), Geol. Soc. Lond. Spec. Publ. 26, p. 153-166.

MULLER, P. J. & SUESS, E., 1979: Productivity, Sedimentation Rate and Sedimentary Organic Matter in the Oceans-1. Organic Carbon preservation. Deep Sea Res. 26A, 1347-62.

MURRIS, R. J., 1984: Middle East: Stratigraphic Evolution and Oil Habitat: In Petroleum Geochemistry and Basin Evaluation, (Eds. Demaison, G., Murris, R. J.), AAPG memoir 35, p. 353-372.

NEWELL, K. D. & HENNINGTON, R. D., 1983: Potential Petroleum Source Rock Deposition in the Middle Cretaceous Wasia Formation, Rub'ALKhali, Saudi Arabia, Proc. SPE 1983, Middle East Oil Technical Conference, Bahrain, March 1983, p. 151-160.

PARRISH, J. J., 1982: Upwelling and Petroleum Source Beds, with Reference to Paleozoic: AAPG Bull., V. 66, p. 750-774.

PARRISH, J. J., 1987: Palaco - Upwelling and the Distribution of Organic-Rich Rocks, In: Marine Petroleum Source Rocks (Eds. Brook, J., Fleet, A. J.), Geol. Soc. Lond. Spec. Publ. 26, p. 199-207.

PARRISH, J. J., CURTIS, R. L., 1982: Atmospheric Circulation, Upwelling, and Organic-Rich Rocks in the Mesozoic and Cenozoic Eras: Paleogeography, Paleoclimate, Paleoechology, V. 40, p. 31-66.

PATTON, T. L. & O'CONNOR, S. J., 1988: Cretaceous Flexural History of Northern Oman Mountain Foredeep, United Arab Emirates: AAPG Bull., V. 72, p. 797-809.

PEDERSEN, T. F. & CALVERT, S. E., 1990: Anoxia Vs. Productivity: What Controls the Formation of Organic-Carbon-Rich Sediments and Sedimentary Rocks? AAPG Bull., V. 74, P. 454-466.

PFLET, R. & DEROO, G., 1983: Versune Sedimentologic De La Matiere Organique, Bull. Soc. Geol. France, V. 25 (4), p. 483-493.

PETERS, K. E., 1986: Guidelines for Evaluating Petroleum Source Rocks Using Programmed Pyrolysis: AAPG Bull., V. 70, p. 318-329.

PETERS, K. E., LSHIWATARI, R., & KAPLAN, R., 1977: Colour of Kerogen as an Index of Maturity: AAPG Bull., V. 61, p. 504-510.

PETERS, K. E., WHELAN, J. K., HUNT, J. M., & TARAFA, M. E., 1983: Programmed Pyrolysis of Organic Matter from Thermally Altered Cretaceous Black Shales: AAPG Bull., V. 67, p. 2137-2146.

PORFIR'EV, V. B., 1974: Inorganic Origin of Petroleum: AAPG Bull., V. 58, p. 3-31.

POWELL, T. G., CREANEY, S., & SNOWDON, L. R., 1982: Limitations of use of Organic Petrographic Techniques for Identification of Petroleum Source Rock: AAPG Bull., V. 66, p. 430-435.

POWERS, R. W., 1962: Arabian Upper Jurassic Carbonate Reservoir Rocks, In Classification of Carbonate Rocks, as Symposium, (Ed. Ham. W. H.), AAPG Memoir 1, p. 122-192.

POWERS, R. W., RAMIREZ, L. F., REDMOND, C. D., & ELBERG, E. L., 1966: Geology of the Arabian Peninsula: Sedimentary Geology of Saudi Arabia: U.S. Geological Survey Professional Paper, 560-D.

PRATT, W. E., 1956; Oil According to Hoyle: AAPG Bull., V. 40, p. 177-179.

RIDGWAY, R., 1912: Colour Standards and Colour Nomenclature: Washington, D. C., Pub. by Author, 43 p.

ROGERS, M. A., 1980: Application of Organic Facies Concepts to Hydrocarbon Source-Rock Evaluation. Proc. 10th World Petrol. Congress, 1979, V. 2, London, Hayden and Sons Ltd., p. 22-30.

SAXBY, J. D., 1970: Isolation of kerogen in Sediments by Chemical Methods. Chem. Geol., V. 6, p. 173-184.

SCHLANGER, S. O. & JENKYNS, H. C., 1976: Cretaceous Oceanic Anoxic Events: Causes and Consequences. Geol. Mynbouw, V. 55, p. 179-184.

SCHLANGER, S. O., ARTHER, M. A., JENKYNS, H. C., & SCHOLLE, P. A., 1987: The Cenomanian-Turonian Oceanic Anoxic Event, I. Stratigraphy and Distribution of Organic Carbon-Rich Beds and the Marine 13C Excursion, In: Marin Petroleum Source Rocks, (Eds. Brook, J. and Fleet, A. J.), p. 371-399.

SOLIMAN, F. A. & AL-SHAMLAN, A., 1982: Review on the Geology of the Cretaceous Sediments of the Rub'al-Khali, Saudi Arabia: Cretaceous Research, V. 3, p. 187-194.

SPENCER, P. W., SUSUMU, H., & BREWER, D. G., 1978: Particles and Particle Fluxes in the Ocean: Oceans, V. 21, p. 20-25.

STACH, E., MACKOWSKY, M. TH., TAYLOR, G. H., CHANDRA, D., TEICHMULLER, M., AND TEICHMULLER, R., 1975: Stach's Textbook of Coal Petrology. (Translation and English Revision by Murchison, D. G., Taylor, G. H., and Zierke, F., 1975). Gerruder Borntraeger, Berlin-Stuttgart, 428P.

STANCLIFFE, R. P. W., 1989: Microforminifera Linings - their Classification, Biostratigraphy and Paleontology, Micropaleontology, V. 35, p. 337-352.

STAPLIN, F. L., 1969: Sedimentary Organic Matter, Organic Metamorphism and Oil and Gas Occurrence: Bull, Canadian Petroleum Geology, V. 17, p. 17, p. 47-66.

STEINEKE, M., BRAMKAMP, R. A., & SANDERS, N. J., 1958: Stratigraphic Relations of Arabian Jurassic Oil: AAPG Symposium Habitat of Oil, p. 1294-1329.

STONELEY, R., 1987: A Review of Petroleum Source Rocks in Parts of the Middle East, In: Marine Petroleum Source Rocks, (Eds. Brook, J., and Fleet, A. J.), Geol. Soc. Lond. Spec. Publ. 26, p. 263-269.

STONELEY, R., 1990: The Middle East Basin: A Summary Overview, In: Classic Petroleum Provinces, (Ed. Brooks, J.), Geol. Soc. Lond. Spec. Publ. 50, p. 293-298.

SUESS, E., 1980: Particulate Organic Carbon Flux in the Oceans - Surface Productivity and Oxygen Utilization. Nature, London, 288, p. 260-263.

TISSOT, B., DEMAISON, G., MASSON, P., DELTEIL, J. R., & COMBAZ, A., 1980: Paleoenvironment and Petroleum Potential of Middle Cret. Black Shales in Atlantic Basins: AAPG Bull., V. 64, p. 2051-2063.

TISSOT, B., DURAND, B., ESPITALIE, J., & COMBAZ, A., 1974: Influence of Nature and Diagenesis of Organic matter in Formation of Petroleum: AAPG Bull., V. 58, p. 499-506.

TISSOT, B. & WELTE, D. H., 1984: Petroleum Formation and Occurrence. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo, 538 p.

TLEEL, J. W., 1973: Surface Geology of Dammam Dome, Eastern Province, Saudi Arabia: AAPG Bull., V. 57, p. 558-576.

TYSON, R. V., 1987: The Genesis and Palynofacies Characteristics of Marine Petroleum Source Rocks, In: Marine Petroleum Source Rocks, (Eds. Brook, J., and Fleet, A. J.), Geol. Soc. Lond. Spec. Publ., 26, p. 47-67.

VAIL, P. R., ET AL., 1977: Seismic Stratigraphy and Global Changes of Sea Level, (Ed. Payton, C. E.), Seismic Stratigraphy - applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 49-212.

VAN KREVELEN, D. W., 1961: Coal, Amsterdam, Elsevier Publ. Co., 514 p.

VASSOEVICH, N. B., AKRMKHODZHAEV, A. M. & GEODEKYAN, A. A., 1974: Principal Zone of Oil Formation, In: (Eds. Tissot, B. and Bienner, F.), Advances in Organic Geochemistry, 1973, Paris, Editions Technips, p. 309-314.

VENKATACHALA, B. S., 1981: Differentiation of Amorphous Organic Matter Types in Sediments, In: Organic Maturation Studies and Fossils Fuel Exploration, (Ed. Brooks, J.), Academic Press, London etc., p. 177-200.

VIDETICH, P. E., MCLIMANS, R. K., WATSON, H. K., AND NAGY, R.M., 1988: Depositional, Diagenetic, Thermal, and Maturation Histories of Cretaceous, Mishrif Formation, Fateh Field, Dubai: AAPG Bull., V. 72, p. 1143-1159.

WAPLES, D. W., 1984: Modern Approaches in Source-Rock Evlaution, In: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region, (Eds. Woodward et al), Denver, Colorado, p. 35-50.

WAPLES, D. W., 1985: Geochemistry in Petroleum Exploration: D. Reidel Publishing Comp., Boston, 232 p.

WILSON, J. L., 1969: Microfacies and Sedimentary Structure in "Deeper Water" Lime Mudstones, Soc. Econ. Paleontologists Mineralogists Spec. Publ. 14, p. 4-19.

WILSON, J. L., 1975: Carbonate Facies in Geologic History: New York, Springer-Verlag, 469 p.

ADDITIONAL LIST OF REFERENCES

BARKER, C. and DICKEY, P.A., 1984: Hydrocarbon habitat in main producing areas, Saudi Arabia: Discussion. AAPG Bull., V. 68(1), p. 108-109.

CORNFORD, C., RULLKOTTER, J. and WELTE, D.W., 1980: A synthesis of organic petrographic and geochemical results from DSDP sites in the eastern central North Atlantic: In Advances in Organic Geochemistry, 1979, A.G. Douglas and J.R. Maxwell (eds.), Pergamon Press, p. 445-453.

GRESSLY, A., 1938: Observations geologiques sur le Jura Soleurois: Neue Denkschr. allg. schweiz, Ges. ges. Naturw., V. 2, p. 1-112.

HUC, A.Y., 1988: Aspects of depositional processes of organic matter in sedimentary basins. Advances in Organic Geochemistry, 1987, Org. Geochem., V. 13(1-3), p. 263-272.

JONES, R. W. and DEMAISON, G.J., 1982: Organic Facies - stratigraphic conecpt and exploration tool. In Proc. 2nd ASCOPE Conf., Manilla, Saldivar-Sali, A.(ed.), p. 51-68.

JONES, R. W., 1984: Comparison of carbonate and shale source rocks: In Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks, J. G. Palacas (ed.), AAPG Studies in Geology No. 18, p. 163-

180.

JONES, R.W., 1985: Hydrocarbon habitat in main producing areas, Saudi Arabia: Reply. AAPG Bull., v. 69(11), p.2031-2033.

KNUDSEN, K., ET AL., 1988: Variation in organic matter quality and maturity in Draupne Formation source rocks from the Oseberg Field region, offshore Norway: Advances in Organic Geochemistry, 1987, Org. Geochem., V. 13(4-6), p. 1051-1060.

MCKIRDY, D.M., ET AL., 1984: Hydrocarbon genesis and organic facies in Cambrian carbonates of the Eastern Officer Basin, South Australia. In Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks, J.G. Palacas (ed.), AAPG Studies in Geology No. 18, p. 13-31.

MILES, J.A., 1989: Illustrated Glossary of Petroleum Geochemistry, Oxford Scientific Publications, 137 p.

PALACAS, J.G., 1984: Carbonate rocks as sources of petroleum: geological and chemical characteristics and oil-source correlations. Proc. 11th World Petroleum Congress, 2, Geology, Exploration, Reserves, p. 31-43.

READING, H.G. (Ed.), 1986: Sedimentary Environments and Facies, Oxford: Blackwell Scientific.