

Geology of the Early Paleogene Phosphorite Deposits of Northwestern Saudi Arabia

by

Wael Saied Ali Matter

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

GEOLOGY

June, 1996

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

GEOLOGY OF THE EARLY PALEOGENE PHOSPHORITE

DEPOSITS OF NORTHWESTERN

SAUDI ARABIA

BY

WAEI SAIED ALI MATTER

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

**In Partial Fulfillment of the
Requirements for the Degree of**

MASTER OF SCIENCE

In

GEOLOGY

JUNE, 1996

UMI Number: 1382791

UMI Microform 1382791
Copyright 1997, by UMI Company. All rights reserved.

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

DHAHRAN, SAUDI ARABIA

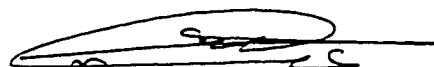
COLLEGE OF GRADUATE STUDIES

This thesis, written by

Wael Saied Ali Matter

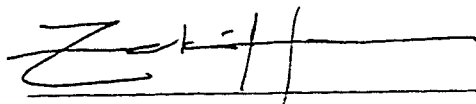
under the direction of his Thesis Committee, and approved by all its members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN GEOLOGY



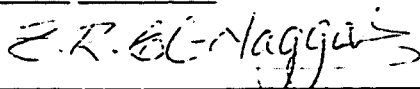
Dean, College of Graduate Studies

Date : 13-11-96

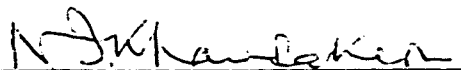


Department Chairman

Thesis Committee



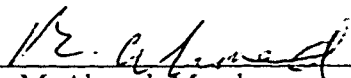
Prof. Dr. Z. R. El-Naggar, Chairman



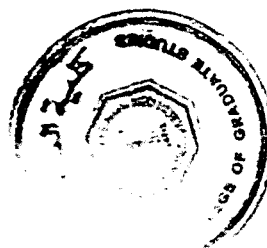
Dr. N. I. Khandaker, Member



Dr. A. Aksoy, Member



Dr. M. Ahmed, Member





**In The Name Of Allah
The Most Merciful
The Most Gracious**

**This Thesis is Dedicated to
My Beloved Parents**

ACKNOWLEDGMENTS

I am most grateful to The Almighty. **ALLAH**, for giving me the patience, strength and ability to accomplish this work. May his peace and blessing be upon all his prophets, and particularly upon his last and most noble prophet, Mohammed, his family, companions and followers to the Day of Judgement.

Much is owed to my thesis committee chairman, Prof. Dr. Z.R. El-Naggar, to whom the writer is indebted for suggesting the problem, laying out the plan of research, supervising the field work, correcting the manuscript as well as invaluable advice, fatherly support, encouragement and helpful discussions throughout all phases of this work.

The writer is also grateful to his thesis committee members, Dr. N.I. Khandaker, Dr. A. Aksoy and Dr. M. Ahmed for their valuable discussions, encouragement and help.

Grateful acknowledgment is made to the King Fahd University of Petroleum and Minerals (KFUPM) for a research grant during which this work was carried out, and to its Department of Earth Sciences for providing its research facilities. I would like to mention Dr. Z. Al-Harari, Dr. G. Korvin, Dr. M. Hariri, Dr. M. Hussain, Dr. A. Abokhodair, Dr. A. Qahwash, Dr. R. Weijermars, Mr. G. Khan, S. Ameeruddin, Mr. S. Hameed, Mr. M. Ahmed, Mr. A. Khan, Mr. K. Khan and Mr. A. Al-Saif.

Thanks should also go to the authorities of the KFUPM Research Institute for providing their most advanced analytical facilities, and for several of its members who helped to make this work a success. The author would like to mention : Dr. K. Al-Hinnai, Dr. F. Al-Adel, Dr. M. Nagady, Dr. M. Al-Haddad, Dr. F. Khiary, Dr. S. Saner, Mr. Keskin, Mr. Rasheedudin, Mr. Siridar and Mr. Belai.

Sincere thanks are also due to all those who generously contributed in many different ways to make this work a success. The assistance received from A. Jarad and H. Al-Sahn is great. May Allah reward them for their brotherly advice, unqualified assistance and encouragement. I am also grateful to my colleagues, A. Al-Zahrani, G. Nijm, U. Magaji, and a host of friends within and outside the University for their spirit of brotherhood and memorable company.

Finally, the author is deeply indebted to his parents and the rest of the family, for much valued sacrifices throughout the various stages of this research and without whose prayers, encouragement and spiritual support the work could never have been carried out.

To all, I am very grateful.

TABLE OF CONTENTS

	Page
Acknowledgment	ii
List of Figures	viii
List of Tables	xv
Abstract (Arabic)	xviii
Abstract (English)	xix
 CHAPTER ONE : INTRODUCTION	 1
1.1 Location and Geological Setting	3
1.2 Physiography	3
1.3 Climate, Precipitation and Vegetation	7
1.4 Water in the region	8
1.5 History of Discovery and Exploration	8
1.6 Previous Studies	11
1.7 Present Status of the Problem	35
 CHAPTER TWO MATERIALS AND METHODS OF STUDY	 39
2.1 Sampling	39
2.2 Laboratory Techniques	40
2.2.1 Sample Preparation	40
2.2.2 Instruments used	41
2.2.2.1 Binocular Microscope	42
2.2.2.2 Scanning Electron Microscope and the attached Electron Microprobe	42
2.2.2.3 Natural Gamma-ray Spectroscopy (NGS)	45
2.2.2.4 Proton Induced X-ray Emission Spectroscopy (PIXE)	55
 CHAPTER THREE STRATIGRAPHY OF THE SIRHAN-TURAYF BASIN	 68
3.1 General Discussion	68
3.2 The Late Cretaceous-Early Paleogene Succession in Saudi Arabia	70
3.2.1 The Late Cretaceous Rocks in Saudi Arabia	70
3.2.2 The Early Paleogene Rocks in Saudi Arabia	77
3.3 Stratigraphy of the Study Area	80
1- The Aruma Group	80
1.1 The Hudayb Limestone	82
1.2 The Zallum Sandstone	83
1.3 The Ar'ar Chalk	84
2- The Hibr Group	85

2.1 The Hazm-al-Jalamid Formation	86
2.1.1 The Thaniyat Phosphorite Member	89
2.1.2 The Kuwaykabah Limestone Member	91
2.2 The Bardawil Formation	93
2.2.1 The Ghinah Phosphorite Member	94
2.2.2 The Hawsa Limestone Member	95
2.2.3 The Mindassah Limestone Member	96
2.2.4 The Sib Limestone Member	96
2.3 The Turayf Formation	97
2.3.1 The Arqah Phosphorite Member	98
2.3.2 The AL-Amud Limestone Member	99
2.3.3 The Hamad Limestone Member	100
2.3.4 The Tarbah Nummulitic Limestone Member	100
2.3.5 The Shihiyah Limestone Member	101
2.3.6 The Jirani Chalky Limestone Member	102
2.3.7 The Hidrij Shale Member	102
 CHAPTER FOUR	
TECTONIC SETTING AND STRUCTURAL FEATURES OF THE SIRHAN-TURAYF BASIN	103
4.1 General Discussion	103
4.2 Geotectonic History of the Study Area	105
4.3 Structural Features of the Sirhan-Turayf Area	106
4.3.1 The Ha'il Arch Complex	106
4.3.2 The Badanah Uplift	107
4.3.3 The Wadi as Sirhan Graben	108
4.3.4 The Khawr Umm Wu'aal Graben	108
4.3.5 The Busayta Lineaments	109
4.3.6 The Ar Riyyatan Fault Complex	109
4.3.7 The Qasa'im Fault System	110
4.3.8 Other Lineaments	110
4.4 Relationship between Structural Features and Phosphorite Occurrences	110
 CHAPTER FIVE	
PETROGRAPHY OF THE STUDIED PHOSPHORITE DEPOSITS	113
5.1 General Discussion	113
5.1.1 Phosphorite nodules	114
5.1.2 Phosphorite grains and pellets	115
5.1.3 Non-Pelletal Phosphorite	121
5.2 Description of the Studied Phosphorite Deposits	123

CHAPTER SIX	MINERALOGY OF THE STUDIED PHOSPHORITE DEPOSITS	131
6.1	Mineralogy of the Hazm al-Jalamid Phosphorite Deposit	134
6.2	Mineralogy of the Thaniyat Turayf Phosphorite Deposit	156
6.3	Nomenclature and Classification	157
CHAPTER SEVEN	GEOCHEMISTRY OF THE STUDIED PHOSPHORITE DEPOSITS	172
7.1	General Discussion	172
7.2	Chemical analysis and Geochemical Significance	176
7.3	Natural Radioactivity	192
7.3.1	Geochemistry of Uranium	195
7.3.2	Uranium Content of the Studied Phosphorite Deposits	196
7.3.3	Factors affecting Uranium Concentration in the Studied Phosphorite Deposits	198
7.3.3.1	Factors affecting the Primary Concentration	198
7.3.3.2	Factors affecting the Secondary Concentrations	200
7.3.4	Geochemistry of Thorium	201
7.3.5	Geochemistry of Potassium	202
7.3.6	Relationship among Uranium, Thorium and Potassium in the studied Phosphorite Deposits	203
CHAPTER EIGHT	ORIGIN OF THE STUDIED PHOSPHORITE DEPOSITS	303
8.1	General Factors Controlling Phosphogenesis	306
8.1.1	The Development of Organic Life	306
8.1.2	The Tectonic Setting	307
8.1.3	Changes in the Sea-Level	307
8.1.4	Bathymetric / Topographic Control	309
8.1.5	The Phosphorite Assemblages	311
8.1.6	Uniformitarianism	315
8.2	Hypotheses on the Origin of Phosphorite Deposits	317
8.2.1	The Biogenic Origin Hypothesis	318
8.2.2	The Biochemogenic Origin Hypothesis	323
8.2.3	The Chemogenic Origin Hypothesis	326
8.2.4	The Diagenic Origin Hypothesis	338
8.2.5	The Volcanogenic Origin Hypothesis	344
8.3	Genesis of Studied Phosphorite Deposits	347
8.3.1	Factors Controlling Phosphogenesis in Northwestern Saudi Arabia	347
8.3.1.1	The Tectonic Setting	348
8.3.1.2	The Structural Framework	349

8.3.1.3	Sea Level Changes	350
8.3.1.4	Upwelling	351
8.3.1.5	Organisms	352
8.3.1.6	Surficial Weathering	353
8.3.2	Formation of Sedimentary Apatite	354
8.3.2.1	Biogenesis	354
8.3.2.2	Direct Precipitation	355
8.3.2.3	Epigenesis or Phosphatization	356
8.3.3	A Proposed Model for the Genesis of The Studied Phosphorite Deposits	358
CHAPTER NINE	SUMMARY AND CONCLUSION	360
REFERENCES		370

LIST OF FIGURES

FIGURE	Page
1.1 Location map of the Wadi Sirhan-Turayf basin	4
1.2 Phosphorite areas in the Wadi Sirhan-Turayf basin	5
1.3 Generalized lithostratigraphic section for the area of the Wadi Sirhan-Turayf basin proposed by Riddler and others (1985 a)	31
2.1 Natural radioisotopes decay chains	46
2.2 Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector	47
2.3 The experimental set up for Natural Gamma Ray Spectroscopy at ERL, KFUPM	50
2.4 Gamma rays spectrum of phosphorite sample from Tubaiq Phosphorite Tunnel	51
2.5 K calibration curve used in natural radioactivity analysis	53
2.6 The Region of Interest of 300 channels wide of 1765 KeV gamma line of Bi-214 which results in from the decay series of U-238	54
2.7 A schematic diagram of the KFUPM tandetron accelerator showing the three beam lines including the microprobe line	58
2.8 Beam optics of the Quadrupole Triplet Lens system	59
2.9 The sample chamber for KFUPM microprobe	59
2.10 The PIXE set up on the KFUPM microprobe facility	60
2.11 Block diagram of the data acquisition and experimental control system	62
2.12 PIXE Spectrum of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit	65
2.13 Experimental against Theoretical fit of PIXE Spectrum	66
3.1 Generalized geologic map of the Arabian Peninsula	71

3.2	Reference Section of the “Aruma Formation” at the vicinity of Wadi Al-Itk, as proposed by El-As`ad (1983 a)	76
3.3	Interpreted cross sections and generalized lithostratigraphy in the Wadi Sirhan-Turayf basin. After, Riddler and others (1986)	88
3.4	Drilling results in the Hazm Al-Jalamid area	90
5.1	Photomicrograph showing well-rounded, ellipsoidal and homogeneous pellet	116
5.2	Random section showing angular phosphorite grains, pseudo oolitic ovules	116
5.3	Photomicrograph showing random sections in phosphorite pellets growing	117
5.4	Photomicrograph showing random sections in phosphorite pellets	117
5.5	Photomicrograph showing abundant quartz grains	118
5.6	Photomicrograph showing an equatorial section in a tooth	118
5.7	Photomicrograph showing phosphorite pellet with a carbonaceous	120
5.8	Photomicrograph showing well-rounded phosphorite ovule	120
5.9	Photomicrograph showing compound pellet	122
5.10	Photomicrograph showing oolith	122
5.11	Photomicrograph showing random sections in skeletal grains	124
5.12	Photomicrograph showing abundant phosphorite pellets and bone lathes	124
5.13	Photomicrograph showing sharply angular quartz grains	126
5.14	Photomicrograph showing phosphorite pellet with a cortex of hyaline apatite	126
5.15	Photomicrograph showing large coprolith with cracks	127
5.16	Photomicrograph showing coprolith with phosphatized nucleus	127
5.17	Photomicrograph showing random sections in fish tooth, coprolith	128
5.18	Photomicrograph showing random sections in sponge spicule	128
5.19	Photomicrograph showing phosphatized planktonic foraminifer	129

5.20 Photomicrograph showing random sections in phosphorite pellets	129
6.1 The apatite mineral series. After, Simpson (1972)	132
6.2 Distribution of the mineral apatite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	140
6.3 Three-Dimensional view for the apatite content in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	141
6.4 Distribution of the mineral apatite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	142
6.5 Three-Dimensional view for the apatite content in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	143
6.6 Distribution of the mineral calcite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	144
6.7 Three-Dimensional view for the calcite content in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	145
6.8 Distribution of the mineral calcite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	146
6.9 Three-Dimensional view for the calcite content in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	147
6.10 Distribution of the mineral dolomite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	148
6.11 Three-Dimensional view for the dolomite content in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	149
6.12 Distribution of the mineral dolomite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	150
6.13 Three-Dimensional view for the dolomite content in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	151
6.14 Distribution of the minerals apatite + calcite + dolomite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	152
6.15 Three-Dimensional view for the Apatite + calcite + dolomite	

contents in the Zone 1 Phosphorite of the Hazm Al-Jalamid area	153
6.16 Distribution of the minerals apatite + calcite + dolomite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	154
6.17 Three-Dimensional view for the Apatite + calcite + dolomite contents in the Zone 2 Phosphorite of the Hazm Al-Jalamid area	155
6.18 Binary diagram for phosphorite classification using % apatite and % calcite	162
6.19 Binary diagram for phosphorite classification using % apatite and % dolomite	162
6.20 Binary diagram for phosphorite classification using % apatite and % quartz	163
6.21 Binary diagram for phosphorite classification using % apatite and % chert	163
6.22 Binary diagram for phosphorite classification using % apatite and % clay	164
6.23 Ternary diagram for phosphorite classification using % apatite, % calcite and % dolomite	165
6.24 Ternary diagram for phosphorite classification using % apatite, % calcite and % quartz	166
6.25 Ternary diagram for phosphorite classification using % apatite, % calcite and % chert	167
6.26 Ternary diagram for phosphorite classification using % apatite, % calcite and % clay	168
6.27 Plotting of the Zone 1 Phosphorite of the Hazm Al-Jalamid area on the ternary classification	169
6.28 Plotting of the Zone 2 Phosphorite of the Hazm Al-Jalamid area on the ternary classification	170
6.29 Plotting of the interval Zone in the Hazm Al-Jalamid area on the ternary classification	171
7.1 Electron beam scan photographs of part of phosphorite sample	255
7.2 Electron beam scan photographs of part of phosphorite sample	255
7.3 Electron beam scan photographs of part of phosphorite sample	256

7.4	Electron beam scan photographs of part of phosphorite sample	256
7.5	Electron line scan profiles of part of phosphorite sample	257
7.6	Electron line scan profiles of part of phosphorite sample	258
7.7	Iso-tenor map for the Zone 1 Phosphorite in the Hazm Al-Jalamid area	259
7.8	Isopach map for the Zone 1 Phosphorite in the Hazm Al-Jalamid area	260
7.9	Three-Dimensional view for the P_2O_5 content in the Zone 1 Phosphorite	261
7.10	Three-Dimensional view for the thickness of the Zone 1 Phosphorite	262
7.11	Iso-tenor map for the Zone 2 Phosphorite in the Hazm Al-Jalamid area	263
7.12	Isopach map for the Zone 2 Phosphorite in the Hazm Al-Jalamid area	264
7.13	Three-Dimensional view for the P_2O_5 content in the Zone 2 Phosphorite	265
7.14	Three-Dimensional view for the thickness of the Zone 2 Phosphorite	266
7.15	Relationship between P_2O_5 % and SO_3 % in the Arqah Phosphorite	267
7.16	Relationship between P_2O_5 % and Cl % in the Thaniyat Phosphorite	268
7.17	Relationship between P_2O_5 % and Ti ppm in the Thaniyat Phosphorite	269
7.18	Relationship between P_2O_5 % and Na_2O % in the Thaniyat Phosphorite	270
7.19	Relationship between P_2O_5 % and Sr % in the Thaniyat Phosphorite	271
7.20	Relationship between P_2O_5 % and Cr % in the Arqah Phosphorite	272
7.21	Relationship between P_2O_5 % and F % in the Thaniyat Phosphorite	273
7.22	Relationship between P_2O_5 % and Y ppm in the Arqah Phosphorite	274
7.23	Relationship between P_2O_5 % and CO_2 % in the Arqah Phosphorite	275
7.24	Relationship between P_2O_5 % and SiO_2 % in the Zone 1 Phosphorite	276
7.25	Relationship between P_2O_5 % and SiO_2 % in the Zone 2 Phosphorite	277
7.26	Relationship between P_2O_5 % and SiO_2 % in the Zone 1 Phosphorite	278

7.27 Relationship between P_2O_5 % and F % in the Arqah Phosphorite	279
7.28 Electron line scan profiles of part of phosphorite sample	280
7.29 Relationship between Al_2O_3 % and Fe_2O_3 % in the Zone 2 Phosphorite	281
7.30 Relationship between CaO % and MgO % in the Zone 1 Phosphorite	282
7.31 Relationship between CaO % and MgO % in the Zone 2 Phosphorite	283
7.32 Spot analysis of part of phosphorite sample	284
7.33 Spot analysis of part of phosphorite sample	285
7.34 Relationship between P_2O_5 % and V_2O_5 % in the Zone 1 Phosphorite	286
7.35 PIXE photographs of part of phosphorite sample	287
7.36 PIXE photographs of part of phosphorite sample	287
7.37 PIXE photographs of part of phosphorite sample	288
7.38 Relationship between Cr % and V % in the Arqah Phosphorite	289
7.39 Relationship between P_2O_5 % and MnO % in the Zone 1 Phosphorite	290
7.40 Iso-tenor map for the Zone 1 Phosphorite in the Hazm Al-Jalamid area	291
7.41 Three-Dimensional view for U_3O_8 content in the Zone 1 Phosphorite	292
7.42 Iso-tenor map for the Zone 2 Phosphorite in the Hazm Al-Jalamid area	293
7.43 Three-Dimensional view for U_3O_8 content in the Zone 2 Phosphorite	294
7.44 Relationship between P_2O_5 % and U_3O_8 ppm in the Zone 1 Phosphorite	295
7.45 Relationship between P_2O_5 % and U_3O_8 ppm in the Zone 2 Phosphorite	296
7.46 Relationship between P_2O_5 % and U ppm in the Saudi Arabian	297
7.47 Relationship between P_2O_5 % and Th ppm in the Saudi Arabian	298
7.48 Relationship between P_2O_5 % and radioactive K % in the Saudi Arabian	299

7.49 Relationship between U ppm and Th ppm in the Saudi Arabian	300
7.50 Relationship between U ppm and radioactive K % in the Saudi Arabian	301
7.51 Relationship between Th ppm and radioactive K % in the Saudi Arabian	302
8.1 Distribution of major sedimentary phosphorite deposits	304
8.2 Distribution of sedimentary phosphorite deposits and occurrences	305
8.3 Surface currents in an idealized ocean	330
8.4 Iso-tenor map for the Zone 3 Phosphorite in the Hazm Al-Jalamid area based on P_2O_5 %.	357

LIST OF TABLES

TABLE	Page
1.1 Phosphoritic intervals in the Paleocene-Eocene succession in the Wadi Sirhan-Turayf basin	10
1.2 General lithostratigraphic subdivision of the Late Cretaceous-Early Paleogene succession in the Wadi Sirhan-Turayf basin	25
1.3 Most suitable phosphorites for use as feedstock	33
1.4 Sirhan-Turayf Phosphorite deposits : Composite samples for Characterization, Beneficiation and Suitability testwork	33
1.5 Normative Mineralogy (wt. %) of composite samples A to E	34
1.6 Results of beneficiation of phosphorite deposits by the process : calcination-slaking-wet grinding-classification	36
3.1 Late Cretaceous-Early Paleogene geochronologic units adopted in the present work	69
3.2 Correlation of the Aruma Group succession in the Arabian Peninsula and surrounding regions	75
3.3 General lithostratigraphic subdivision of the Late Cretaceous-Early Paleogene succession in the Sirhan-Turayf basin	81
6.1 Mineralogical Composition of the Zone 1 Phosphorite	137
6.2 Mineralogical Composition of the Zone 2 Phosphorite	138
6.3 Mineralogical Composition of the Interval Zone	139
6.4 Proposed Classification and Nomenclature for the Phosphorite Deposits	160
7.1 Chemical Composition of the Zone 1 Phosphorite (Hazm Al-Jalamid area)	205
7.2 Chemical Composition of the Zone 2 Phosphorite (Hazm Al-Jalamid area)	215
7.3 Chemical Composition of the Interval Zone (Hazm Al-Jalamid area)	223

7.4	Chemical Composition of the Zone 1 Phosphorite (Thaniyat Turayf area)	231
7.5	Chemical Composition of the Zone 2 Phosphorite from the Drill Hole (P.11)	232
7.6	Chemical Composition of the Zone 5 Phosphorite from the Drill Hole (P.1)	233
7.7	Chemical Composition of the Arqah Phosphorite Member (Umm Wu'aal North area)	234
7.8	Chemical Composition of the Arqah Phosphorite Member (Al-Amud area)	236
7.9	Chemical Composition of the Thaniyat Phosphorite Member (Southwestern area)	237
7.10	Chemical Composition of the Thaniyat Phosphorite Member (Hazm Al-Jalamid area)	238
7.11	Microprobe analysis for a phosphorite thin section (P1-8) from Drill Hole (P1), Turayf area	240
7.12	Microprobe analysis for a phosphorite thin section (P11-98) from Drill Hole (P11), Turayf area	241
7.13	Microprobe analysis for a phosphorite thin section (S-3) from West Bardawil anticline	242
7.14	Microprobe analysis for a phosphorite thin section (W-1) from 60 Km East Turaf area	243
7.15	Microprobe analysis for a phosphorite thin section (P1-6) from Drill Hole (P1), Turayf area	244
7.16	Microprobe analysis for a phosphorite thin section (S-5) from West Bardawil Anticline	245
7.17	Microprobe analysis for a phosphorite thin section (S-33) from East Khawr Umm Wu'aal	247
7.18	Microprobe analysis for a phosphorite thin section (S-35) from East Khawr Umm Wu'aal	249
7.19	Average Microprobe analysis of eight phosphorite thin sections from Northwestern Saudi Arabia	250
7.20	PIXE analysis for a phosphorite thin section	

(S-33) from East Khawr Umm Wu'aal	251
7.21 PIXE analysis for a phosphorite thin section (P1-6) from Drill Hole (P1). Turayf area	252
7.22 Natural Radioactivity analysis for selected phosphorite samples from Northwestern Saudi Arabia	253

خلاصة الرسالة

اسم الطالب	:	وائل سعيد علي مطر
عنوان الدراسة	:	جيولوجية الرسوبيات الفوسفاتية في صخور الباليوجين المبكر بشمال غرب المملكة العربية السعودية
التخصص	:	جيولوجيا
تاريخ الشهادة	:	٨ يونيو ١٩٩٦ م

اكتشفت رسوبيات فوسفاتية في تتابع حقبية الباليوجين المبكر في شمال غرب المملكة العربية السعودية، في عام ١٩٦٥، وقد تم دراسة التتابع الطبقي والمحتوى الاحفوري والسحني الدقيق لهذه الرسوبيات، الا أنه لم تجر أية محاولة تفصيلية لدراسة التركيب المعدني للخام ولا للعناصر النادرة الموجودة فيه ولا لخصائصه الجيوكيميائية، ولم يتم بعد مناقشة منشأ الخام، كما لم توضع أية طرق عملية لتصنيف درجاته المختلفة .

يتكون الخام بصورة رئيسية من معدن الأباتيت دقيق التبلور (بمتوسط ٤٦.٣٥٪)، والدونوميت (بمتوسط ٣٦.٦٩٪)، والكالسيت (بمتوسط ١٣.١٤٪) وكميات وافرة من العناصر النادرة مثل اليورانيم (الذي تصل نسبته حتى ٣٠٠ جزء في المليون) والفاناديوم (والذي تصل نسبته حتى ٣٠٠٠ جزء في المليون)، ومثل هذه القيم المرتفعة نسبياً يمكن أن تضمن استغلالاً اقتصادياً للخام ليس فقط لمحتواه من معادن الفوسفات ولكن أيضاً لوجود هذه العناصر النادرة والتي يمكن أن تبرز بمفردها استغلاله الاقتصادي.

وقد تم تصنيف رسوبيات الخام على أشكال ثنائية وثلاثية عند ثلاث نقاط حدية هي ١٨٪، ٨٪، ١٪ من خامس أكسيد الفوسفور والتي تفصل صخور الفوسفات عن الصخور الفوسفاتية وصخور قليلة الفوسفور على الترتيب ، أما القيم الأقل عن ١٪ من خامس أكسيد الفوسفور فقد أهملت.

كذلك أوضحت التحاليل التفصيلية للتكوين المعدني والصخري والجيوكيميائي للخام بالإضافة لعلاقاته الطبقة أن له أصلاً كيميائياً حيوياً تم ترسيبه في رصيف قاري محدود جزئياً. ولقد هيئ هذا التحديد الجزئي بواسطة عدد كبير من النتوءات والقيعان الأرضية التي كانت نشطة بصورة ملحوظة قبل ترسيب خام الفوسفوريت، وبالتالي وفرت التشكيل اللازم لقاع البحر لترسيب هذا الخام.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

يونيو ١٩٩٦

THESIS ABSTRACT

NAME OF STUDENT **Wael Saied Ali Matter**

**Geology OF THE Early Paleogene
Phosphorite Deposits OF Northwestern
Saudi Arabia.**

MAJOR FIELD **GEOLOGY**

DATE OF DEGREE **JUNE, 8, 1996**

Economic phosphorite deposits were discovered in the Early-Paleogene succession of northwestern Saudi Arabia in 1965. The stratigraphy, micropaleontology and microfacies analyses of the succession have already been carried out, but no attempt has yet been made to study the mineralogical composition of the ore, its trace elements and geochemical characteristics in any detail, or to discuss its origin or provide a practical means for classifying its various grades.

The ore is mainly composed of microcrystalline apatite (with an average of 46.35 %), dolomite (with an average of 36.69 %) and calcite (averaging 13.14 %) and abundant trace elements, such as uranium (up to 300 ppm) and vanadium (up to 3000 ppm). Other than its rich phosphorous content, such relatively high values of trace elements can warrant the exploitation of the ore which can alone justify its economic exploitation.

A practical classification for the phosphorite deposits in both binary and ternary diagrams was attempted, with three cut points at 18 % , 8 % and 1 % P_2O_5 , separating phosphorites from phosphoritic and slightly phosphoritic rocks, respectively. Values below 1 % P_2O_5 were ignored.

The detailed mineralogical, petrographical and geochemical analyses of the ore as well as its stratigraphical relationships suggest a biochemical origin, in a partially restricted continental shelf. Such partial restriction was mainly provided by a large number of swells and basins that were apparently active prior to the deposition of the phosphorite sequence, and hence provided the necessary configuration of the sea-bottom for the deposition of the ore.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

JUNE, 1996

CHAPTER ONE

INTRODUCTION

Phosphorus is an element vital for human, animal and plant growth, and hence, is used in many pharmaceutical products, animal foodstuff and fertilizers. It is also used in the manufacturing of phosphorus bombs, insecticides, phosphoric acid and many other phosphorus compounds such as the superphosphate and diammonium phosphate. The main raw materials for phosphorus and its compounds are the diversified sedimentary phosphorite deposits, which contain minerals of the apatite (calcium fluorophosphate) group in appreciable quantities. although both guano and apatite-rich igneous rocks can also be considered as natural sources.

Trace elements commonly associated with sedimentary phosphorite deposits include Uranium (U), Vanadium (V), Thorium (Th) and a number of the Rare Earth Elements (REE). These can be extracted from the phosphorite solution during the process of acidulation which precedes the production of phosphoric acid, phosphorus, or many of its compounds such as the superphosphate.

Phosphorite deposits were first recorded in Saudi Arabia by Sheldon (1965), in cuttings from water wells drilled by ARAMCO close to the Tapline. A following

reconnaissance and drilling program established the potential for substantial resources in the both the Turayf and the Thaniyat Turayf areas (Mineral Resources of Saudi Arabia, 1994). Since that time exploration continued and a regional assessment was undertaken over the whole of the Wadi Sirhan-Turayf region by many companies such as the BRGM, Riofinex, and the USGS mission.

Geologic reconnaissance maps for an area more than 100,000 km² were prepared, exploration holes were drilled, tunnels were dug, and both surface and subsurface samples were collected and analyzed.

The results of these geologic studies together with a feasibility study were completed in 1992 and indicate the presence of a huge quantity of a high quality phosphorite deposit in northwestern Saudi Arabia (Mineral Resources of Saudi Arabia, 1994). A significant resource, by world standards, is present which comprises identified resources totaling 7800 million tons at 19.7 % P₂O₅, which include a demonstrated resource of 1200 million tons at 20.3 % P₂O₅, in turn made up of an indicated resource of 890 million tons at 19 % P₂O₅ and a reserve base of 310 million tons at 23.07 % P₂O₅. The regional mineral endowment, which involves no economic criteria, is a measure of total quantity of phosphorite that may be present in the region in such a form that it could possibly be extracted in the future, and is estimated to be 140000 million tons at 15.9 % P₂O₅ (cf. Riddler & others, 1986).

These deposits have been mapped and studied from the stratigraphical point of view, but no trace element analysis, genesis, diagenesis or classification has yet been attempted. Consequently, the present work is proposed to fill an existing gap in our knowledge of such an important deposit.

1.1 Location and Geological Setting :

The Sirhan-Turayf basin is part of a large phosphorite-bearing sedimentary region that extends into Palestine, Jordan, southern Iraq and Syria (fig. 1.1). It lies in the northwestern part of Saudi Arabia between latitudes 29° 00 and 32° 00 N and longitudes 36° 30' and 41° 00 E. covering an area of approximately 107,000 km². This vast region has been subdivided into eight broad phosphorite areas, namely, the Umm Wu'aal North and South, Jalamid, Ar'ar North, Shuwayhitiyah, Quraymiz, Al Amud and the Southwestern phosphorite area (fig. 1.2).

Access to the region is good, paved highways link all the towns southeastward to the Arabian Gulf, westward to Jordan, and southwestward to Dhiba on the Red sea coast via Al Qalibah and Tabuk.

1.2 Physiography :

The Sirhan-Turayf region consists of six quite distinct physiographical units (fig. 1.2) as follows :

a. The Al Hamad Plain :

A vast, relatively featureless, undulating stony desert plain with elevations between 700 m and 900 m above sea level. It stretches southwards from central Syria to constitute the northern and eastern parts of the region. Within the Al Hamad is the narrow, north-northwesterly trending depression of the Khawr Umm Wu'aal. The eastern edge of the Al Hamad plain is progressively being destroyed by erosion that

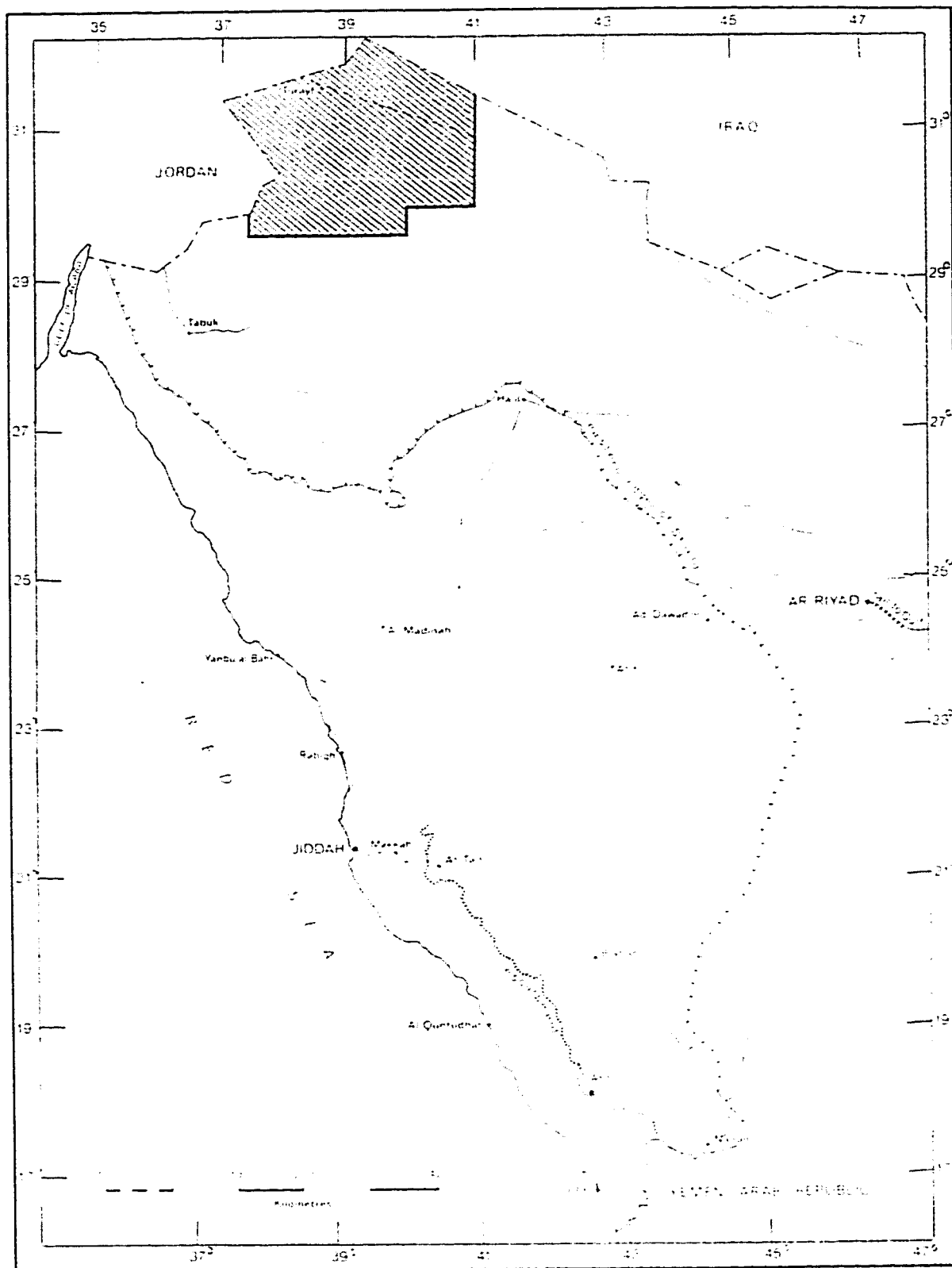


Fig. 1.1 : Location map of the Wadi Sirhan-Turayf basin.

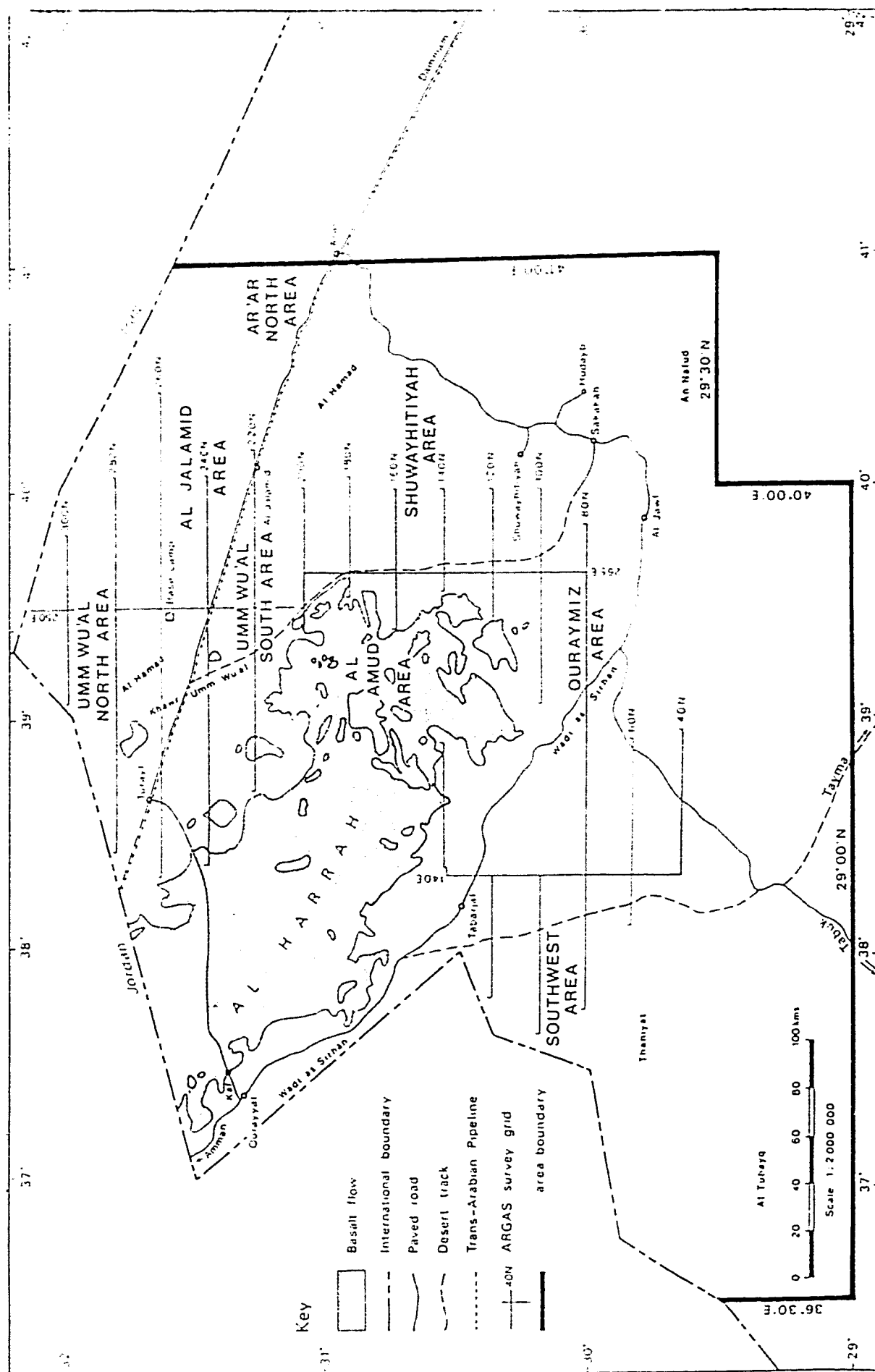


Fig. 1.2 : Phosphorite areas in the Wadi Sirhan-Turayf basin.

forms deep, meandering valleys flanked by table-like remnants of the old plain. Major valleys drain east or northeast, and some minor valleys drain into the Khawr Umm Wu'aal.

b. The Al Harrah Basalt :

It is a part of an enormous basalt plateau that stretches unbroken from the Dead Sea Rift Valley in Jordan, to near Al Jawf, and from w. as-Sirhan on the west to Khawr Umm Wu'aal on the east, forming the southwesterly boundary to the Al Hamad plain. Elevations in Al-Harrah range between 700 m above sea-level to about 1100 m on some basalt peaks.

c. The Wadi as Sirhan and its flood plain area :

It is a north-westerly trending depression comprising a stony plain of low relief, rarely exceeding 550 m in elevation. It separates Al Harrah from Al-Busayta or the Thaniyat Turayf plateau.

d. The Thaniyat Turayf Plateau :

It is a rugged area to the southwest consisting of deeply dissected carbonate rocks with elevations of 700 to 1100 m above sea level.

e. At-Tubayq area :

It is a region of parallel ridges and valleys that delimit the Thaniyat Turayf plateau on the west. Its southern margin is delineated by an escarpment, about 100 m high.

f. The Mughayra Sandstone Plain :

It is a low, flat lying plain to the southwestern part of the region, with abundant irregularly shaped monadnocks of sandstone. It is separated from At-Tubayq by a ridge about 100 m high.

To the south and southwest, the sand dunes of An Nafud cover the region forming an effective barrier, which begins just south of Sakakah and Al Jawf. These dunes fill a major depression that is centered along a line connecting Al Jawf and Al-Qurayyat.

1.3 Climate, Precipitation and Vegetation :

In general, the climatic conditions of the Sirhan-Turayf area can be described as arid-continental. Hot, dry summers (April to November) that normally have cool nights due to the altitude, alternate with cold, relatively wet winters with temperatures frequently below freezing point. Summer day-time temperatures vary between 35°C and 45°C and the average annual temperature is around 20°C (cf. Torrent, 1975).

High winds, that often develop into sandstorms, blow principally between November and May, the prevailing direction being from the west.

Precipitation, almost all in the form of rain fall (though hail storms, and even snow are not unknown in the area) reflects the desert conditions. The regional average annual rainfall is about 61 mm, with a range between 42 mm at Tabarjal and 89 mm at Jalamid. The months of June to September normally are completely dry with pluvial maximal occurring in November, January and March-April (cf. Torrent, *op. cit.*). Evaporation rates reach 2000 mm per year.

The desert climate of the area has its great effect on flora and fauna. During much of the year vegetation is sparse, mainly scattered low bushes. but in winter months a more abundant flora is evident, particularly in rain-filled depressions and along wadi courses.

1.4 Water in the region :

Water in the region is an important factor for both population life and industrial purposes including future mining activities. In the Wadi as Sirhan area, water in near-surface aquifers is in quantities sufficient for agriculture, but, it is unknown whether such shallow aquifers can stand industrial drawdown. In the Al Hamad, wells around Ar'ar, Al Jalamid and Turayf yield brackish water from depths below 200 m, and are adequate to meet the demands of the present population. For industrial use such as the processing of the phosphorite ore tapping deeper aquifers, at depths down to 1500 m or more may deem necessary.

A number of deep water wells have been drilled in the region, gravity and magneto-telluric surveys have been conducted and water level contour maps of the saq aquifer, south of Al Jawf, have been constructed, but the feasibility of using such fossil ground water in the Sirhan-Turayf region for industrial purposes is not yet clear.

1.5 History of discovery and Exploration :

Phosphorite deposits were first discovered in Saudi Arabia from cuttings of water wells drilled in the Turayf area 1965 (cf. Sheldon 1967). From October 19 to December 11, 1965, Mytton, mapped the surface extent of the Turayf phosphorite deposits and discovered the Thaniyat occurrence, 250 km to the southwest of Turayf (cf. Mytton,

1966). A subsequent 3-year reconnaissance and drilling program by the USGS then established the potential for substantial resources in both the Turayf and the Thaniyat Turayf areas.

Exploration under license was resumed in 1977 at the Thaniyat Turayf area by Granges International Mining in conjunction with Petromin and continued until 1979. The results of field work and bench testing were used to produce a major study (cf. Granges, 1980), but the partners withdrew because mining of the deposit appeared commercially unattractive.

Riofinex (1977), began a resource evaluation of the whole Sirhan-Turayf region at the request of the DMMR then the DGMR. The first task was to prepare geologic reconnaissance maps of an area greater than 100,000 km². Because of the subdued topography and the poor rock outcrop, geologic mapping and sampling was supplemented by drilling, trenching, geochemical and radiometric surveys, and a lithostratigraphic succession was built up with the aid of sedimentological and paleontological studies.

This regional evaluation identified five phosphoritic intervals in the Paleocene to Eocene succession (table 1.1), of which only those at the base of the Umm Wu'aal and Jalamid Formations appear to be economically important. The work also helped in the better understanding of the two phosphorite areas discovered earlier (Turayf, now known as Umm Wu'aal, and Thaniyat Turayf) and led to the discovery of four more phosphorite areas, at Al Amud, Quraymiz, Al Jalamid, and Ar'ar North.

Riofinex (1980-1985), started exploration of the Umm Wu'aal phosphorite area, as this was the most promising at the time. This work resulted in reconnaissance geologic mapping, followed by 1 : 100,000 scale and 1 : 40,000 scale maps.

Table 1.1 : Phosphoritic Intervals in the Paleocene-Eocene succession in the Sirhan Turayf basin.

Age	Group	Formation	Phosphorite Member	Phosphorite areas
Neogene		(baslt)		
Miocene	Sirhan Group	(in grabens)		
Eocene	Hibr Group	Umm Wu'aal Formation	Arqah Phosphorite Member 2-27 m	Umm Wu'aal Al Amud
		Turayf Formation	Minor phosphoritic unit at top of Sib Member	Umm Wu'aal* Al Amud* Quraymiz*
Paleocene			Hibr Group	Ghinah Phosphorite Member 5-26 m
		Hazm Al-Jalamid Formation		Thaniyat Phosphorite Member 0-40 m
Upper Cretaceous	Aruma Group	Ar'ar Formation	Contains some minor phosphorite beds	
*Phosphorite in theses areas probably have no development potential				

Riofinex (1984-1986) started evaluation of the Al Jalamid area after its discovery in 1984, where a total of 305 holes were drilled.

Farasani and Dini (1988) discovered the As-Sanam phosphorite deposits. The area has not yet been explored in detail, but reconnaissance mapping, drilling and trenching has indicated resources of 70 million tons.

The USGS and Jacobs International (1988-1989), resumed Investigation at al Jalamid, and produced a preliminary feasibility study in 1989, which showed measured reserves of 213 million tons.

During the period 1990-1992, three exploration shafts were sunk through the upper ore horizon, percussion drilling of the area surrounding Al Jalamid was carried out, three deep water wells were drilled and a new feasibility study was prepared (1992).

1.6 Previous Studies :

The Arabian American Oil Company (ARAMCO, 1952 *a,b*) produced gravimetric contour maps covering most of the Sirhan-Turayf region except for the Al-Harrah basalts. ARAMCO also drilled the "S series" of exploration holes, and later on, cuttings from some of these wells helped on the discovery of phosphorite deposits in Saudi Arabia.

A German Geological Mission (1961-1965) mapped prospective phosphorite areas in Jordan, which included the Late Cretaceous phosphorite 15 km east of Kilwe, on the Thaniyat escarpment (cf. Bender, 1974).

Bramkamp and others (1963 *a,b*) mapped the region at the 1 : 500,000 scale, where Late Cretaceous rocks were included under the name Aruma Formation (Ka) and

undifferentiated Paleocene-Eocene limestone and chert (Tic) were informally called the Hibr Formation¹.

Sheldon (1964), following Kazakov (1937) proposed that phosphorites formed as a result of direct inorganic precipitation of apatite, from ascending phosphorus-rich deep ocean waters. Such a hypothesis was later amplified by many workers leading to the recognition of several phosphoritic provinces around the globe. Sheldon (*op. cit.*) suggested the name "Mediterranean phosphogenic province" to include Late Cretaceous-Early Paleogene phosphorite rocks extending from Morocco to Iraq, and expected their presence in the northern part of Saudi Arabia. He visited the Directorate General Of Mineral Resources (DGMR) in August 1965 and studied some well logs, cuttings and geologic reports where his expectations came true. During this visit, Sheldon made an excursion to the Turayf area and discovered phosphorite rocks within the Paleocene-Eocene Hibr strata about 70 km to the east of Turayf town (cf. Sheldon, 1967). Sheldon (*op. cit.*) described the Hibr strata to be "a crude cyclical sequence" in which each cycle consists of sandy limestone, chert, phosphorite rock, marl, phosphorite rock, chert, and sandy limestone.

Mytton (1966 *a,b*), traced out the surface extent of the Turayf phosphorite and discovered similar deposits in both the Thaniyat Turayf and the Quraymiz areas. He recognized 3 informal members within the Hibr Formation as follows : Lower Hibr Member, Middle Phosphate Member and Upper Hibr Member. Mytton (*op. cit.*) recognized two phosphorite zones within the phosphate member : a Lower phosphorite

¹ The informal name "Hibr Formation" was originally given by Berg, E. and Owens L.D. in 1964

zone with an average thickness of 33.5 m and an upper zone with an average thickness of 15.2 m.

Cathcart (1966-1968), studied and described the petrographical and the chemical analyses of 100 phosphorite rock samples from the Mytton's collection. About 90 percent of the Turayf samples were of the hard, calcareous or siliceous phosphorite (due to the surface leaching of the flat-lying rocks in the Turayf plain), while Thaniyat Turayf samples were soft and friable.

Cathcart (*op. cit.*) concluded that it would be possible to produce superphosphate or triple superphosphate from the calcareous and siliceous phosphorite rock, but the cost probably would be excessive. He believed that the unconsolidated phosphorite was the most promising because it was easily upgraded and might be economic, provided the tonnage's were large enough and the beds were accessible.

Mytton (1966 *a.b*) and Sheldon (1967), proved the possibility of finding pods or lentils of friable phosphorite in the subsurface at Turayf by the detection of loose phosphorite pellets in sample cuttings from test holes previously drilled by ARAMCO.

Powers and others (1966) briefly described the geology of the region in their coverage of the sedimentary rocks of Saudi Arabia. They summarized the stratigraphy of the area, and recognized, at Khashm Zallum, a 61 m-thick sandstone succession overlying an 11 m-thick basal Aruma Limestone unit, which they called, the "Zallum sandstone facies". The Paleocene-Eocene Hibr Formation was presumed to be a Mediterranean facies, deposited in a sea way not directly connected with the Arabian Gulf basin and at

(unpublished report) as mentioned by both Powers and others (1966) and Powers (1968).

least partly equivalent to the Umm-er-Radhuma and overlying Rus and Dammam Formations.

The DGMR commissioned the United State Geological Survey (USGS) to investigate the phosphorite potential of the Turayf and the Thaniyat Turayf areas during the period 1966-1968. (USGS follow-up work). Drill-hole data from wells previously drilled by ARAMCO (S series) and the Trans-Arabian Pipeline were collected and studied. Following this, fifty two cored holes (TA through TE series) in the Turayf discovery area were drilled (cf. Meissner & Ankary, 1972).

Similar work, but on a much smaller scale, was carried out over the Thaniyat Turayf phosphorite area, where, six cored holes (WT-series) were drilled and a 25 m long adit was driven into the phosphorite beds at the locality designated " west Thaniyat". in

Mineral processing testwork was carried out in conjunction with this program by the Tennessee Valley Authority (TVA) on the west Thaniyat material and by Cerphos and the United State Bureau of Mines (USBM) on the Turayf phosphorites. The results of this work were reported by Meissner (1967) and Meissner and Ankary (1972).

Meissner (1967), found better phosphorite rocks to the west of the Thaniyat Turayf area (bed 2), which he named the West Thaniyat area (this is now classified as part of the Thaniyat phosphorite member of the Jalamid formation). Meissner (*op. cit.*) differed from Mytton (1966 *b*) in considering the lowest phosphorite horizon in the Thaniyat Turayf area to represent the top of the Cretaceous (Late Cretaceous), not the base of Paleogene.

Meissner and Ankary (1972), recognized five phosphorite zones (each zone consisting of several phosphorite units) which they numbered 1-5 from top to bottom.

Following the subdivisions of the Hibr formation proposed by Mytton (1966 a). These authors (*op. cit.*) placed zone-5 at the top of the Aruma Formation , zone-4 near the top of the lower one third of the Lower Hibr Member and zones-3, -2, and -1 within Mytton's Middle Phosphatic Hibr Member of the Hibr Formation.

Meissner and Ankary (*op. cit.*) estimated the phosphorite reserves in the West Thaniyat locality to be approximately 190 million tons, with an average grade of 23 % P_2O_5 , an average thickness of 1.65 m, covering an area of about 50 km² and with specific gravity of a 2.3 gm / cm³. Beneficiation testwork on this phosphorite, indicated a clay content that could adversely affect its use (cf. Riddler & others, 1986).

Regarding the phosphorite potential of the " Turayf area", (now called the Umm Wu'aal area) Meissner and Ankary (*op. cit.*) gave an estimate of 722 million tons of phosphorite, with an overall average grade of 18 % P_2O_5 , an aggregated thickness of phosphorite beds of 4 m and with a specific gravity of 2.3, underlying a circular area of 78.5 km² designated the "Turayf Select area".

Beneficiation testwork by CERPHOS and USBM gave different results, but indicated that calcination could provide a marketable product, whereas physical beneficiation methods proved to be inadequate (cf. Riddler & others, 1986).

El-Khayal (1974) studied cutting samples from the Hibr formation penetrated by the ARAMCO water well WW 6-2 which had been drilled in the Turayf town. He stated that the Hibr Strata are of Early Paleocene (Danian) to Early Middle Eocene (Early Lutetian) age.

Slansky (1974), visited the "West Thaniyat locality" and the "Turayf Selected area" for the BRGM and compared it with similar deposits in both Senegal and Morocco.

He concluded that the relatively low grade of the ore and its vast distance from the coast, and the irregularity of its beds in case of "Turayf Select area" are not favorable factors and would adversely affect the exploitation potential of the deposit.

Torrent (1975), mentioned that shallow aquifers in the region cannot face the need for water in the case of establishing a phosphorite beneficiation plant, and hence he advised resorting to deep aquifers in the region.

Granges International Mining in conjunction with Petromin (1977-1981) explored the "West Thaniyat Turayf" locality and its surrounding area under an exploration license for exploitable phosphorite deposit. The results of this work were collected in a comprehensive report (cf. Granges, 1980), with the following main conclusions :

- a. There are two discrete phosphorite deposits : (1) A Western Deposit², at the western end of the Thaniyat Turayf Escarpment (or the "West Thaniyat" deposit of Meissner and Ankary, 1972) with an estimated "reserve" of 123 million tons at an average grade of 20.6 % P_2O_5 and a thickness of 1 to 5 m, covering an area of 46 km². and (2) an Eastern deposit, at the eastern end of the Thaniyat escarpment, with an estimated reserve of 34 million tons at an average grade of 24 % P_2O_5 , an arbitrary value of 1.8 was used for the specific gravity in the tonnage estimate,
- b. The grade and thickness of the main phosphorite layers improve towards the northeast; whereas to the northwest, the incoming of progressively more interbedded non-phosphoritic rock decreases the overall grade,

- c. Clay (in NNE-trending belts) and carbonate (scattered through the area) could adversely affect the beneficiation process (cf. Berge & Jack, 1982). Calcination, however, followed by grinding and flotation based on pilot scale tests, could produce high quality ore.
- d. The main phosphorite mineral is apatite.

In view of the high cost of the underground mining method proposed, the cost of overcoming beneficiation problems, infrastructure costs, water supply problems and the low, prevailing world market price of phosphorite at the time, Granges International concluded that, the economics of such a mining project in the short- and medium- term looked uneconomic, and this license area was abandoned in 1980.

Riofinex (1977-1986), began a resource evaluation of the Sirhan-Turayf area at the request of the DMMR (then the DGMR), with the following objectives :

- a. To assess the resource potential for phosphorite deposits in the Sirhan-Turayf area,
- b. To establish the stratigraphic intervals in which the phosphorite occurs throughout the region, noting depositional patterns and / or structural controls affecting the phosphorite accumulations and to identify, as a result, those areas most favorable for phosphorite deposits,
- c. To establish the regional distribution of the phosphorite deposits.

² Meissner and Ankary (1972) report 190 million tones over 50 km, with a thickness of 1.65 m and a specific gravity of 2.3 from the same area.

- d To identify areas of possible phosphorite mining potential with regard to overburden features, thickness, grade and beneficiation characteristics of the phosphorite.
- e. To prepare geologic reconnaissance maps to the scale of 1 : 250.000 for an area greater than 100.000 km².

After the discovery of Al Jalamid phosphorite deposits, the following objectives were also added :

- a. To outline potential areas of commercially exploitable phosphorite deposits,
- b To classify the resources and reserves of the phosphorite deposits based on the USGS / USBM resource classification system,
- c To optimize the drillhole spacing for the purpose of resource and / or reserve evaluation (cf. Smith, M., 1976; Riofinex, 1977 *a*; Collenette, 1977; Deputy Ministry for Mineral Resources, 1981, 1982, 1983, 1984, 1985, 1986).

The resource assessment of the Sirhan-Turayf region was completed in a systematic manner. The combination of mainly geochemical surface sampling, regional geological mapping, trenching and pitting and air-flush core and percussion drilling, supplemented by topographic surveying, stratigraphical, sedimentological, and petrographical studies, downhole geophysics and bench-scale beneficiation testwork, have been used to complete the resource assessment of the region.

Soil geochemistry, using anomalous phosphorite, proved to be very effective, reflecting all the localities now known to have significant near-surface phosphorite accumulations. A trenching program to follow-up geochemical soil survey was done. Trenches were usually 3-4 m long and up to 2 m deep. Phosphorite values up to 33.3 %

P₂O₅ were recorded at locality 285 N / 208 E, at depths of between 110 cm and 200 cm (cf. Riofinex, 1983) which reflect the presence of subcropping phosphorite (Arqah Phosphorite Member).

Regional geological reconnaissance led to the discovery of extensive phosphorite-bearing beds in the region, away from the previously established localities near Turayf and Thaniyat Turayf.

Geological mapping for over 107,000 km² of the region was completed, with a total of 69 geological maps at 1 : 50,000 scale, 16 at 1 : 100,000 scale, 2 at 1 : 250,000 scale and 1 at 1 : 500,000.

Drilling has played a major role in the exploration for and evaluation of the phosphorite deposits in the region, due to the general lack of good outcrops, the repetitive nature of the carbonate succession and the flat lying attitude of the beds. Five major drilling programs were completed totaling 681 drill holes and comprising 6474 meters of coring, 24,819 meters of rotary down-the-hole hammer percussion drilling, and 98 meters of reverse circulation percussion drilling (cf. Riddler & others, 1986).

The Riofinex Geological Mission also carried out biostratigraphical and sedimentary petrographical studies, together with chemical analysis on cores, percussion chips and surface samples. The results were incorporated in a series of "Open file Reports" and two "Technical Records".

Robertson Research International Ltd., was commissioned by Riofinex to carry out project review, followed by a series of studies on literature, and on selected core, cutting and surface samples. (This resulted in a series of reports by Pritchard, 1978; Cater, 1978; Cater and others, 1978; Bruinsma and others, 1978; Futyan, 1979; Futyan

and Nicholson, 1979; Futyan and others, 1979; Futyan, 1980 *a,b*. and by Futyan and Nicholson, 1980 *a, b*). The results of this review work can be summarized as follows :

- a. The phosphorite-bearing deposits in the Umm Wu'aal work area (the Arqah Phosphorite Member) are of middle Eocene age,
- b. The phosphorite at West Thaniyat (the Thaniyat Phosphorite Member) is not middle Eocene in age as it was initially dated. Three major phosphorite zones were later recognized in the strata of the Sirhan-Turayf region of Eocene, Paleocene and Late Cretaceous age, along with other minor intermediate, regionally persistent, phosphoritic rock beds,
- c. Extensive lithofacies unit continuity was questioned,
- d. Sedimentologically, twelve microfacies types were recognized, namely; calcareous phosphorite, siliceous phosphorite, shale, sandstone, chert, dolomite, silicified limestone, coquina, sparite, microsparite, biomicrosparite and micaceous sparite,
- e. The Cretaceous- Paleogene boundary, as drawn by Bramkamp and others (1963, *b*) is incorrect and rocks of the Middle Eocene age crop out much further east than was originally thought,
- f. The eastern limit of deposition during the Late Cretaceous-Early Paleogene time delimited by a tectonic axis known as the Ha'il arch, the position of which was further west in earlier times,
- g. The Sirhan-Turayf region represents the eastern limit of an extensive Late Cretaceous-Early Paleogene phosphorite belt extending from Morocco to Iraq, along what was the southern edge of the Tethys Sea,

- h. The Late Cretaceous phosphorite deposits of Egypt, Palestine, Jordan, Syria and Iraq are commercially exploited, while the Paleogene phosphorites, except for those of Middle Eocene age found in Morocco and Iraq, tend to be low grade.

Futyan and others (1979) using sedimentological and biostratigraphical techniques, examined cuttings from 13 ARAMCO wells and 148 Riofinex field samples and produced a basic stratigraphic table for the Late Cretaceous-Paleogene units of the area as follows :

- a. Paleogene and Neogene basalts,
- b. Paleogene-Neogene limestones and sandstones,
- c. Paleogene limestones, chert, dolomites, marls, and phosphoritic rocks (zones 1, 2 and 3 phosphorites from top to bottom).

Zone 1 Phosphorite, is associated with the limestone, chert unit and is of middle Eocene age,

Zone 2 Phosphorite, is associated with the Middle Eocene dolomite-chert unit, having only limited distribution,

Zone 3 Phosphorite, is associated with dolomites, marls and cherts of Late Paleocene to Early Eocene age,
- d. Cretaceous sandstones, shales, dolomites, limestones, and phosphoritic rocks (zone 4 phosphorite). These phosphoritic rocks are associated with dolomites, cherts and shales and are considered to be of Maastrichtian age,
- e. Triassic sandstones, shales, dolomites and limestones,

f. Paleozoic sandstones and shales.

Kluyver and others (1981). suggested the following informal lithostratigraphic subdivision for the Late Cretaceous-Early Paleogene sequence in the area (from base to top) :

Rock Unit	Thickness (m)
A - Late Cretaceous rocks (Aruma Formation)	
(based mostly on surface information)	
1. Zallum Sandstone unit	0-20
2. Shale-carbonate unit	10-30
3. Bioclastic dolomite unit	2-5
4. Chalky dolomite unit	0.25-10
B - Lower Tertiary succession	
5. Lower Nummulite unit	20-80
6. Silicified limestone and chert unit	80-125
7. Phosphatic lithosome	50-200
8. Middle limestone and chert unit	0-50
9. Upper Nummulite unit	5-20
10. Upper limestone and chert unit	10-> 60

These authors (*op. cit.*) did not use the term : "Hibr Formation", and suggested its redefinition, considering its base as drawn by Meissner and Ankary (1972) to be incorrect. Consequently, this boundary was shifted between 30 to 50 km to the east, on the 1 : 1.250.000 geologic map presented in their report (Kluyver & others, *op. cit.*).

These authors (*op. cit.*) described the Cretaceous-Paleogene sedimentary sequence of the region to comprise four main carbonate cycles (1 - 4 from base to top). Of these, cycles 1 and 2 are of late Senonian / Maastrichtian age, while cycles 3 and 4 are represented by a Nummulitic facies of Early Eocene-Early-Middle Eocene, and Late Middle-Eocene age respectively. Cycles 1-3 are well developed (incorporating phosphorite zones), whereas the cycle 4 is really a composite one of several imperfectly developed cycles, following each other in quick succession. Uplift and erosion prepared the tops of composite facies bodies for sedimentation of the following carbonate cycle. Such a cycle would show a basal development of peloid phosphorite accumulations, similar to basal conglomerates in clastic, non carbonate, sedimentary cycles.

Kluyver and others (*op.cit.*), considered phosphorite deposition to indicate a disconformity at the beginning of each carbonate cycle, and they concluded that the phosphorite zones 1, 2, 3, 4, and 5, introduced by Meissner and Ankary (1972), may have the following distribution :

Phosphorite Zone	Carbonate Cycle	Outcrop Area	Approximate Age
1 - 2	4 (Composite)	Central Area East of Khawr Umm Wu'aal	Late Middle Eocene
3	3	Central SE Area	Early Middle Eocene
4	2	Thaniyat Turayf Area	Late Maastrichtian
5	1	Thaniyat Turayf Area	Late Senonian to Maastrichtian

This subdivision differs essentially from that adopted during the earlier USGS work. In that zones 1 and 2 were regarded as probably being part of a single Eocene sequence.

Kluyver and others (*op. cit.*), indicated that the most interesting cycle in terms of potential economic importance is cycle 4 which is of Middle Eocene age and outcrops close to the Khawr Umm Wu'aal graben. Also of potential economic interest is the cycle 1 carbonate sequence which outcrops in the Thaniyat Turayf area and was considered by them to be of Late Cretaceous age. They, also, considered zone 4 phosphorite (cf. Meissner and Ankary, 1972) to be of Late Maastrichtian age, on the basis of the occurrence of a well dated Late Cretaceous sequence with silicified algal mats, large domal stromatolites, and calcareous phosphoritic layers in the northern region close to the border of Iraq. These lie in a dolomitic sequence, which was dated in the succession penetrated by the p18 well, as well as at the surface, north of Ar'ar.

El-Naggar and others (1981-1985), conducted a stratigraphical analysis for the phosphorite deposits in Northern Saudi Arabia, for the Saudi Arabian National Center for Science and Technology (SANCST). In this study, they summarized the lithostratigraphical classification of the Late Cretaceous-Early Paleogene succession in the area (Table 1.2).

Arabian Chevron reviewed the potential of the Turayf area, without doing any further work (cf. Clegg, 1981).

Bayliss (1981 *a, b*, 1982 *a, b, c*) reviewed and re-examined ditch samples, picked slides and washed residues previously analyzed by Robertson Research International Ltd., and completed additional lithostratigraphic and biostratigraphic studies. The primary

Table 1.2 : General lithostratigraphic subdivision of the Late Cretaceous- Early Paleogene succession in the Wadi Sirhan-Turayf basin proposed by El-Naggar and others (1982).

Undifferentiated Miocene / Pliocene Sediments and / or Pliocene Basalts		
B. The Hibr Group	4. The Turayf Formation (65-80 m) (Late Middle Eocene)	The Turayf Cherty Limestone Member (60 m) The Turayf Phosphate Member (5-20 cm)
	3. The Bardawil Formation (50-250 m) (Early Middle Eocene)	The Bardawil Cherty Limestone Member (0-50 m) The Bardawil Phosphate Member (50-200 m)

	2. The Hazm Al-Jalamid Formation (100-290 m) (Early Eocene)	The Hazm Al-Jalamid Cherty Limestone Member (80-185 m) The Hazm Al-Jalamid Phosphatic Member (20-105 m)

	1. Unnamed Formation (64 m) (Paleocene)	Dolomitic Cherty Marl Member with phosphate beds (27 m) Cherty Marly Limestone Member (37 m)
A. The Aruma Group (or its equivalents) (60 m) Late Cretaceous		Thaniyat Turayf Phosphate (10 m) Khashm Zallum Sandstone (50 m)

objective was to establish a chronostratigraphic framework for the phosphorite beds in the region. The principal conclusions of these studies are as follows :

- a. Well-preserved, identifiable fossils are rare in rocks of all ages in the Sirhan-Turayf region, either due to the restrictive depositional environment, or to destruction of fossils by diagenesis.
- b. Nevertheless, sufficient fossil evidence was accumulated, to establish that, rocks in the region range in age from Late Cretaceous to Middle or even to Late Eocene. This age assignment was reached by using a combination of foraminiferids and ostracods from marls and carbonates and dinoflagellate cysts from claystones,
- c. Based on facies analysis, the main phosphorite accumulations are directly related to major sedimentary breaks and are probably of Paleocene age at West Thaniyat (Thaniyat Phosphorite Member), Late Paleocene at Thaniyat (Ghinah Phosphorite Member) and Middle Eocene north around the Khawr Umm Wu'aal (Arqah Phosphorite Member).

Bayliss (1983) mentioned that, five principal rock groups outcrop in the Sirhan-Turayf region, with two significant phosphorite-bearing units. He recommended that these units should be given formal names. The obvious scarcity of identifiable fossils in the rock units was explained to be due to the original restricted environments over most of the area , which had probably prevented the development of diverse and abundant organisms and also to diagenetic changes, which had altered the carbonates and destroyed the fossils. Carbonate removal by leaching and the substitution of chert and calcite spar for original fabrics has made fossil search extremely difficult.

Bayliss (*op. cit.*) mentioned that the shales associated with the phosphorite in the Thaniyat Turayf area were sampled and studied for fossils, but no evidence for age was found.

Bayliss (1984), did further age-dating studies and concluded Maastrichtian age for both the Thaniyat and the Ghinah Phosphorite Members.

Berge and Jack (1982) published the results of the work of their company on the phosphorite of West Thaniyat Turayf area. This work was mainly concerned with the beneficiation of zone-5 phosphorite, its composition and possible genesis.

Ryder and Kluyver (1983), indicated the presence of at least two other, geologically older carbonate cycles in the sedimentary succession of northern Saudi Arabia and four phosphoritic levels in the Cretaceous and Eocene instead of the five levels previously identified. These authors (*op. cit.*) also compiled the detailed logs and cross sections for all the boreholes previously drilled by the Riofinex Geological Mission in the Sirhan-Turayf basin, numbering from P1 to P86. The cross sections covered the area to the northeast of Wadi Sirhan, only, as the distribution of successful drill holes south of the Wadi did not help to construct cross sections in that area with any confidence.

Notholt (1983) mentioned that, the best developed phosphoritic unit in the Sirhan-Turayf basin occurs within the Middle Eocene carbonate cycle 4 of Kluyver and others, (1981); which crops out along both the Khawr Umm Wu'aal graben and Al-ḥud area. This author (*op. cit.*) also mentioned that the Thaniyat Turayf / Wadi Al-Ghinah area appears to offer considerable phosphorite potential, and that priority should be given to :

- a. The compilation of paleobathymetric, isopachyte, P_2O_5 anomaly and other relevant maps.
- b. A detailed examination of the petrographical, mineralogical and chemical characteristics of the prospective ores.

He (*op. cit.*) presented two appendices, one on the beneficiation of phosphorite rock and the second on a bibliography of phosphorite resources in the Kingdom of Saudi Arabia and neighboring countries.

Riddler and others (1983) assigned all the phosphorite zones in the area to the Paleocene-Eocene, rejected the name Hibr formation and suggested the name Turayf Group to include the Paleocene-Eocene succession in the region. The Turayf Group was proposed to include three main formations (base to top) as follows : the Jalamid, the Mira, and the Umm Wu'aal, further subdivided into different members (12 in total), out of which 3 are phosphoritic, each laying at the base of a carbonate formation. The three phosphoritic member were named as the Thaniyat, Ghinah and Arqah Phosphorite Members (base to top) and were indicated to be of Danian (Early Paleocene), Thanetian (Late Paleocene) and Lutetian (Middle Eocene) age respectively. A Danian age was assigned to the Thaniyat Turayf Phosphate Member on the basis of dinoflagellates. These authors (*op. cit.*) also presented a generalized geologic map for the area, with the locations of the suggested type sections.

Smith (1983) examined the Cretaceous-Tertiary (Paleogene) rocks of the Thaniyat-Turayf-Quraymiz area, and concluded that :

- a. A 3-dimensional facies model is necessary for the geological understanding of the area. Micropaleontological and lithostratigraphical studies can provide a

basis for the model. in which the time dimension should have an important influence.

- b. The phosphoritic horizons occur at the base of transgressive marine cycles,
- c. Chert deposits are useful indicators for phosphoritic rocks. as they formed during a sedimentary hiatus, followed by active sedimentation during which both phosphorite deposition and winnowing take place.
- d Phosphorite Zones 4 and 5 were not observed in the rocks east and south of Thaniyat ar Rilan.
- e. The deposits of Zone 5 phosphorite outlined by the USGS and Granges International Mining have limited potential due to the considerable thickness of overburden. The best potential seems to be associated with near surface occurrences of Zones 4 and 5 in broad flat plains and mature wadi channels. north of the original discovery area,
- f. Stratigraphically the "Zone-5 Phosphorite" is the oldest-known phosphorite rock in the Sirhan-Turayf basin and the correct terminology would, therefor be "Zone-1 Phosphorite rock". To avoid confusion, he decided to retain the old usage until a new name is introduced when the total stratigraphy of the basin is revised.
- g. Both the Zallum Sandstone and The Zone-5 Phosphorite unit are of Late Cretaceous age.
- h. The calcareous, friable Zone-4 Phosphorite which is underlain by brecciated and nodular chert, brown shales and minor dolomite constitute the base of the Early Tertiary (Paleogene) succession.

Capetta and Riddler (1985) using suites of fish remains from phosphorite beds for age-dating, established the age of the Thaniyat Phosphorite Member on the Thaniyat escarpment, as Late Cretaceous (Maastrichtian) and a similar probable age for the Lower bed of the Thaniyat Phosphorite Member in the Al Jalamid area. The Arqah Phosphorite Member in the Umm Wu'aal area was dated as Early to Middle Eocene (Ypresian to Lutetian). The age of the Ghinah Phosphorite Member was less conclusive due to the state of preservation of the fossil teeth, but it was considered to be younger than Cretaceous and older than Lutetian.

Lozej (1985) carried out a stratigraphical study of pre-Tertiary (pre-Paleogene) rocks, which had not been previously studied in detail by Riofinex. The main purpose of the study was to meet the objectives of the 1 : 250,000-scale geological map compilation. This study correlated such rocks, with the standard cover rocks succession and ensured consistency for mapping.

Riddler and others (1985 *a*) completed the regional mapping and map compilation for the Late Cretaceous to Tertiary (Paleogene) carbonate rocks in Sirhan-Turayf region (fig. 1.3). A similar scheme based on Lozej, 1985, was used and modified during mapping by Van Eck (1986) and Meissner and others (1986).

Riddler and others (1986) discussed the results of mineralogical studies and chemical analysis carried out by Peers (1983, 1984) Basham (1984) and Mcpheat and others (1985) to determine the nature and association of minerals present in the phosphorite and to assess the liberation characteristics of the obtained apatite and gangue minerals. the results of the mineralogical studies are summarized as follows :

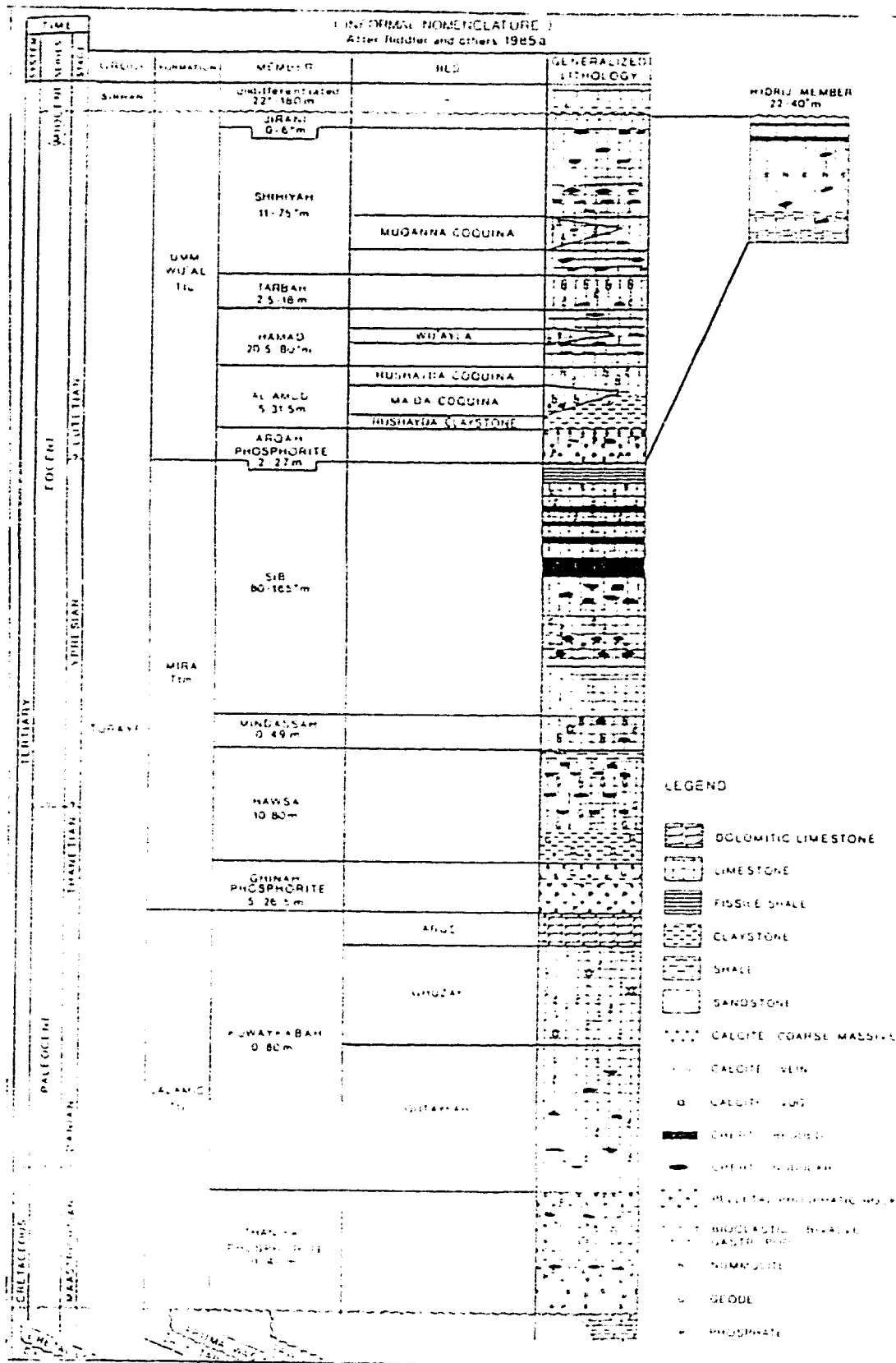


Fig. 1.3 : Generalized lithostratigraphic section for the area of the Wadi Sirhan-Turayf basin proposed by Riddler and others (1985 a).

- a The phosphorites of the region are all broadly similar in nature; and vary in phosphate content from 8 % to 33 %.
- b. Samples investigated consist mainly of carbonate-apatite (francolite or dahlite $\{Ca_3(PO_4,CO_3)_3(OH,F)\}$) with gangue minerals consisting of calcite and dolomite with varying amounts of Quartz, gypsum and bassanite and minor amounts of a yellow secondary mineral metayuyamunite $\{Ca(UO_2)(VO_4)_2 \cdot 3-5 H_2O\}$.

The phosphorite members which appear most suitable to produce concentrates for use as feedstock for the manufacture of fertilizer products, with or without beneficiation, are indicated in table 1.3.

Four suites of phosphorite samples were sent to the Australian Mineral Development Laboratories (AMDEL) in Adelaide, South Australia, for preliminary mineralogical characterization, beneficiation and suitability testwork. Three of these suites were taken from cores of 3 drillholes at Al Jalamid, and the fourth was obtained from a channel in Trench Tx2 in the Umm Wu'aal North area. Five composite samples, A through E, were prepared from these four suites (table 1.4). The principal objective was to determine whether suitable concentrates for commercial use could be obtained, using a flowsheet which minimized water and energy consumption. The target grade for the concentrates was specified at 33 % P_2O_5 .

Chemical analysis of these composite samples was used to calculate the normative mineralogy for each composite sample (table 1.5). This normative mineralogy is in good agreement with x-ray diffraction results and petrological descriptions, and is considered to be a good reflection of the actual mineralogy .

Table 1.3 : Most suitable Phosphorites for use as feedstock based on chemical composition (after, Riddler and others, 1986).

Phosphorite Member	Area	Impurities	
		Major	Minor
Arqah	Umm Wu'aal	carbonate minerals magnesium	sulphate, cadmium possibly uranium
Arqah	Al-Amud	carbonate minerals	cadmium
Ghinah	Southwestern	carbonate minerals magnesium	-
Thaniyat (Upper bed)	Al-Jalamid	carbonate minerals magnesium	-

Table 1.4 : Sirhan-Turayf Phosphorite Deposits : Composite Samples for Characterization, Benefication and Suitability Testwork (after, Riddler and others, 1986).

Composite Sample	Area	Phosphorite Member	Bed	Sample Type	Phosphorite* Description
A	Umm Wu'aal	Arqah	-	Channel	F, S-F, C
B	Al-Jalamid	Thaniyat	Upper	1/2 Core	F, S-F, C
C	Al-Jalamid	Thaniyat	Upper	1/2 Core	F, S-F, C
D	Al-Jalamid	Thaniyat	Lower	1/2 Core	F, S-F, C
E	Al-Jalamid	Thaniyat	Upper	1/2 Core	F, C

*Phosphorite Description : F - soft, friable; S-F - semi-friable; C - medium to hard calcareous and carbonate cemented ; S - siliceous.

**Table 1.5 : Normative Mineralogy (wt. %) of
Composite Samples A to E (after,
Riddler and others, 1986).**

Composite	A	B	C	D	E
Apatite	56.5	46.0	59.8	43.5	45.6
Calcite	28.6	41.1	32.7	5.9	49.5
Dolomite	0.9	6.6	1.8	48.4	1.5
Quartz	7.2	4.6	4.2	0.5	2.3
Gypsum	5.4	1.7	1.1	1.1	1.1
Others	1.4	-	0.4	0.2	-
Total	100	100	100	100	100

The composite samples all respond best to concentration by calcination, slaking, wet grinding and classification to reach the target grade of 33 % P_2O_5 (table 1.6). Dry grinding after calcination and slaking has potential to produce concentrates of suitable grade but at a lower P_2O_5 recovery than the wet-grinding process, although it is attractive in that water consumption would be halved, approximately.

Based on the results of this testwork, both McPheat and others (1985) and Riddler and others (1986) came to the following conclusion :

- a. The five composite samples are broadly similar in nature with apatite occurring as rounded pellets which are generally well liberated in material finer than 0.5 mm.
- b. Carbonates are the dominant gangue minerals.
- c. With the exception of composite sample D, where the MgO content would make it unsuitable, but only for superphosphoric acid production, all concentrates so far produced by this process would be attractive feed materials for the manufacture of fertilizer products because of their relatively high grade and low level of detrimental impurities.

1.7 Present status of the problem :

In previous studies on the NW Saudi Arabia Phosphorite deposits, no trace element analysis, genesis, diagenesis or classification of the phosphorite rock were seriously attempted. Similarly, no definite conclusion about the age of the different phosphorite members was reached. Discrepancies still exist in assigning an appropriate age to the main phosphorite horizon in the Thaniyat Turayf area. Both Meissner and

Table 1.6 : Results of beneficiation of phosphorite deposits by the process : calcination-slaking-wet grinding-classification (after, Riddler and others, 1986).

Composite Sample	Area	Interval Member	Phosphorite Type	Head Grade % P_2O_5	Concentrate Grade % P_2O_5	% P_2O_5 Recovery
A	Umm Wu'aal North	Arqah Phosphorite M.	Friable, semi-friable carbonate-cemented	22.6	32.6	76.6
B	Jalamid	Top of the Upper bed Thaniyat Phosphorite M.	Friable, semi-friable carbonate-cemented	18.6	34.8	90.1
C	Jalamid	Upper bed Thaniyat Phosphorite M.	Mainly friable	23.9	36.2	92.1
D	Jalamid	Lower bed Thaniyat Phosphorite M.	Friable to semi-friable	17.4	39.1	87.3
E	Jalamid	Upper bed Thaniyat Phosphorite M.	Carbonate-cemented	18.3	35.6	91.3

Ankary (1972) and Klyver and others (1981) considered this horizon (zone-5) to be of Late Cretaceous age, while both Bayliss (1983) and Riddler and others (1983) considered it to be of Danian (Early Paleogene) age. This discrepancy has hampered prospection in the area and has made proper geological interpretations rather difficult. Consequently, the main objectives of the present work include :

1. Assessment of the economic importance of the phosphorite deposits of northwestern Saudi Arabia in terms of both major and trace elements,
2. Petrographical and mineralogical study of the phosphorite ore composition,
3. Geochemical analysis of the studied phosphorite deposits, based on the data obtained from the μ -PIXE analysis, natural gamma-ray spectroscopy, SEM and field data in the studied areas,
4. Interpreting the paleoenvironmental conditions of deposition of the studied phosphorite deposits, based on both field and laboratory investigations. Such data can be utilized in the interpretation of phosphorite genesis and diagenesis in the studied areas,
5. Proposition of a practical classification for the sedimentary phosphorite deposits based on observations and data obtained from the present study.

Such objectives will be achieved using the following procedures :

- a. Field studies including collection of representative samples from the phosphorite-bearing succession in surface and subsurface sections,
- b. Lithostratigraphical subdivision of the studied succession into groups, formations, members and beds wherever possible.

- c Preparation of thin sections from selected specimens for petrographical study, μ -PIXE analysis and SEM investigation,
- d. Preparation of selected samples for natural gamma-ray spectroscopy,
- e. Determining Uranium, Vanadium, Thorium, Potassium, and Rare Earth Element (REE) in the collected phosphorite samples,
- f. Drawing isograde (isotenoer), isopachyte, and other related maps for P_2O_5 , U, and other important elements,
- g. Drawing graphic relationships between various pairs of the recorded elements, such as P_2O_5 and U contents.

CHAPTER TWO

MATERIALS AND METHODS OF STUDY

2.1 Sampling :

The area of the present investigation has been studied and sampled through successive field trips supervised by Prof. Dr. Z. R. El-Naggar since 1980, and the collected samples are deposited in the Department of Earth Sciences, KFUPM. The samples chosen for the present study were selected from this collection and were supplemented by samples collected during four recent field trips. These cover both surface and subsurface sections (including core samples and well cuttings) and were described both as hand specimens and under the binocular microscope.

Whenever phosphorite beds were encountered as surface outcrops and / or in trenches and tunnels, the thickness of the beds and the intervening layers were carefully measured and sampled.

The samples collected during the earlier field trips to the area in 1980, 1983 and 1984 include representative samples from the two cored wells P.1 and P.11 and a total of 224 core samples from other two wells, namely P-4A, and P-6A, drilled in the southern part of the Turayf area, added to a large number of surface samples collected from

traverses that cover both the Turayf and the Thaniyat Turayf areas, and samples collected from a water well that was being drilled at the entrance of Turayf town at that time.

Recently, more samples have been collected during 4 successive field trips, supervised by Prof. Dr. Z. R. El-Naggar and included the writer, during the period from 1994-1995. These include representative samples from the phosphorite and the associated chert and limestone outcrops in the Turayf area particularly those of Al-Khatebah tunnel (about 40 km to the NE Turayf town).

A total of 100 phosphorite samples were selected for the present study for the petrological and mineralogical descriptions of the ore, as well as for its trace elements' microanalysis and radiometric measurements. The samples were chosen from both surface and subsurface sections of different localities but, with more concentration on both the Hazm-Al-Jalamid and the Thaniyat Turayf areas, which are the best known localities - so far - for phosphorite mining in the whole Sirhan-Turayf basin.

2.2 Laboratory Techniques :

2.2.1 Sample Preparation :

The 50 samples selected for petrographical analysis are distributed as follows :

Surface Sections	29
Well No. P.1	12
Well No. P.11	9

These samples were thin sectioned using the facilities available in the Earth Sciences Department. The following steps were followed in the preparation of the thin sections :

- a. A slab, 0.5 cm-thick, was taken from each rock sample using the Mutta Cutta Rock cutting Machine,
- b. The slabs were then cut into a rectangular shape having a surface area that can fit the used glass slide,
- c. One surface of each slab was leveled on a rotary disc, using both the 400-and the 600-grit carborundum,
- d. Leveled slabs were mounted on the glass slides, using the lakeside cement,
- e. The slab was then ground down to about 1 mm thickness on the rotary disc of the Mutta Cutta Machine,
- f. Final polishing was then carried out by the use of the LP 30 machine. Slides were held on the precision lapping Jig with the calculations made to achieve a final thickness of about 100 microns, then manual polishing was used to get the desired final thickness of about 60 microns.

2.2.2 Instruments Used :

The following instruments were used to achieve the desired results :

1. Binocular Microscope,
2. Scanning Electron Microscope (SEM) & the attached Electron Microprobe,
3. Natural Gamma-Ray Spectroscopy (NGS),

4. Proton Induced X-ray Emission (PIXE) Spectroscopy.

2.2.2.1 Binocular Microscope :

Binocular microscope facilities at the Earth Sciences Department were used to examine the mineralogical and petrographical characteristics of the selected phosphorite samples. During this examination, important features were marked for further microanalyses using SEM and Micro-PIXE techniques and were photographed using a Karl Zeiss petrographical photomicroscope and Kodak colored films.

2.2.2.2 Scanning Electron Microscope and the attached Electron Microprobe :

The SEM / EDS¹ at the Central Analytical & Materials Characterization Laboratories of the Research Institute (KFUPM.) were used to study and photograph microstructures of the phosphorite ore and to carry out microchemical analysis for 10 selected phosphorite samples as follows :

Surface Sections 8 samples

Well No. P.1 2 samples

These samples were first thin sectioned and ground down to a thickness of about 60 microns and were then carbon coated

The JSM-5800LV scanning microscope is a digital system that is easily operated by various automatic functions (focusing, stigmation, contrast / brightness control, alignment, heating of the filament, etc.) menu operations with the mouse, operation

condition memory, frame store function, magneto-optical disk drive, etc. Both the energy-dispersive X-ray spectrometer (EDS) and the wavelength-dispersive X-ray spectrometer (WDS) can be simultaneously attached to the SEM giving it a large extendibility as an analytical tool.

Maximum 8-inch diameter wafer can be loaded in this system and a full 7-inch diameter area can be observed by using the rotating function (R-movement) of the stage. The specimen can also be moved along five axes (X, Y, R, T, Z) by motor-driven movements which are controlled by the computer. By using the position memory function, the specimen position can be memorized and reproduced, and hence, IC wafers, etc. can be observed continuously and subsequently.

By a single touch operation, the JSM-5800LV scanning electron microscope is operable in either the low vacuum or the high vacuum modes, for the observation of uncoated, non-conductive and coated, conductive specimens, respectively. In the first case, the specimen chamber is evacuated by a rotary pump (RP) to keep it with a low vacuum (high pressure) while the electron gun chamber and the lens system are evacuated by an oil diffusion pump (ODP) to keep both under a high vacuum (low pressure) condition. In the low vacuum specimen chamber, gas molecules still surround the electrically neutral, non-conductive, uncoated specimen surface, and hence, can make it easily observed.

Some important performance characters of the system under both the high and the low vacuum modes are indicated below :

¹ Energy-Dispersive X-ray Spectrometer

- Resolution
 - Low-vacuum mode : 5.5nm in BEI mode (WD5mm, Accv. 30kV)
 - High-vacuum mode: 3.5nm in SEI mode (WD8mm, Accv. 30kV)
- Magnification
 - Low-vacuum mode : X 15 (WD48mm) to 300,000 (136 steps) digital indications (observable mag. depends on the types of specimen)
AMC built-in
Instantaneously resettable from any mag. being used
 - High-vacuum mode : X 15 (WD48mm) to 300,000 (136 steps) digital indications
AMC built-in
Instantaneously resettable from any mag. being used
- Image modes
 - Low-vacuum mode : BEI (3 modes : composition, topography and mixed images)
 - High-vacuum mode : SEI, BEI (detected by SE detector)
- Probe current
 - Low-vacuum mode : 10^{-12} to 10^{-8} A
 - High-vacuum mode : 10^{-12} to 10^{-6} A (when the orifice is removed)

Measurements :

The uncoated slides were mounted on holders for observation under low vacuum. using an accelerating voltage of 20 kV., and imaging was carried out in backscattered electron mode. Carbon-coated slides were observed under high-vacuum and imaging was carried out in backscattered electron mode.

Micrographs were taken to show the grain structure of the examined ore sample. EDS microanalysis was performed at various spots on each sample. X-ray mapping and line scans were also carried out to show the distribution of the various elements present in the sample. Twenty two (22) micrographs, one hundred and four (104) EDS spectra, twelve (12) line scans and thirty six (36) X-ray maps were taken. Examples of such micrographs, EDS spectra, line scans and X-ray maps are shown in chapter 7.

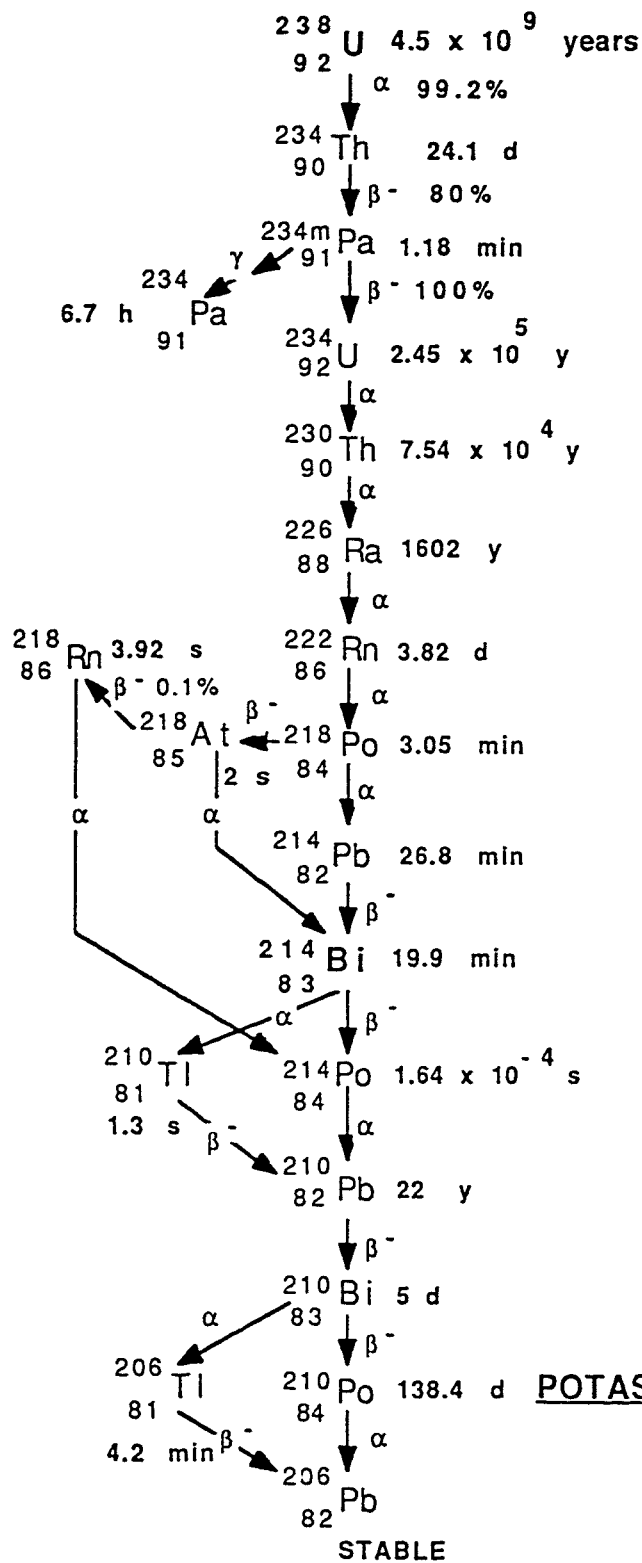
2.2.2.3 Natural Gamma-ray Spectroscopy (NGS) :

This tool (NGS) detects naturally occurring gamma rays of various energies emitted from a sample. Natural gamma radiations come mainly from the decay of three radioactive isotopes : Uranium-238 (^{238}U), Thorium-232 (^{232}Th) and Potassium-40 (^{40}K), (fig. 2.1).

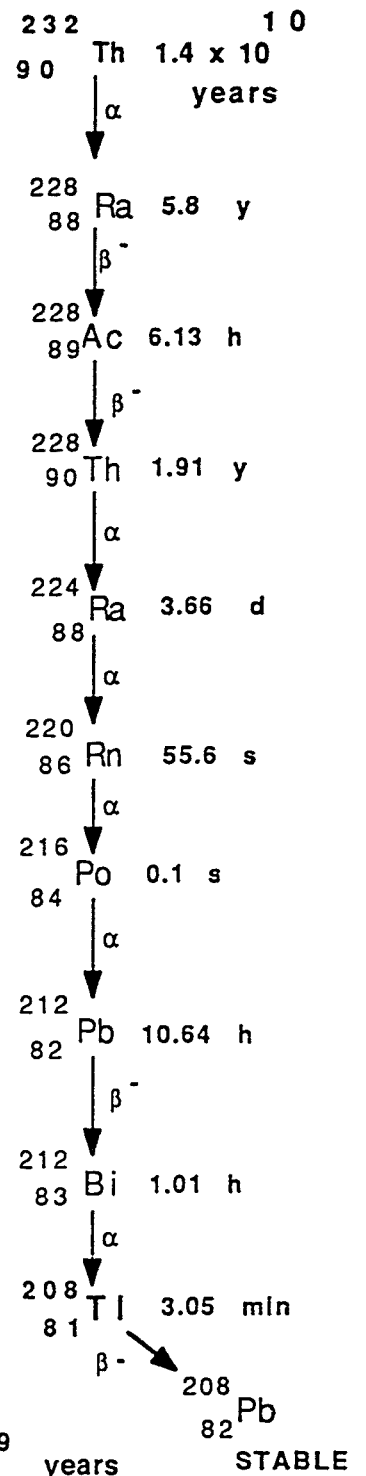
Two main techniques are in common use in natural gamma-ray spectroscopy : Thallium-activated sodium iodide ($\text{NaI}\{\text{TI}\}$) scintillation systems and lithium-drifted germanium ($\text{Ge}\{\text{Li}\}$) semiconductor systems. The latter has significantly better energy resolution but poorer counting efficiency than the former (fig. 2.2).

The low-level, gamma-ray spectroscopy facility at the Energy Research Laboratory (ERL) of the Research Institute (KFUPM) has already been calibrated and used to quantitatively measure the natural gamma-ray activity in some selected phosphorite samples(i.e. to measure the concentration of the three radioelements : U, Th, and K). The standard samples used in this activity were supplied by both NIST (National Institute of Standards and Technology, USA) and IAEA (International Atomic Energy Agency, Vienna, Austria).

URANIUM DECAY



THORIUM DECAY



POTASSIUM DECAY

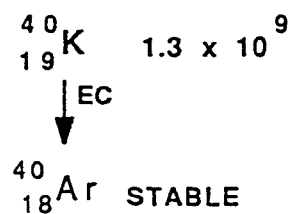


Fig. 2.1 : Natural Radioisotopes Decay Chains.

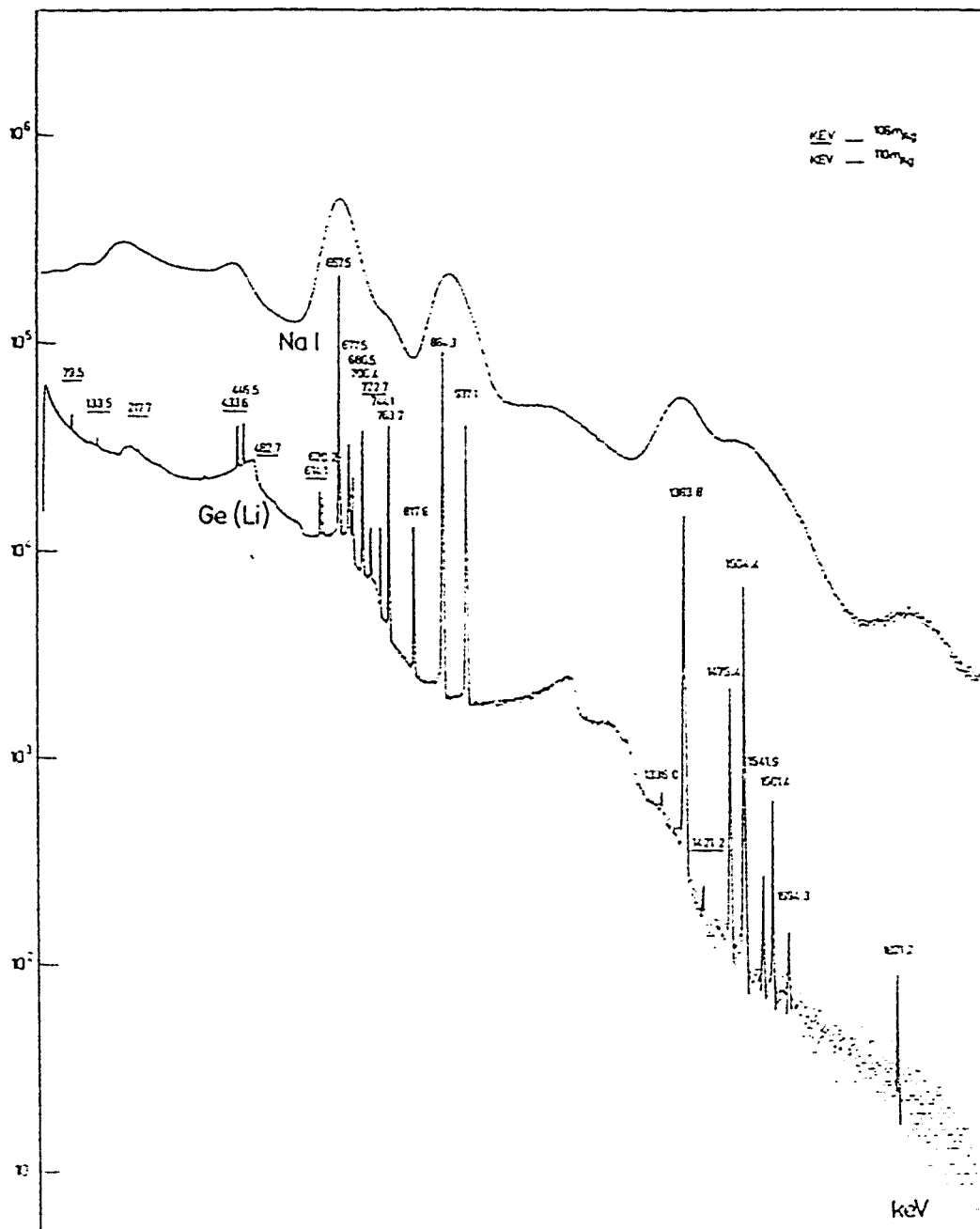


Fig. 2.2 : Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector. Energies of peaks are labeled in KeV. From G.F. Knoll, Radiation detection and Measurement (1979).

Sample preparation :

In the present study 46 samples were selected for radiometric measurements as follows :

Surface Sections	25 samples
Well No. P.1	12 samples
Well No. P.11	9 samples

The following steps were followed to prepare the samples :

- a. The phosphorite samples were dried, crushed and milled to 50 mesh in an agate Tema mill,
- b. The milled samples were packed inside already weighted, clean plastic containers (about 8 cm in diameter and 1.5 cm in height) and were carefully weighted with a sensitive balance (with sensitivity down to 1 mg range) and the net sample weight was calculated.
- c. The sample containers were sealed with silicon rubber and placed in heat sealed thin plastic bags to prevent any emanating radon gas from escaping,
- d. To enable the radon gas in the ^{238}U series to return to equilibrium with other daughter isotopes of the series, the sealed samples were left for about four (4) months (21 half-lives) before counting.
- e. For the background radiation measurements, several pure quartz samples (because pure quartz $\{\text{SiO}_2\}$ is free from any natural radioactivity) with a geometry identical to that of the phosphorite samples were prepared.

Experimental Set up :

The low level gamma-ray spectroscopy set-up at the ERL consists of a shielded 135 cm³ hyper pure Germanium (HPGe) detector and a 5 in. x 5 in. NaI(Tl) detector (in this work the latter has mainly been used) together with signal processing equipments and a data acquisition and analysis system (fig. 2.3). The detector is so well shielded that the room background radiation is reduced to a very low level and the dead time of the system is negligibly small. The set up was calibrated with standard gamma-ray sources to make sure that all three selected gamma line energies of 1460 keV from ⁴⁰K, 1765 keV from ²¹⁴Bi and 2615 keV from ²⁰⁸Tl could be seen. Here the line of 1765 keV of ²¹⁴Bi comes from ²³⁸U and the line of 2615 keV of ²⁰⁸Tl is from ²³²Th.

Measurements :

The samples were first counted with the Na(Tl) detector and a signal was sent to the preamplifier. After preamplification, the signal is processed through a Spectroscopy Amplifier and an ADCAM Multichannel Buffer model 918 A from EG & G ORTEC to an IBM-PC computer. The spectra are acquired in 4096 channels and calibrated with standard gamma-ray sources (⁶⁰Co and ¹³⁷Cs). In the calibration, standard samples with high concentrations of K, U and Th were also used.

In order to have better statistics, the gamma-ray activity of each sample was measured for 24 hours and the acquired spectrum (fig. 2.4) was stored under a separate file for later off-line data analysis.

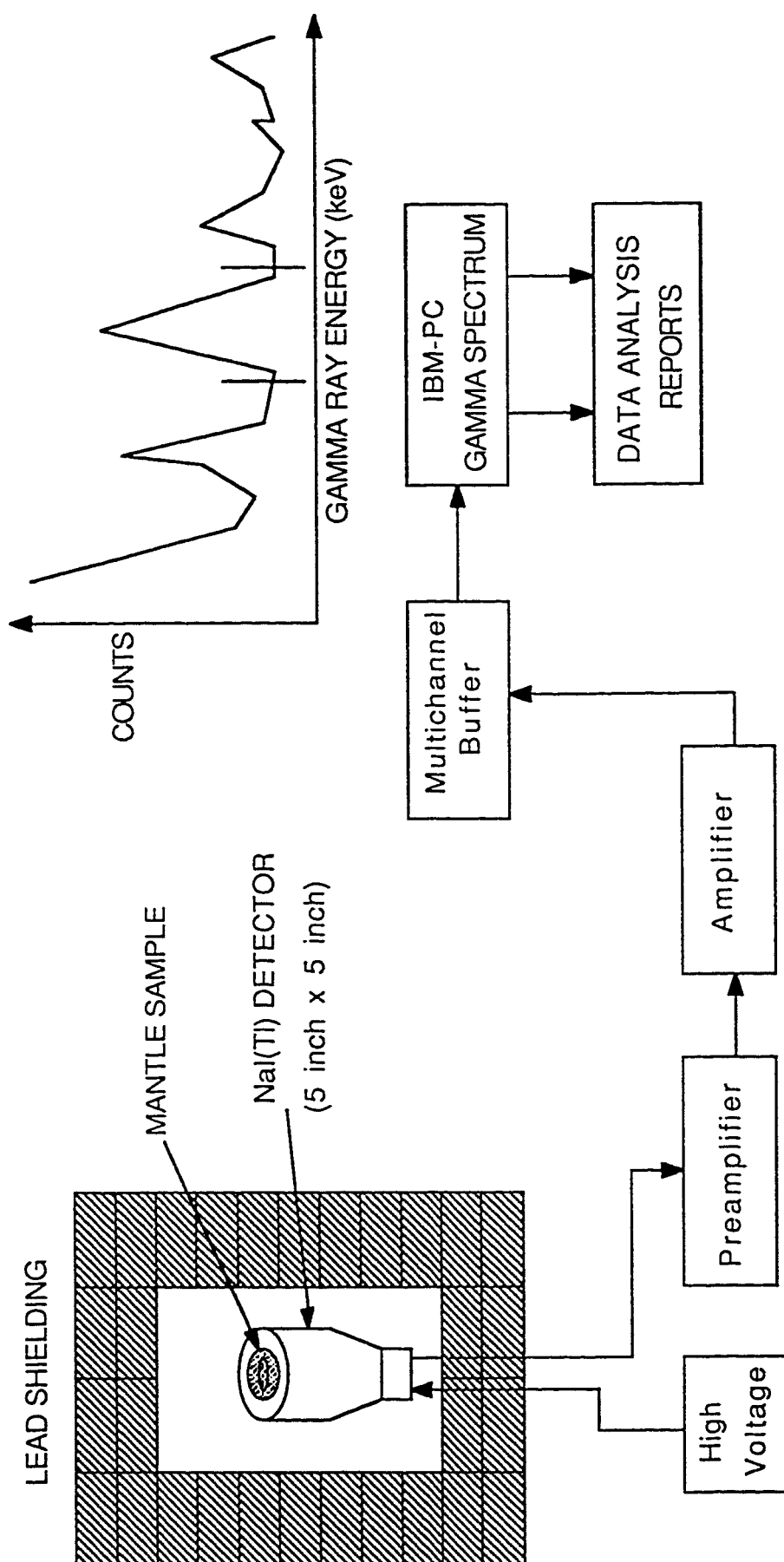


Fig. 2.3 : The experimental setup for Natural Gamma Ray Spectroscopy at ERL, KFUPM.

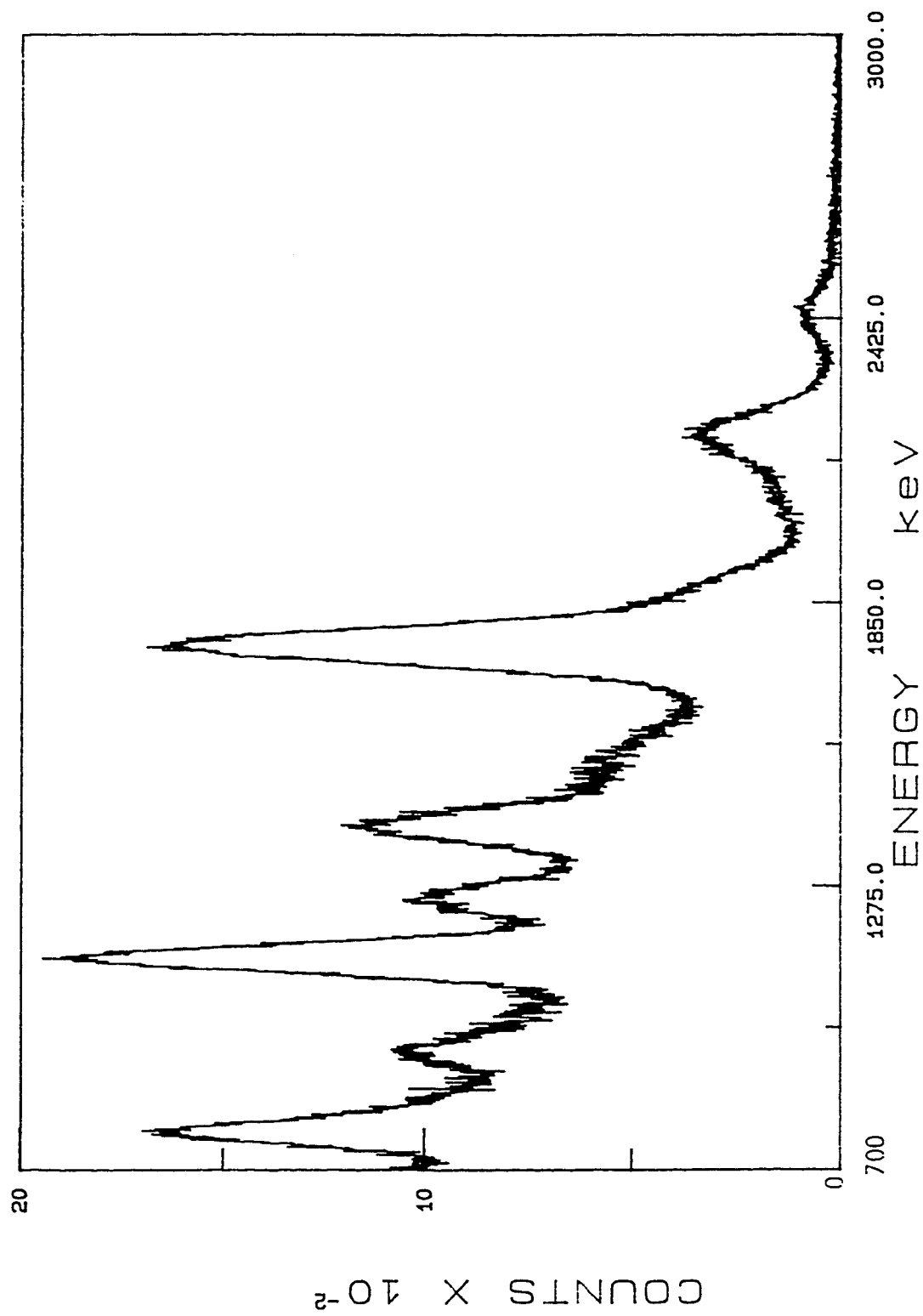


Fig. 2.4 : Gamma rays spectrum of phosphorite sample from Tubaig Phosphorite Tunnel, Turayf area.

Samples of pure quartz were used for room background radiation measurements, which were carried for the same period as the phosphorite samples (24 hours) several times, and the average value was used in the data analysis. Similar measurements were done for the standard samples which have certified values of K in percentage by weight (wt. %), Th, and U in parts per million (ppm) range, respectively.

Calibration curves for K, Th and U :

The certified values of K in wt. %, Th and U in ppm versus the net counts were plotted using a detailed graphic software package. The data were then fitted with the best function of $y^2 = a + bx^2$ (fig. 2.5). Similar curves were obtained for both U and Th, and the calibration constants (i.e. the number of counts per 1 % K, 1 ppm Th and 1 ppm U) were determined. These calibration constants were utilized in the analysis of the data obtained from the phosphorite samples and the concentration of K in wt. %, Th and U in ppm were determined.

Data Analysis :

The collected spectra were analyzed off-line by putting the region of interest (ROI) around the 1460 keV peak of ^{40}K , 1765 keV peak of ^{214}Bi (from ^{238}U) and the 2615 keV peak of ^{208}Tl (from ^{232}Th). The width of these gates were taken large enough to cover the whole peak (fig. 2.6). The intervals of these gates were 250 channels for K, 300 channels for U, and 390 channels for Th. The net counts under the K and U peaks and the gross counts under the Th peak were calculated.

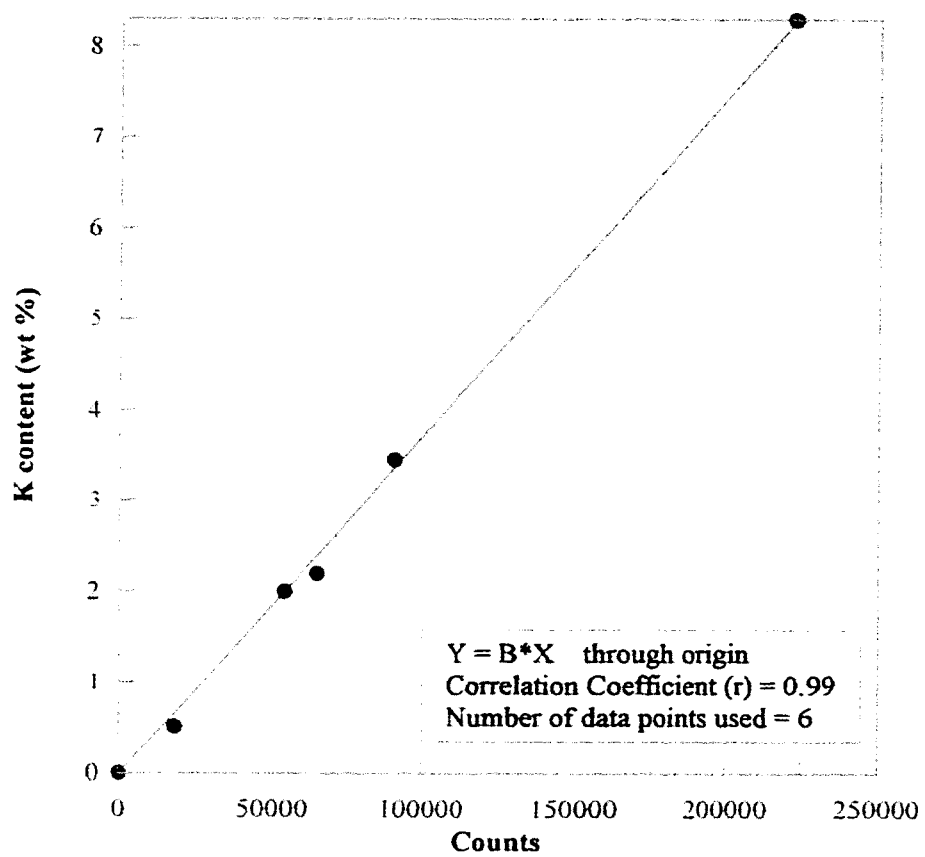


Fig. 2.5 : K Calibration curve used in Natural Radioactivity analysis.

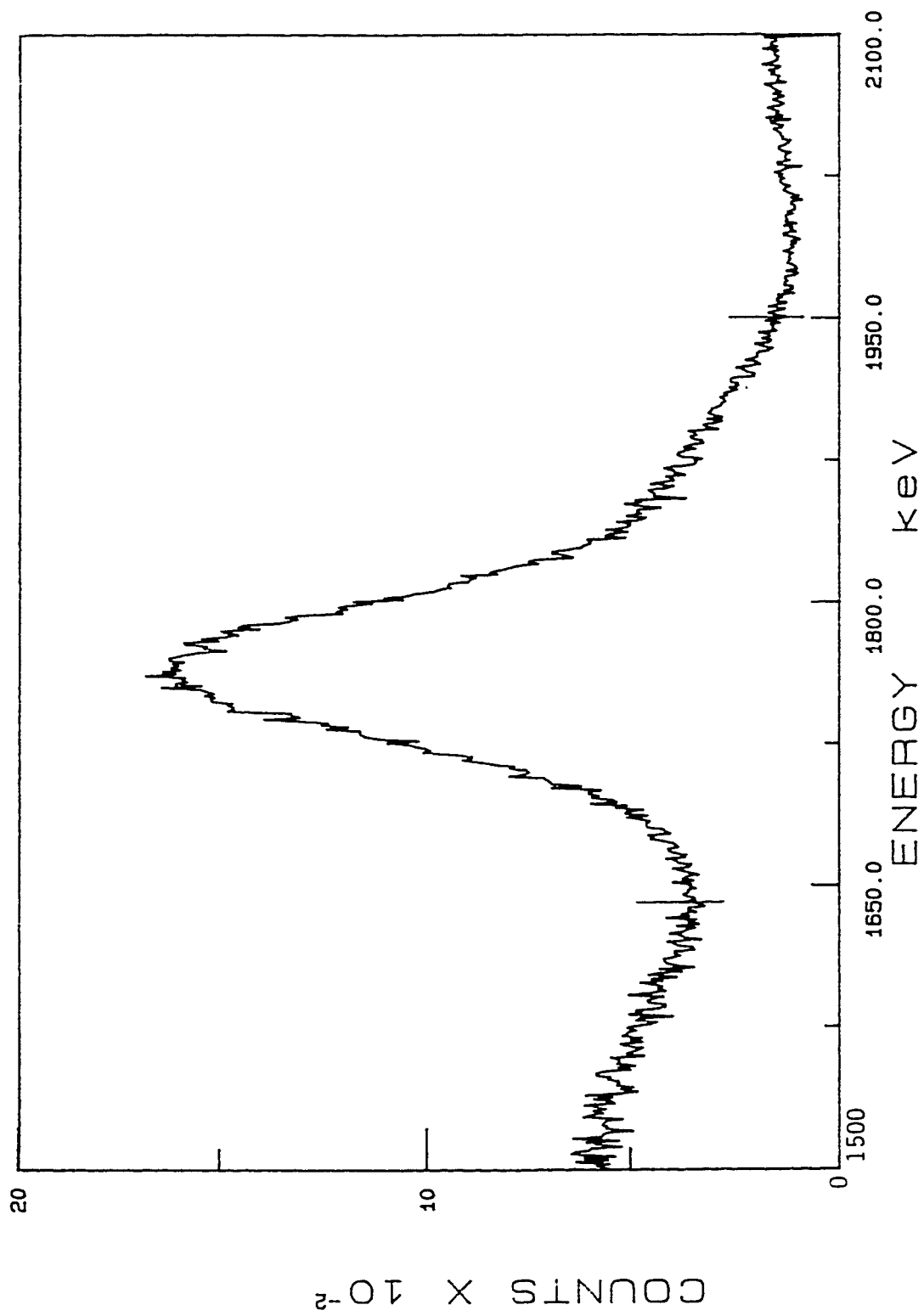


Fig. 2.6 : The Region of Interest of 300 channels wide of 1765 KeV gamma line of Bi-214 which results in from the decay series of U-238.

These measured counts were then corrected for dead time and background effects. the corrected counts (net or gross) under each peak were obtained by subtracting the appropriate background from the measured counts in the same ROI of the spectra. The stripping factors (which are the effects of scattering of high energy gamma-rays to lower energy peaks) were obtained from the measurements of pure thorium and uranium and the corrections were incorporated. Sample weight normalization corrections were also included, and the calibration factors were determined from the measurements of the standard.

Comparison of the corrected net and gross counts for each of the sample and the standards was used to determine the concentrations of K in wt. %, and of both Th and U in ppm in the studied phosphorite samples (table 7.22).

The statistical uncertainties of the measurements can be calculated as follows :

$$\% \text{ Error} = \frac{(\text{Sample gross counts} + \text{Background gross counts})^{1/2}}{(\text{Sample gross counts} - \text{Background gross counts})}$$

2.2.2.4 Proton Induced X-ray Emission (PIXE) Spectroscopy :

If a vacancy is created somehow in an electron shell, it will be filled immediately time by an electron from an outer shell and the excess energy will be emitted as an X-ray photon. These characteristic X-rays serve as “fingerprints” for the atoms they have originated from and thereby help to identify the elements present in a sample. Consequently, X-ray emission spectroscopy is based on the ejection of electrons from the

inner shells of the atoms in the analyzed sample, and the subsequent detection of the emitted X-rays.

Several processes can remove an electron from the inner shells of an atom, and this is usually followed by the characterization of the excited x-rays accompanying this process. The excitation of the characteristic X-rays from a sample is usually performed by one of the following methods :

- a. by radiation from radioactive sources;
- b. by X-rays from an X-ray tube (XRF);
- c. by a beam of electrons from a scanning electron microscope (SEM);
- . by charged particles produced by accelerators (usually protons). In this case, the technique is called PIXE (Particle Induced X-ray Emission).

Detection of the characteristic X-rays is carried out by using solid state Si(Li) detectors which have excellent energy resolution to separate X-rays of the neighboring elements. Since the detector crystal must be kept in vacuum, its front face has a thin beryllium window which allows most of the X-rays from the sample to pass through except for the very low energy ones from low Z elements. Hence PIXE is limited to the analysis of elements with $Z > 11 - 12$.

PIXE has proved to be an effective technique for sensitive and accurate analysis of major and trace elements in rock samples. Because of the high mass of the proton, the continuous Bremsstrahlung background from the primary beam is virtually absent, resulting in analytical sensitivities at the level of parts per million for most elements heavier than sodium in the periodic table. Microbeam-PIXE (PIXE using a focused proton beam) has recently added a new dimension to research in geological science by allowing

measurements of trace element distribution profiles on a sample at a spatial resolution of a few μm . The micro-PIXE set up at ERL consists of three main systems :

i) The high energy proton microbeam system :

The complete facility consists of an ion source / accelerator system (fig. 2.7) which acts as a source of high energy protons, and a slit / lens system (fig. 2.8) which reduces the size of the proton beam. Energetic protons from the Tandetron accelerator pass through a pair of small apertures (object / collimator slit sets). They are then compressed to a small dimension by three magnetic quadrupole lenses and focused on the sample plane. A scanning coil placed before the lens system allows moving the microbeam over the sample surface in a controlled raster pattern.

ii) The PIXE system :

The PIXE system consists of a target chamber, an X-ray detector and its associated electronics. The chamber (fig. 2.9), 20 cm in diameter, is made from stainless steel. It has eight ports, and a removable top cover plate which supports a goniometer assembly. It is mounted on an independent base adjustable in all six degrees of freedom with an accuracy of about 0.5 mm. The chamber can be accessed from the top for installing the samples.

The PIXE set up, shown schematically in figure 2.10, is used for detecting and processing the X-ray signals from the sample generated by the proton microprobe. It consists of a high resolution Si(Li) X-ray detector, a charge-sensitive preamplifier, a high

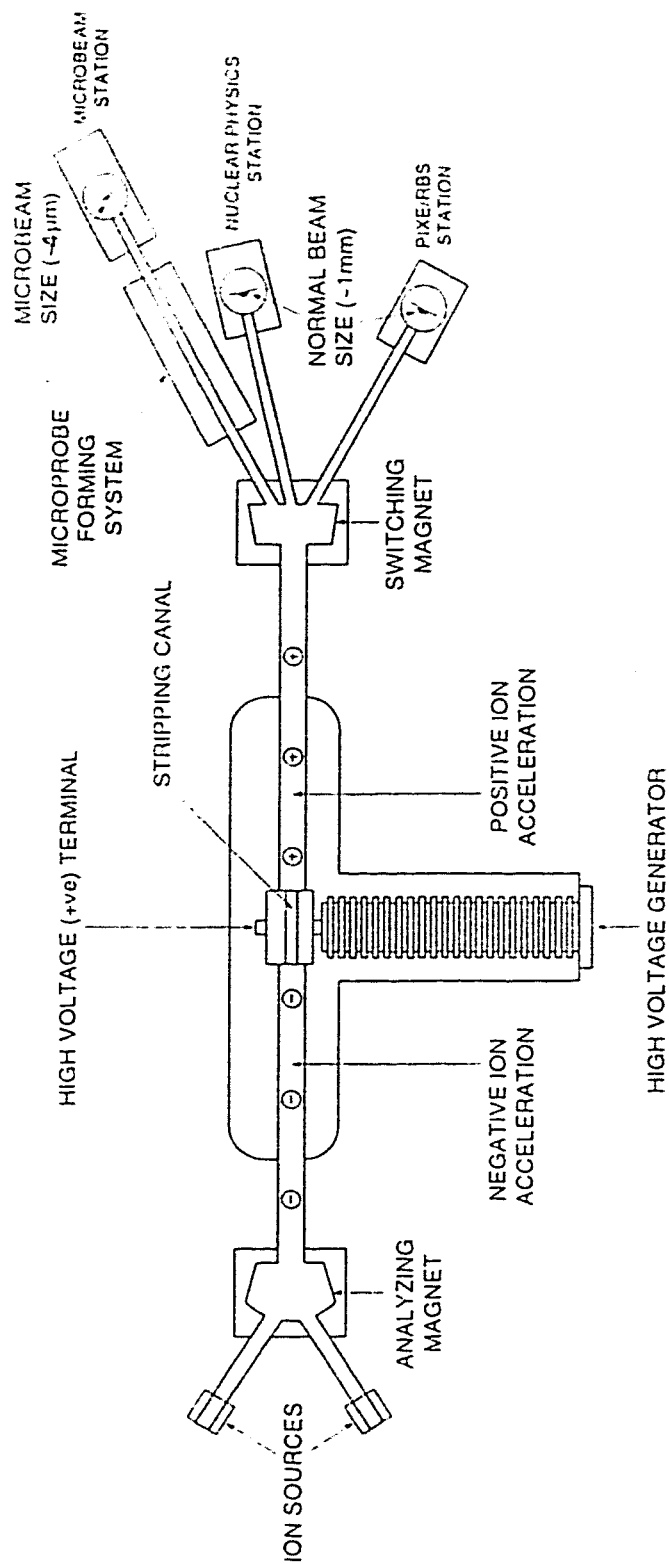


Fig. 2.7 : A schematic diagram of the KFUPM tandemron accelerator showing the three beam lines including the microprobe line.

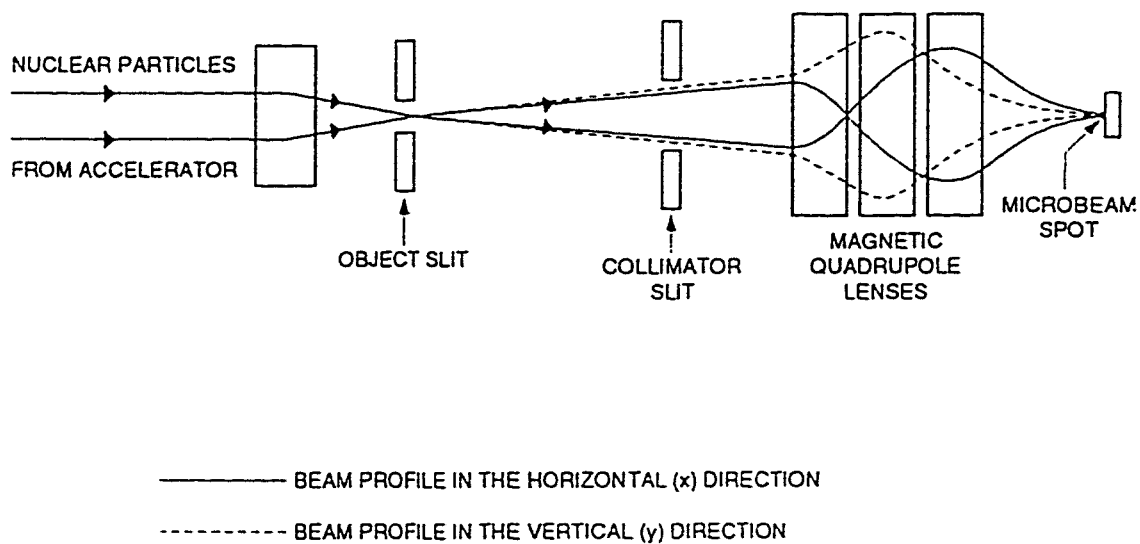


Fig. 2.8 : Beam optics of the Quadrupole Triplet Lens system.

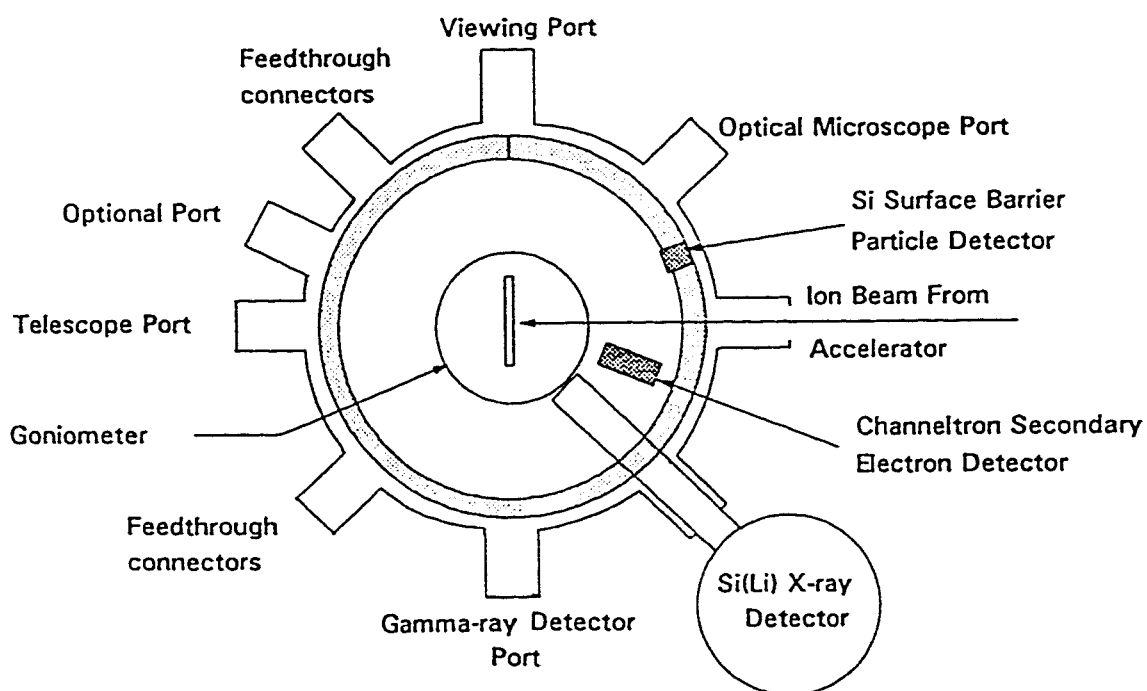


Fig. 2.9 : The sample chamber for KFUPM microprobe.

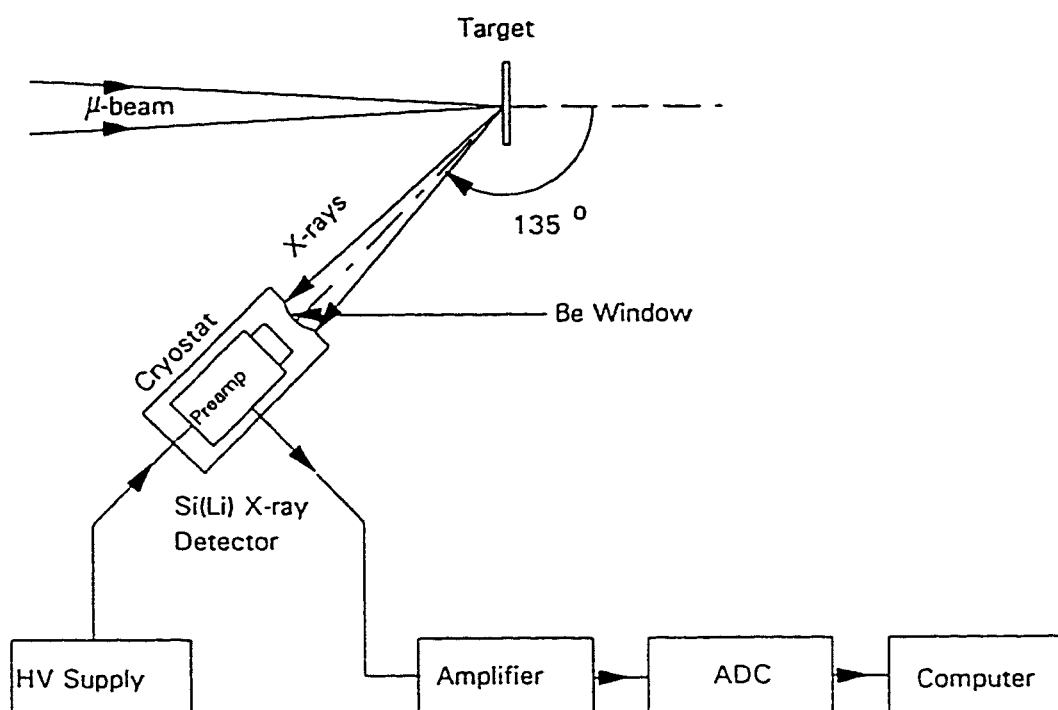


Fig. 2.10 : The PIXE set up on the KFUPM microprobe facility.

voltage supply, a spectroscopy amplifier, an analog-to-digital converter and personal computers.

iii) *The data acquisition and experimental control system :*

A schematic illustration of experiment control and data acquisition electronics layout is shown in figure 2.11. The system comprises a complete hardware and software package for the collection of PIXE elemental maps and energy spectrum from the scanning high energy proton microbeam system.

The scanning proton microprobe at the Energy Research Laboratory (ERL) of (KFUPM) was used to carry out detailed microanalysis for selected phosphorite samples.

The main objectives of such analysis include :

- a. The identification of important trace elements associated with the phosphorites (e.g. uranium, thorium, vanadium, rare earth elements, etc.).
- b. The interpretation of the geochemical processes by which both the phosphorus and its associated trace elements were deposited in the studied phosphorite samples. This was achieved by measuring the spatial distribution of the identified elements in the analyzed samples,
- c. The interpretation of post-depositional changes (weathering, leaching, replacement, etc.) by analyzing the grain / matrix / cement relationship (cement stratigraphy).

Ten phosphorite samples were selected for the PIXE spectroscopic analysis as follows :

Surface Section	6 samples
Well No P.1	2 samples
Well No P.11	2 samples

Polished thin sections (about 50 μm) were prepared by standard techniques and mounted on petrographic slides with epoxy resin. The thickness of the samples was dictated by the requirements of the petrological microscope which was used to record relevant mineralogical and petrographical characteristics, and to mark areas of interest for the micro-PIXE analysis. The thickness was also just about enough to stop 2.5 MeV protons or reduce their energy to an extent making them unproductive to generate X-rays from high Z traces, if any, in the glass mounts. For micro-PIXE analysis, the samples were coated with a thin layer of carbon to make the surfaces electrically conducting. The carbon layer was too thin to have any significant effect on PIXE measurements.

The samples were analyzed, using a 2.5 MeV proton microbeam of about 4 μm spatial resolution, at a current ranging from 40-60 pA, and a maximum scanning range of 540 μm in each of the X and Y directions. A secondary electron detection system was used to quickly obtain a map of the surface topography of the thin section so that the microbeam can easily be positioned on any region of interest on the sample for subsequent PIXE analysis. The microbeam was scanned over the selected area in a controlled raster pattern. It is important to emphasize here that a carbon absorber in front of the Si(Li) detector was used to cut out most of the X-rays from elements below Ca, in order to optimize the detection of high Z trace elements.

From each scanned area, elemental composition spectra as well as multiple elemental distribution maps (540 μm x 540 μm) have been produced simultaneously during each scanning cycle of the beam. From the measured elemental composition spectra, peak areas were estimated using a PIXE analysis software which carried out background subtraction, matrix absorption and detector efficiency corrections. The relative concentrations of the elements were then determined from these peak areas and were used together with SEM data to calculate absolute concentrations (tables 7.20, 7.21). In addition, 31 average elemental composition spectra and 31 multiple elemental distribution maps were also taken.

Figure 2.12 shows an example of an elemental spectrum of one mineral grain. The spectrum shows that in addition to the major constituents such as Ca, a number of trace elements including V, Cr, Fe, Ni, Cu, Zn, Hg, As, U, Sr and Y could be detected. Theoretical analysis of this spectrum was carried out using the PIXE software GUPIX. Figure 2.13 shows the theoretical fit to the experimental spectrum along with the residual. Excellent fits were obtained as indicated by typical small chi-square value of 0.74.

Examples of the elemental distribution maps in the analyzed samples are shown in figures 7.35-7.37. Each map represents an area of 540 μm X 540 μm on the sample surface.

Relative concentrations of the detected elements from this analysis are given in column 2 of tables 7.20 and 7.21. Knowing Ca concentrations in the same sample by SEM-EDS measurements, the relative PIXE values were converted to absolute concentrations and are shown in column 3. Column 4 gives the % errors (both statistical

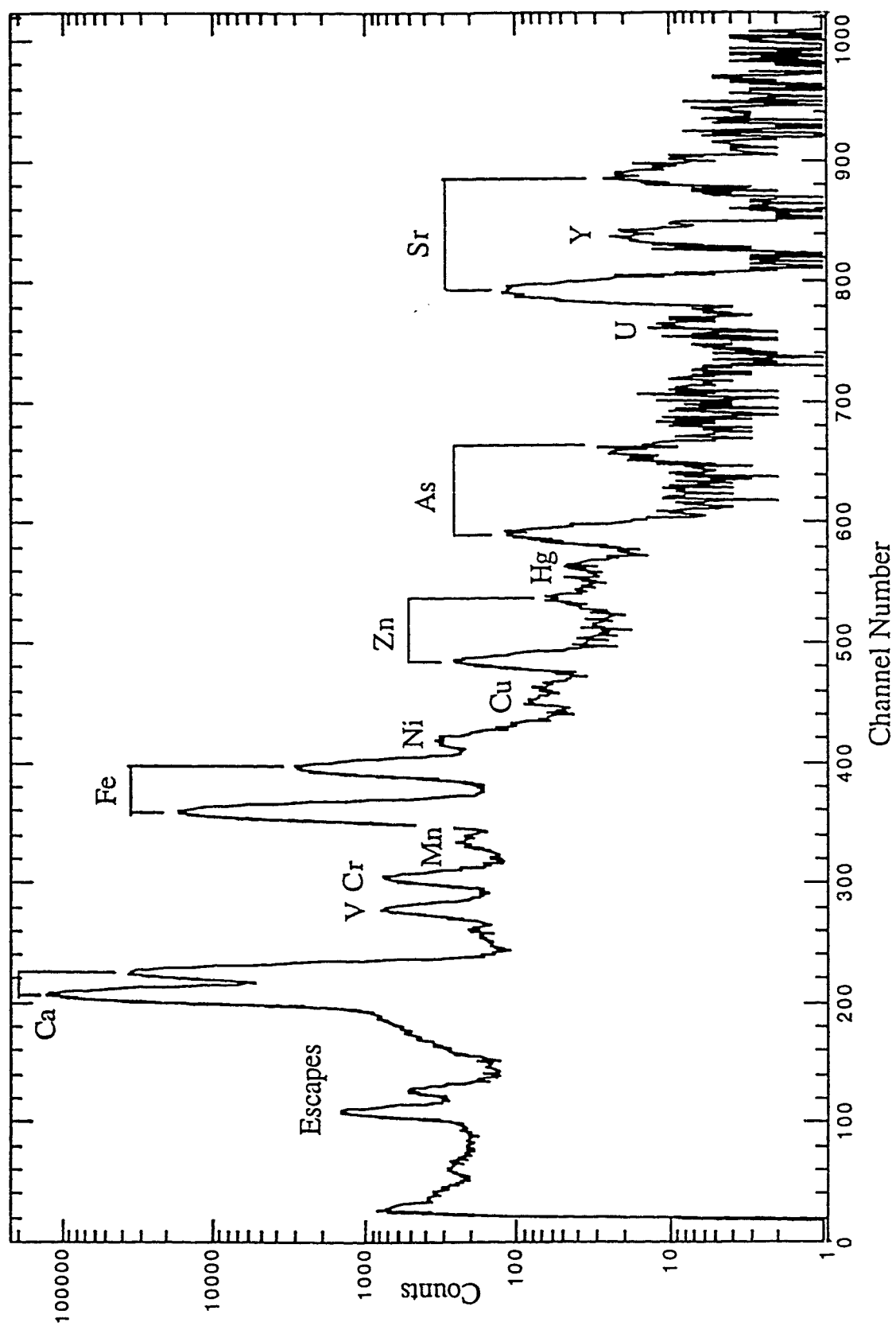


Fig. 2.12 : PIXE Spectrum of part of phosphorite sample from
East Khawr Umm Wu'at Phosphorite deposit.

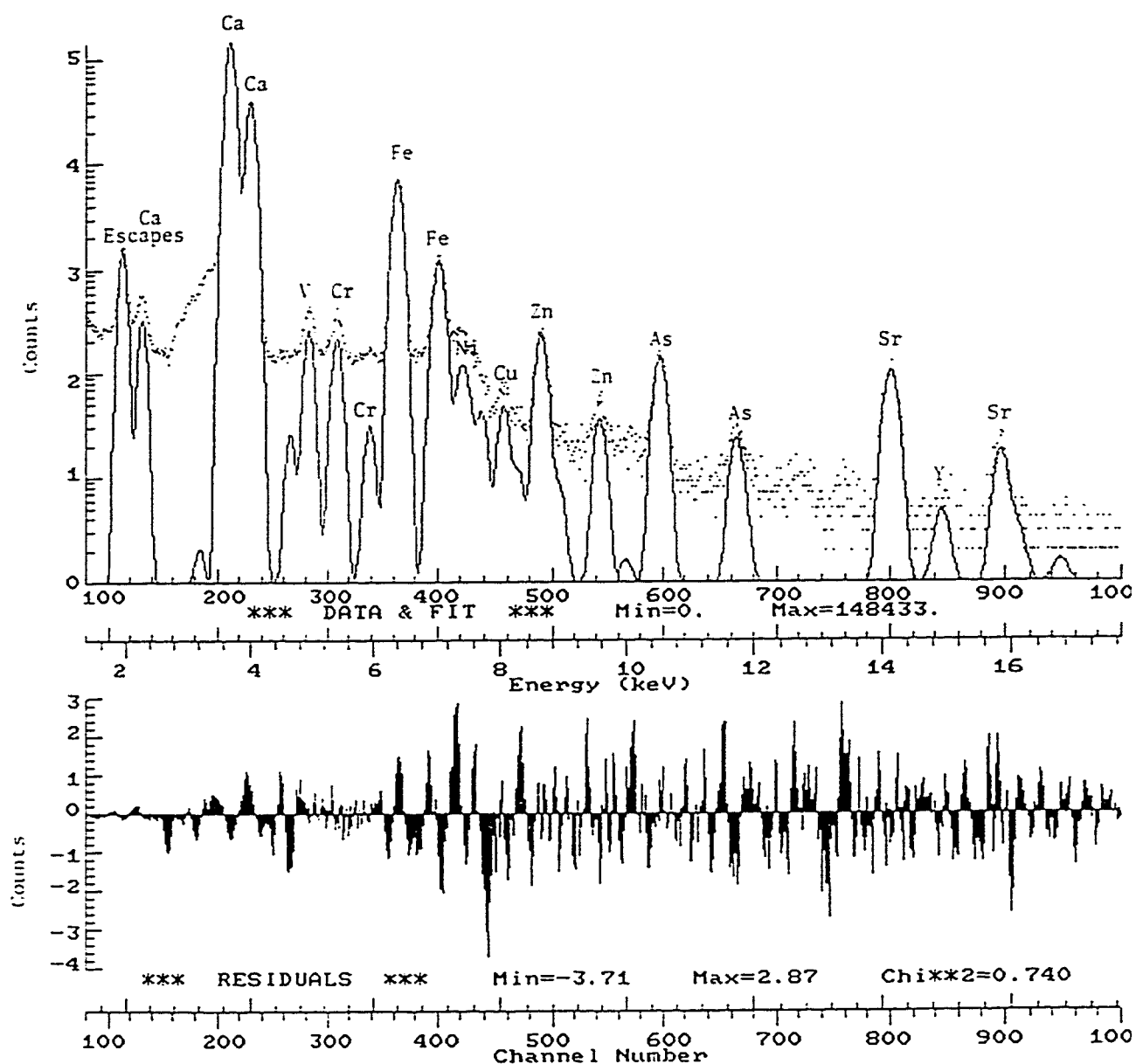


Fig. 2.13 : -Top, Theoretical fit (solid line) to the experimental spectrum (dots) of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit. The experimental spectrum contains the background.

-Bottom, Residuals after fitting experimental data by theoretical values.

and systematic errors). Decisions on the presence of any element, based on the minimum detection limit and the quantization limit for that element as calculated by the program, are also included in column 5.

CHAPTER THREE

STRATIGRAPHY OF THE SIRHAN-TURAYF BASIN

3.1 General Discussion :

The last few decades witnessed prolonged controversies about the stratigraphy of the Late Cretaceous-Early Paleogene epochs. Several stages and substages were suggested with loose definitions, and varied interpretations by different authors, which made it difficult to establish their true stratigraphical relationships. However, these controversies have now been settled by the establishment of world-wide planktonic foraminiferal and other zonations (cf. El-Naggar 1966, 1967 a,b, 1969; Blow 1969, 1979; Van Hinte, 1976; Berggren, 1969, 1971, 1972).

The present study is mainly concerned with the period from the Late Cretaceous (Campanian) to the Early Paleogene (Paleocene-middle Eocene). The main points of disagreement about the stratigraphy of this period have already been treated in detail by El-Naggar (1966, p. 15-32), and need not be repeated here, but, the Late Cretaceous-Early Paleogene geochronologic units adopted in the present study are summarized in table 3.1.

Table 3.1 : Late Cretaceous-Early Paleogene geochronologic units adopted in the present work (mainly after El-Naggar and Dawood, 1979; Van Hinte, 1976 and Berggren, 1972).

Era	Period	Epoch	Age	Chron	Age of commencement of unit (Ma)
Cainozoic	Paleogene	Eocene	Priabonian		45
			Lutetian		49
			Ypresian		54
			Landenian		59
		Paleocene	Heersian		63
			Danian		65
			Maastrichtian		70
Mesozoic	Cretaceous	Late Cretaceous	Senonian	Campanian	78
				Santonian	82
				Coniacian	86
		Middle Cretaceous	Turonian		

3.2 The Late Cretaceous-Early Paleogene Succession in Saudi Arabia :

Rocks of Late Cretaceous-Early Paleogene age in Saudi Arabia are mostly calcareous in composition and are sandwiched between dominantly clastic rocks of Middle Cretaceous age below (Wasia Group), and of Mio-Pliocene age, above. This led both Powers and others (1966) and Powers (1968) to consider these rocks as a distinct division in the outcropping sedimentary section of Central Arabia, and to group them under the name “ Upper Cretaceous to Eocene carbonate rocks”. In Central Arabia these rocks crop out in a narrow curved belt that widens greatly north of latitude 28° N. (fig. 3.1), probably due to a sudden reduction in the rate of dip (cf. Powers and others, 1966).

Outcropping Late Cretaceous-Early Paleogene rocks in Arabia have been grouped into : the Late Cretaceous Aruma Group, below, and the Early Paleogene Hasa Group, above. The latter group changes laterally to the northwest (west of long. 40° E) into phosphorite-bearing, chalks and silicified limestones which are here included under the name Hibr Group.

3.2.1 The Late Cretaceous Rocks in Saudi Arabia :

The Cretaceous succession in Saudi Arabia is divided into three main groups from the base upward as follows :

1. A lower carbonate group composed of aphanitic limestone, calcarenitic limestone and calcarenite, of Early Cretaceous age (the Thamama Group),
2. A middle sandstone group with intercalating shaly and calcareous beds near the top, of Early-Mid Cretaceous age (the Wasia Group),

3. An upper carbonate group of Late Cretaceous age (the Aruma Group).

The name Aruma was first suggested by Burchfiel and Hoover (1935, unpublished report) to include the Late Cretaceous succession of limestones, dolomites and shales that disconformably overlie the Early-Middle Cretaceous clastic Wasia Group and underlie the Early Paleogene Umm-er-Radhuma Formation. It was named after Al'Aramah Plateau (Lat. 25° 38' N., Long. 46° 22' E).

First published reference to the term Aruma Formation was presented by Steineke and Bramkamp (1952), while Steineke and others (1958) presented the first formal definition of the term. The type section was later described by Powers and others (1966) and Powers (1968).

The Aruma was treated as a formation by Steineke and Bramkamp (1952), Thralls and Hasson (1956), Steineke and others (1958), Sander (1962), Powers and others (1966), Powers (1968), Kluyver and others (1981), Riddler and others (1983) and El-As'ad (1983 a, b, 1987). Other authors (e.g., Owen and Naser, 1958; Van Bellen and others, 1959; Fox and Brown, 1968; El-Naggar and Al-Rifa'iy, 1972 a, b; El-Nakhal and El-Naggar, 1990; and Al-sharhan and Naim, 1990) consider it as a group, and Darmonoian (in Buday, 1980) raised it to a supergroup status.

In the present study, the Arumā is treated as a group on the basis of its varied lithology and the stratigraphical breaks separating its component lithologic units both at outcrop and in the subsurface sections. This is sustained by the fact that in the area of study, the lower part of the Late Cretaceous succession is represented by sandy facies (the

Zallum Sandstone) and is separated from an overlying chalky part (the Ar'ar Chalk) by a clear unconformity.

Rocks of the Aruma Group are dominantly shallow-water carbonates that blanket the area of outcrop (cf. Powers and others, 1966). As the distance increases from the basin margin, the Aruma rocks change in the subsurface of Eastern Arabia into deeper water shales and limestones. The sandstone facies recorded in northwestern Saudi Arabia (near Sakaka and along the escarpment north of Sakaka till the southern fringes of Thaniyat Turayf) reflect more shallowing in that direction.

Powers and others (1966) and Powers (1968) described the 142 m thick type Aruma as being composed of four lithologic units from the base to top as follows :

- a. A basal unit of about 40 m of cream, fine-grained, calcarenitic limestone with impure sandy layers near the bottom, commonly with a basal bed of red-brown, vuggy dolomite, and containing benthonic foraminifera,
- b. A second unit of about, about 41 m thick, consisting of 3 m of basal olive-green, calcareous shale followed upwards by about 38 m of cryptocrystalline, chalky limestone with benthic foraminifera,
- c. A third unit of about 28 m of blue-gray to cream dolomite with thin limestone interbeds near the top, and abundant benthic foraminifera,
- d. A fourth, uppermost unit consisting of about 32 m of yellow-brown dolomite and calcareous shale, olive shale and argillaceous dolomite with limestone and dolomite interbeds, and benthic foraminifera.

S.J. Roach (1952, in Powers & others, 1966) had already recognized two units at the type Aruma section that served to group most of the shale and impure carbonate into a

single member "The Lina Shale Member" (= unit 4 above), overlying a somewhat purer carbonate sequence "The Atj Limestone Member" (= units 1,2 and 3 above) with a disconformable contact between them (Table 3.2).

Powers (1968) mentioned that in the subsurface section there is a widely recognizable stratigraphic break within the Aruma Formation, therefore this unit was divided into the 'Lower' and 'Upper' Aruma. The Lower Aruma was partly equated with the basal lithologic unit in the type section, while the Upper Aruma was equated with the upper three units.

El As'ad (1983 a, b) described the surface section of the Aruma Formation in central Arabia as consisting of nodular, dolomitic, argillaceous limestones and subordinate shales, divisible into three distinctive members from the base upwards as follows : (i) the Khanasir Limestone Member, (ii) the Hajajah Limestone Member, and (iii) the Lina Shale Member. He (*op. cit.*) correlated these members with the 'Lower Atj', 'Middle Atj' and 'Lina Shale' members of Powers and others (1966), respectively (fig. 3.2) (table 3.2). El As'ad (*loc. cit.*) also suggested a reference section for the 'Aruma Formation' in the area of Wadi Al-Itk.

The lateral extensions of these units of the Aruma Group to both the southwest and the northwest are mostly sandstones (cf. Powers and others, 1966). The progressive transition of the Aruma rocks from carbonate to sandstone can be seen south of Wadi al Sahba (lat. 24° N and long. 48° E). Further to the south, the group is only represented by sandstones till the southern end of the outcrop (cf. Powers and others, *op.cit.*). The latter authors (*loc. cit.*) also added that, in the vicinity of Sakaka, a succession of sandstones, 61 m thick (the Zallum Sandstone), overlies an 11 m-thick basal Aruma limestone unit (the

Table 3.2 : Correlation of the Aruma Group succession in the Arabian Peninsula and surrounding regions (after, El-Nakhal and El-Naggar 1990).

UPPER CRETACEOUS					CHRONO-STRATIGRAPHIC UNITS	
Upper Turonian	Coniacian	Santonian	Campanian	Maastrichtian		
				Aruma Formation	(1)	CENTRAL SAUDI ARABIA
				Atj Limestone Member	(2)	
				Lina Calc. M.	(3)	
				Aruma Formation	(2)	COASTAL SAUDI ARABIA
				Unit 1 Unit 2 Unit 3 Unit 4	(3)	
				Aruma Formation	(2)	OMAN
				Khanasir Member	(3)	
				Hajajah Member	(4)	ABU DHABI
				Lina Member	(5)	
				Aruma Formation	(2)	QATAR
				Lower Aruma Limestone Member	(3)	
				Upper Aruma Shale Member	(4)	KUWAIT
				ARUMA GROUP	(5)	
				Laffan Formation	(6)	S. IRAQ
				Ilan Formation	(7)	
				Piqa Fm.	(8)	N. IRAQ
				Sinsina Fm.	(9)	
				ARUMA GROUP	(10)	OFFSHORE IRAN
				Laffan Formation	(11)	
				Halul Formation	(12)	
				Piqa Fm.	(13)	
				Sinsina Fm.	(14)	
				ARUMA GROUP	(15)	
				Laffan Formation	(16)	
				Halul Formation	(17)	
				Shargi Fm.	(18)	
				Sinsina Fm.	(19)	
				ARUMA GROUP	(20)	
				Laffan Formation	(21)	
				Halul Formation	(22)	
				Rullat Fm.	(23)	
				Sinsina Fm.	(24)	
				ARUMA GROUP	(25)	
				Gudair Formation	(26)	
				Bahr-ab Fm.	(27)	
				Tayarat Fm.	(28)	
				Khasib Member	(29)	
				Tanuma Member	(30)	
				Mutriba Member	(31)	
				Sa'di Member	(32)	
				Hartha Member	(33)	
				Qurna Fm.	(34)	
				ARUMA GROUP	(35)	
				Gudair Formation	(36)	
				Bahr-ab Fm.	(37)	
				Tayarat Fm.	(38)	
				Khasib Member	(39)	
				Tanuma Member	(40)	
				Mutriba Member	(41)	
				Sa'di Member	(42)	
				Hartha Member	(43)	
				Qurna Fm.	(44)	
				ARUMA GROUP	(45)	
				Gudair Formation	(46)	
				Bahr-ab Fm.	(47)	
				Tayarat Fm.	(48)	
				Khasib Formation	(49)	
				Tanuma Fm.	(50)	
				Sa'di Fm.	(51)	
				Hartha Fm.	(52)	
				Qurna Fm.	(53)	
				ARUMA SUPERGROUP	(54)	
				S A ' D I GROUP	(55)	
				Hartha Group	(56)	
				Arabian Gulf Group	(57)	
				Shatt al Arab Formation	(58)	
				Qarnat Ali Formation	(59)	
				Mherjan Formation	(60)	
				Siba Fm.	(61)	
				Hasan Fm.	(62)	
				Qurna Fm.	(63)	
				Tayarat Fm.	(64)	
				ARUMA GROUP	(65)	
				Khasib Formation	(66)	
				Tanuma Formation	(67)	
				Sa'di Fm.	(68)	
				Hartha Fm.	(69)	
				Qurna Fm.	(70)	
				Tayarat Formation	(71)	
				Shiranish Formation	(72)	
				BANGISTAN GROUP	(73)	
				Ilan Formation	(74)	
				Gurpi Formation	(75)	
				ARUMA GROUP	(76)	
				Ilan Formation	(77)	
				Gurpi Formation	(78)	
				ARUMA GROUP	(79)	
				Ilan Formation	(80)	
				Gurpi Formation	(81)	

Long. $46^{\circ} 20' 25''$, $46^{\circ} 12' 06''$, $46^{\circ} 20' 36''$.

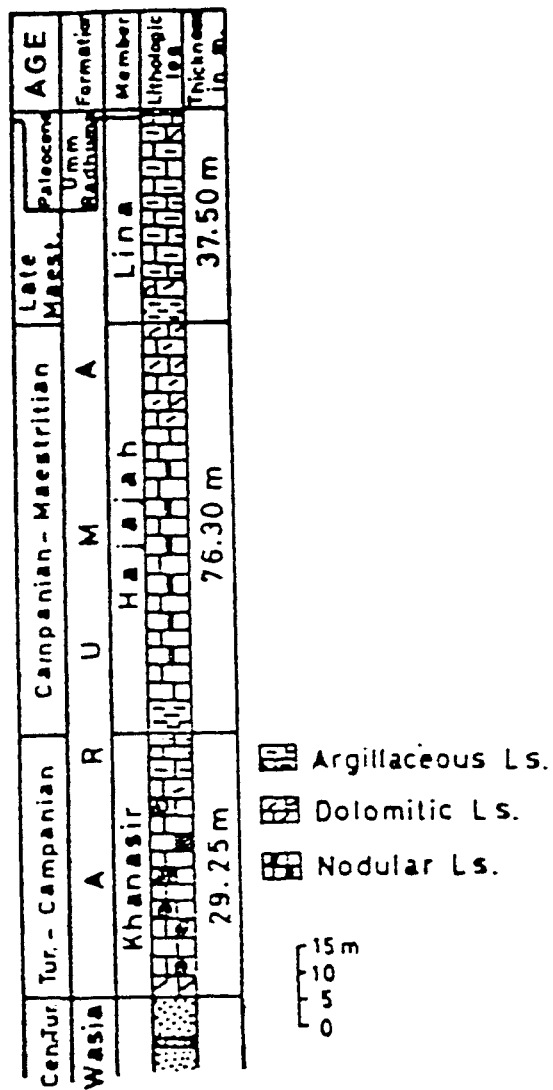


Fig. 3.2 : Reference Section of the "Aruma Formation" at the vicinity of Wadi Al-Itk, as proposed by El-Asa'd (1983a).

Hudayb Limestone) at Khashm Zallum. This sandstone is disconformably overlain by a sequence of limestones, chalks and dolomites, treated as the Ar'ar Chalk by El-Naggar and others, 1981, 1985.

Thralls and Hasson (1956), Powers and others (1966) and Powers (1968) considered the outcropping Aruma to be of probable Campanian-Maastrichtian age, while El-As'ad (1983 a, b) extended its age to the Coniacian-Late Maastrichtian.

3.2.2 The Early Paleogene Rocks in Saudi Arabia :

The Standard Oil Company of California (now ARAMCO) initiated studies of the Paleocene-Middle Eocene rocks in Saudi Arabia in the early 1930's (early days of oil discovery in the country). These studies were concentrated on the coastal area of the Eastern Province and were later extended to cover the rest of the country. The results of these studies have been recorded in ARAMCO's unpublished reports.

Powers and others (1966) and Powers (1968) summarized the results of these studies as follows :

- a. In 1935, S.B. Henry and C.W. Brown presented the name Umm Al-Radhuma Formation to include the Paleocene-Early Eocene rocks encountered in the Umm Al-Radhuma Well (lat. 28° 41'N, long. 44° 41'E),
- b. In 1936, M. Steineke and J.W. Hoover designated a reference section for this formation in Wadi al Batin,
- c. In 1941, R.A. Bramkamp introduced the name Dammam Formation for the Early-Middle Eocene rocks exposed in the Dammam Dome,

d. In 1946, Bramkamp introduced the name Rus Formation to include the Early Eocene marls and limestones of the Umm Al-Rua'us Hill, in the vicinity of Dhahran, and in the same year, E.L. Berg and L.D. Owens used the name "Hibr Formation" to embrace the Early Paleogene rocks exposed in the vicinity of Tall al-Hibr (lat. 31° 51'N, long. 38° 08'E).

In 1951, N.J. Sander introduced the name "Hasa Series" to include strata of Paleocene and Eocene age extending along the western shores of the Arabian Gulf.

Steineke and Bramkamp (1952) made the first published reference to the Umm Al-Radhuma Formation, while both the Rus and the Dammam Formations were first formally mentioned by Thralls and Hasson (1956). These rock units were later formally defined by Steineke and others (1958), and the name "Hasa Series" was corrected to "Hasa Group" by Owen and Nasr (1958).

Both Powers and others (1966) and Powers (1968) treated the name "Hibr Formation" as an informal name, but this was formalized and raised to group status by El-Naggar and others (1982).

Paleocene-Eocene rocks in Arabia outcrop in many areas other than the central Arabian belt, and have been subdivided into three units : (i) A lower carbonate unit (the Umm Al-Radhuma Limestone), (ii) A middle evaporite unit (the Rus Anhydrite) and (iii) an upper carbonate unit (the Dammam Limestone). In the northwestern part of Saudi Arabia equivalent rocks of the Hibr Group are phosphate-bearing carbonates.

El-Naggar and others (1982) raised the Hibr Formation to group status, and recognized three formations within it, from the base upwards as follows : (i) the Hazm-

Al-Jalamid Formation, (ii) the Bardawil Formation and (iii) the Turayf Formation. The subsurface sections of Paleocene-Eocene strata encountered by drill holes at Hazm-Al-Jalamid, west Bardawil and the area around Turayf city were designated as the type sections of these formations which are characterized by units rich in limestone, chalk and chert with minor shaly and marly intercalations, and abundant *Nummulites spp.* The three formations are apparently conformable with each other, wherever exposed, and discordant with the basaltic flows wherever encountered.

The Hibr Group is considered to be a cyclical sedimentary phosphorite-bearing carbonate rock succession comprising three formations. The succession was deposited in a marine shelf environment, which was open to the north and north-west, and lay on the southern margin of the ancient Tethys Sea. The Hibr group is part of the Mediterranean phosphogenic province which extends from Morocco to Iraq.

However, deviating from this classification of the Hibr Group, Riddler and others (1983) included the of Paleocene-Eocene succession of northwestern Arabia under the name Turayf Group, and subdivided it into three main formations : (i) the Jalamid, (ii) the Mira and (iii) the Umm Wu'aal Formations respectively.

From the above mentioned discussion, it is clear that, the Early Paleogene rocks in Arabia can be grouped into two chronostratigraphic rock units : (i) the Hasa Group in the Eastern Province (the Eastern or the Main Arabia basin) and (ii) the Hibr Group in the Northwestern Province (the Sirhan-Turayf basin). The two groups are separated by the Ha'il Arch Complex, a broad, block-faulted north-west trending structure, which now manifests itself at surface as a broad, doubly plunging fold complex in the northwestern Saudi Arabia. The arch is of some importance as it controls the regional dip in the region.

It probably acted as a complex of stable positive anticlines and depressed synclines during early sedimentation and was reactivated and / or modified by later folding (e.g. the Badanah uplift) along an axis, a little further to the east of the earlier axis. Subsequent Early Paleogene deposition indicates a separation of sedimentation and faunal assemblages, along the Badanah uplift axis, between the Main Arabia basin to the east and the Sirhan-Turayf basin (Tethys Seaway) to the west (Powers and others, 1966; El-Khayal, 1974). This has led to the traditional separation of the Hibr Group, west of the uplift axis, from the Hasa Group of the main Arabia basin.

3.3 Stratigraphy of the Study Area :

The succession in the study area can be subdivided into two groups and six formations (table 3.3) as follows :

	Turayf Formation
2- Hibr Group	Bardawil Formation
	Hazm Al-Jalamid Formation
1- Aruma Group	Ar'ar Formation
	Zallum Formation
	Hudayb Formation

1- The Aruma Group :

The Aruma Group within the region crops out in the eastern part of the study area, being centered on Wadi Al Mira (lat. 30° 45'N, long. 40° 15'E) from where it crosses into

Table 3.3 : General lithostratigraphic subdivision of the Late Cretaceous-Early Paleogene succession in the Sirhan-Turayf basin, Northwestern Saudi Arabia.

Group	Formation	Member	Bed	Age
Undifferentiated Miocene / Pliocene Sediments and / or Pliocene Basalts				
Hibr Group Early- Paleogene (Paleocene- Middle Eocene)	Turayf Formation	Hidrij Member		Middle Eocene (Lutetian)
		Jirani Member		
		Shihiya Member		
		Tarbah Member		
		Hamad Member		
		Al Amud Member	Rushayda Coquina	
			Rushayda Claystone	
			Ma'da Coquina	
	Arqah Phosphorite Member			
	Bardawil Formation	Sib Member		early Middle Eocene (Early Lutetian) to Early Eocene (Late Ypresian)
		Mindassah Meber		
		Hawsa Member		
		Ghinah Phosphorite Member		
	Hazm-al- Jalamid Formation	Kuwaykabah Limestone Member	Arus	Early Eocene (Early Ypresian) to Middle Paleocene (Heersian)
			Ghuzah	
			Qutayfah	
		Thaniyat Phosphorite Member		
Aruma Group (Late- Cretaceous)	Ar'ar Formation			↑ Maastrichtian ↓
	Zallum Formation			
	Hudayb Formation			
Wasi'a Group or older rocks				

Iraq. It is found in wadi sections northwest and southeast of the town of Ar'ar (Badanah) (lat. 30° 59'N, long. 40° 59'E), and occurs along the southern escarpments of Jal al Jubah ash Sharqi and extends southward to Khashm Zallum (lat. 30° 19'N, long. 40° 18'E) and from there along Jal al Jubah al Gharbi towards the Quraymiz hill (lat. 29° 51'N, long. 39° 24'E).

The Aruma Group within the region is subdivided into three formations, The Hudayb Limestone, The Zallum Sandstone and The Ar'ar Chalk (base to top), the three being separated by disconformable boundaries, and can be briefly described as follows :

1.1 The Hudayb Limestone :

The Hudayb Limestone was described as an 11-m thick basal Aruma Limestone by Powers and others (1966), as a pelsparite unit by Kluyver and others (1981), and as the Aruma carbonate (Unit 2) Hudayb limestone by Lozej (1985). It is well exposed just east of the Hudayb village (lat. 30° 02'N, long. 40° 25'E), in the form of a prominent ledge, capping the Jal al Jubah ash Sharqi escarpment. The base of the unit, which is the base of the Aruma Group here, unconformably overlies the clastic sediments of the Wasia Group.

The Hudayb Limestone consists of fine-to medium-grained, white, gray to gray-brown, thinly bedded, slabby, algal limestone, which is dolomitic and argillaceous, and locally contains chert beds. Near Hudayb, the unit is only 10-15 m thick, thickening steadily to the southeast (Lozej, 1985). It thins to the northwest and near where it pinches out, a thin wedge of oolitic grainstone is developed as a local facies within the unit (formerly described as the pelsparite unit).

The Hudayb Limestone contains marine fossils comprising gastropods, pelecypods, and foraminifera including *Loftusia*, which indicate a Late Cretaceous (Maastrichtian) age. Lithologies suggest a shallow-marine environment. The contact with the overlying Zallum Sandstone is described as unconformable (cf. Van Eck, 1985b).

1.2 The Zallum Sandstone :

The Zallum Sandstone was described at its type section (Khashm Zallum) by Powers and others (1966) as a highly variegated, poorly sorted sandstone section (50 m thick) with a basal limestone band (11 m thick) containing fossils that relate it to the Aruma Group ($\cong$ Hudayb Limestone). Kluyver and others (1981) used the same name for this rock unit which was later described as Lower Aruma / Lower Clastic Unit (unit 3) "Zallum" facies by Lozej (1985). The Zallum Sandstone crops out to the east and northeast of the Sakakah town. It extends from there westward to the Thaniyat Turayf area where it thins out steadily. Throughout its outcrop, The Zallum Sandstone is unconformably overlying the Hudayb Limestone, or, stepping over either the Middle-Late Devonian Sakakah Sandstone or the Early Devonian Jauf Formation. It is disconformably overlain by either the Ar'ar Formation or by various members of the Hibr Group.

The sandstone facies of the Zallum with its readily visible, bright, variegated nature is a very conspicuous marker horizon for the Cretaceous rocks in the southern escarpments of the region. At Kahshm Zallum (lat. 30°19'N, long. 40° 18'E) it is 50 m thick, but, gradually thins out westwards to 2.5-5 m and pinches out towards the Quraymiz hills, (Aspinall & others, 1986, in Riddler & others, 1986). It occurs at the

base of the Thaniyat escarpment, in places, where it attains a maximum thickness of 20 m. The Zallum Sandstone facies consists of ferruginous, conglomeratic, and argillaceous sandstones, alternating with varicolored shale, and mudstones. The sandstone is friable, cross-bedded, and contains sub-rounded to subangular, fine-grained to cobble-sized quartz fragments, while the shales and mudstones weather purple, maroon, red, tan, green and yellow. This shallow-water clastic facies gives way to a deeper water carbonate and shale facies towards the north around Ar`ar (cf. Van Eck, 1985*b*).

1.3 The Ar`ar Chalk :

This formation had been named after the town of Ar`ar, Northern Province, Saudi Arabia. The name was introduced by El-Naggar and others (1982) to describe a succession of limestones and chalks in the upper part of the Aruma Group outcropping in the northwestern parts of Saudi Arabia. The exposure in and around Wadi Ar`ar (lat. 30°31`N, long. 40° 27`E) have been designated as the type section

The Ar`ar Formation has been previously described as “Limestone, chalky limestone and marl” by Powers and others (1966), as “ bioclastic dolomite (Bd)” and “chalky dolomite (Cd)” by Kluyver and others (1981) and as the “Upper Aruma : grainstone (Unit 4), chalky limestone (Unit 5) and bioclastic, chalky mudstone (Unit 6)” by Lozej (1985).

The Ar`ar Formation has been subdivided into three mappable units, a basal argillaceous unit, an overlying massive, bioclastic, carbonate ledge and an upper unit which is a sequence of chalky, friable, interbedded bioclastic and non-bioclastic

carbonates. Within the outcrop area of the Ar`ar Formation, the soft, chalky limestones form scattered outliers within the bioclastic limestone mass. The formation is exposed in wadi sections to the east of the region, and crops out over the plunging anticline associated with the Badanah uplift in the northeast. It can be up to 80 m thick. The formation pinches out in a southwesterly direction somewhere north of Shuwayhitiyah, and westwards from there, the Zallum Formation is unconformably overlain by the Paleogene Kuwaykabah member of the Hazm-al-Jalamid formation.

The thickness of the formation is variable due to the instability of the region during the time of its deposition and its upper part contains minor phosphorite deposits.

The Ar`ar Formation is disconformably overlying the Zallum Formation or is stepping over the Jauf Formation, and is disconformably overlain by various members of the Hazm-al-Jalamid Formation. The latter boundary is believed to be a fault line boundary.

The Ar`ar Formation is here given a Late Cretaceous (Maastrichtian) age on the basis of the presence of the two index larger foraminiferid species : *Lofusius elongata* Cox, and *L. minor* (Cox). This age assignment is also supported by the record of the planktonic foraminiferid "*Globigerinelloides*" sp. cf. *G. bollii*" Pessagno and of an ammonoid cast (cf. Kamel, 1985).

2- The Hibr Group :

The Paleocene-Middle Eocene cyclical sedimentary phosphorite-bearing carbonate succession in the Sirhan-Turayf region is here included under the name Hibr Group. The name was first introduced informally by Berg and Owens in 1946 as the Hibr Formation

(cf. Powers, 1968). With the discovery of phosphorite deposits in the Turayf area, more efforts were given to the study of the succession and several subdivisions of the Hibr Formation were introduced. Some authors raised the whole unit to group status and retained the name Hibr group (e.g. El-Naggar & others, 1982), while others suggested to replace the old name with the name Turayf Group (e.g. Riddler & others, 1983). However, following the law of priority and the suggestions of El-Naggar and others (*op. cit.*), the name Hibr Group is adopted in the present work.

The Hibr Group is sub-divided into three main formations from the base upwards) as follows :

1. The Hazm-al-Jalamid Formation
2. The Bardawil Formation
3. The Turayf Formation

These formations represent three periods of cyclic, carbonate sedimentation, comprising repetitive, short, sweeping, on-lapping, transgressive-regressive events over a shallow marine shelf. Significant phosphorite members occur at the base of each sedimentary cycle, with some minor intermediate beds, reflecting high-energy marine transgressions at the start of each of the repetitive cycles, where lag deposits of phosphorite and organic (bioclastic) fragments were formed by reworking of primary deposits. A brief description of each of these formations is given below.

2.1 The Hazm-al-Jalamid Formation :

This rock unit was introduced by El-Naggar and others (1982) as one of four formations of the Hibr Group (Table 1.2). It was said to overlies an unnamed Paleocene

formation and underlie the Early Lutetian Bardawil Formation. The stratigraphic position has suggested an Early Eocene age for the rock unit, but it was later extended downward by El-Naggar & Kamel (1988) to include the underlying Paleocene succession.

A complete section of the Hazm-al-Jalamid Formation was encountered in the cored-hole No. P.11, and hence this well was considered by El-Naggar and others (*op.cit.*) to be the type section of the formation. In its type section, the Hazm-al-Jalamid Formation has a total thickness of 175 m., and is mainly composed of chalky, silicified, phosphatic, marly, argillaceous and / or recrystallized, and locally nummulitic limestones, with two phosphorite zones near the base.

The Hazm-al-Jalamid Formation is widely exposed in the Thaniyat Turayf region, where it ranges in thickness from 45 m to 120 m. It thickens to the west and northwest from the Thaniyat escarpment towards Wadi al Ghinah. Conversely, towards the southeast, in the direction of the Tabuk road, the formation thins out, passing laterally into a probable nearshore facies. Progressing eastward from the Thaniyat escarpment, the formation dips below younger formations and reappears between al-Quraymiz (lat. 29°57'N, long. 39° 30'E) and Ar Riyyatan (lat. 30°00'N, long. 39° 40'E) (fig. 3.3 b). It is assumed that the intervening area between the Thaniyat Turayf area and the Quraymiz hills was a paleo-topographic high and the formation was not deposited. The formation caps the escarpment west and north of al-Shuwayhitiyah, and crops out over the eastern part of the region on the Hamad plain which extends northward to the Iraq border, pinching out around the nose of a plunging anticline in the northeast of the region, north of the Al Jalamid pumping station.

Erosional remnants of the Hazm-al-Jalamid formation, resting on the bioclastic, dolomitic limestones of the Ar`ar Formation form scattered outliers on the plunging anticline east of the drill-hole No. P15 (fig. 3.4). Consisting of bioclastic and stromatolitic limestones as well as phosphorite, they indicate an intertidal shallow-water environment over one of the Ha'il Arch Complex swells (the Badanah uplift). The formation is assumed to pass laterally into the Umm er Radhuma Formation east of the Ha'il Arch complex structures.

The Hazm-al-Jalamid Formation was deposited in a transitional, intertidal to inner-shelf sub-tidal environment and can be divided into two members (from the base upwards) as follows :

1. The Thaniyat Phosphorite Member
2. The Kuwaykabah Limestone Member

2.1.1 The Thaniyat Phosphorite Member :

The Thaniyat Phosphorite Member crops out along the length of the Thaniyat escarpment, in Wadi al Ghinah and Wadi al Kuwaykabah. Along the eastern part of the escarpment (lat. 29°41`N, long. 37° 52`E), the member comprises a relatively compact interval of phosphorite, chert, shale and dolomicrite, with up to 7 discrete phosphorite beds, ranging in thickness between 3-7 m and in grade up to 34 % P₂O₅. The footwall phosphorite within the member is generally the thickest, ranging from 1 -5 m. All phosphorite beds have a range of types from friable to hard, with or without bioclastic debris and shark's teeth.

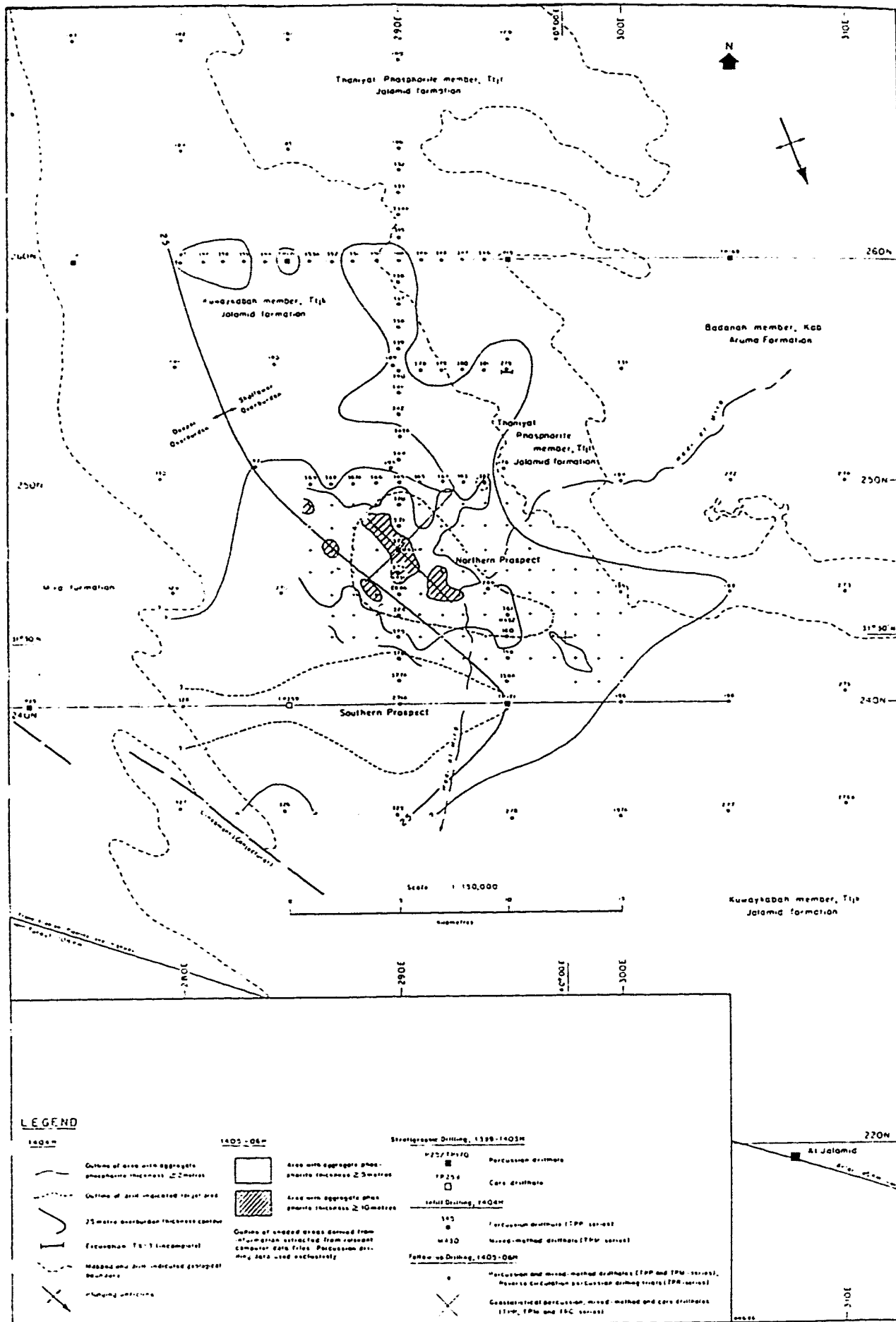


Fig. 3.4 : Drilling results in the Hazm Al-Jalamid area. After, Riddler and others (1986).

At al-Quraymiz, the Thaniyat Phosphorite Member is up to 2 m thick, with a strike length of 10 km. A typical section of this locality comprises a silicified coarse bivalve coquina at the base of the member overlying a lateritic sandstone facies of the Zallum formation, above the coquina, a semi-friable to friable calcareous phosphorite interval, 10-30 cm thick which is conglomeratic, cherty and bioclastic in places, contains average grades up to 20 % P_2O_5 ; this interval is overlain by argillaceous and phosphatic limestones.

Northwards from this apparently nearshore facies of al-Quraymiz, the Thaniyat Phosphorite Member rapidly pinches out and reappears again north of the ARGAS line 180 N at a depth in excess of 100 m, in drill holes P11 and P41 (fig. 3.3), where it attains a thickness of 25 m, with grades of up to 20 % P_2O_5 .

At the Jalamid area, the member comprises two extensive friable, semi-friable to hard, carbonate-cemented, phosphorite beds, with an aggregate thickness of up to 13 m and an average grade of 21 % P_2O_5 . These are enclosed in micritic, bioclastic limestones, which are dolomitic towards the base

At the extreme eastern part of the region, northwest Ar'ar, the Thaniyat Phosphorite Member is poorly developed or absent. A blackened, variably silicified and commonly pelletal carbonate capping to the Ar'ar Formation in this area is probably equivalent to the Thaniyat Phosphorite Member.

2.1.2 The Kuwaykabah Limestone Member :

The Kuwaykabah Limestone Member crops out along the top of the southern escarpment between al-Quraymiz, Ar Riyyatan, Khashm Zallum and Jal al Amghar (lat.

30°45'N, long. 40° 30'E). It composed of irregularly bedded bioclastic, stromatolitic, dolomitic limestones, argillaceous limestones and shales, with detrital quartz grains near the base. It comprises 3 beds (from the base upwards) as follows : the Qutayfah Bed (up to 30 m of non-bioclastic, silty, micritic limestones and cherts), the Ghuzah Bed (mainly leached bioclastic micritic or sparry limestone), and the Arus Bed which is only seen in drill-holes, and may have an equivalent in the hard dolomitic limestone at the top of the Ghuzah bed in the Thaniyat Turayf area.

South of Wadi as Sirhan, towards Kahshm al Uqab (lat. 29°35'N, long. 39° 20'E), the Kuwaykabah Limestone Member has a thickness of 30 m and comprises a crystalline, slightly sandy, and in places conglomeratic, dolostone.

The Kuwaykabah Limestone Member crops out in the flat, featureless Al Hamad plain, where the plain dissected by wadis. In these wadi cuts, the member is represented by a leached, chalky dololimestone, variably silicified, bioclastic, buff to off-white dolomitic limestone, with bivalve and gastropod debris. In the Jalamid area, it is represented by a coarse bioclastic carbonate intercalated with argillaceous limestones.

North of the ARGAS Line 250 N, The Kuwaykabah Limestone Member thins out (fig. 3.3 a) and along with the Thaniyat Phosphorite Member pinches out towards the northwest, east of the Turayf town, where the Bardawil Formation directly overlies probable Late Cretaceous (Aruma Group).

2.2 The Bardawil Formation :

This formation was named after Wadi Al-Bardawil, which drains in the northern extension of the Khawr Umm Wu'aal graben. The term was introduced by El-Naggar and others (1982) to include early Middle Eocene rocks that overlie the Hazm-al-Jalamid Formation and underlie the Turayf Formation (table 1.2). This definition was followed by El-Naggar & Kamel (1988) where the age of the formation was extended to cover most of the Early Eocene (Ypresian) in addition to the early Middle Eocene (early Lutetian).

The Bardawil Formation was apparently deposited in an inner shelf subtidal to restricted shelf environment, with fluctuating sea levels. The formation is best exposed in the Thaniyat Turayf area (fig. 3.3 b), where it ranges in thickness from 30 m to 190 m.

The base of the formation possibly marks a depositional break during which the sediments of the Hazm-al-Jalamid Formation might have been eroded and reworked prior to the onset of another transgression and the renewal of phosphorite deposition of the Ghinah Phosphorite Member. The initial transgressive phase of the Bardawil Formation appears to have been less energetic or short lived than that of the Jalamid, and phosphorite accumulations at its base are less well developed.

Deposition of the Bardawil Formation appears to have been relatively continuous across previously emergent areas between the Thaniyat Turayf and the Quraymiz areas (cf. Riddler and others, 1985).

The Bardawil Formation is divided into four members (from the base upwards) as follows :

1. The Ghinah Phosphorite Member

2. The Hawsa Limestone Member
3. The Mindassah Limestone Member
4. The Sib Limestone Member

2.2.1 The Ghinah Phosphorite Member :

The Ghinah Phosphorite Member is best exposed in the Thaniyat Turayf area, where it occurs as float and bedded outcrop. Regional thickness and facies variations are not so marked within the member, except for an increase in chert at the expense of phosphorous content. The member ranges in thickness from 0 m to 15 m and comprises an interbedded sequence of thin (10-30 cm) phosphorite beds (up to 4 beds) with interbeds of weakly phosphatic, micrites, claystones, chert, minor bioclastic beds and buff to yellow fissile shales. Near the base of the member is a coarse silicified bioclastic limestone bed.

The phosphorite beds are generally semi-friable to hard, calcareous, with medium-sized pellets, bioclastic debris and sharks' teeth. The top phosphorite bed is commonly conglomeratic, with a slightly sandy, glauconitic matrix and poorly sorted coarse phosphorite pellets and chert pebbles.

Thirty kilometers north of Shuwayhitiyah (lat. 30°16'N, long. 40° 14'E), the member is exposed, with a thickness that rarely exceeds 25 m .

Between the Wadi as Sirhan and the Quraymiz escarpment, the Ghinah Phosphorite Member is absent (fig. 3.3 b).

North of al Quraymiz, drillhole data indicate the Ghinah Phosphorite Member to be absent; its presence is detected in the vicinity of the ARGAS line 160 N, from where it develops northwards and forms the base of the Bardawil Formation, and extends through to the Iraq border (fig. 3.3 a).

2.2.2 The Hawsa Limestone Member :

The Hawsa Limestone Member consists of chalky, dolomitic, argillaceous or crystalline limestone, that is rarely bioclastic but has characteristic white chert bands and abundant quartz geodes, as well as fine nodules. It is best developed in the Thaniyat Turayf area, where. well-bedded, occasionally weakly-phosphoritic geode-bearing claystones, overlain by a thin interval of carbonate-cemented and siliceous phosphorites and chert occur at its base.

East of the Wadi as Sirhan, the Hawsa Limestone Member is not so well-developed. It crops out just north of Wadi Naysubah (lat. 30°03'N, long. 39° 50'E) and extends northwards from there, attaining thickness of 3 - 10 m, until it pinches out east of Khabrat Arus (lat. 31°10'N, long. 39° 92'E).

Northwest of al Shuwayhitiyah (near lat. 30°30'N, long. 40° 00'E), the member forms elongate mesa ridges capped by the Mindassah Limestone Member, in minor graben structures.

2.2.3 The Mindassah Limestone Member :

The Mindassah Limestone Member consists of buff, weathered, vuggy to hard, recrystallized, micritic bioclastic limestone. Coquina beds occur locally comprising gastropods, bivalves and foraminifera including *Nummulites*; minor interbeds of non-bioclastic limestone are also present.

North of al-Quraymiz, The Mindassah Limestone Member forms banks of nummulitic, bioclastic limestone and coquina, with thickness varying from 3-80 m, which constitute an important lithostratigraphic marker (fig. 3.3).

2.2.4 The Sib Limestone Member :

The Sib Limestone Member is the most distinctive lithological unit within the Bardawil Formation due to its high silica content and its resistivity to the processes of weathering. It is well exposed in wadi sections of the Thaniyat Turayf area and is represented by siliceous float capping gently undulating hills. It consists of thinly bedded (20-50 cm), pale-gray, silicified limestone and chert, phosphatic chert with lesser coarse calcite, chert, breccia and recrystallized sparry non-silicified micrite, calcareous nummulitic bioclastic limestone and several thin phosphorite beds. The Sib Limestone Member crops out north of Ar Riyyatan and covers a broad north to south trending belt 230 km long and up to 60 km wide, over Al Hamad plain, east of the Khawr Umm Wu'aal to the Iraqi borders. It is best exposed at the southeastern end of the Harrah basalts in the Wadi Mu'arak area (centered near lat. 30°28'N, long. 39°21'E) just north of Khabrat as Sib from which it takes its name

2.3 The Turayf Formation :

This formation has been named after the Turayf town, around which it is known to outcrop (cf. El-Naggar and others, 1982). It includes thinly bedded, Lutetian limestones and cherts that outcrop in the extreme northwestern corner of Saudi Arabia and extends westwards into Jordan, where these become capped by marly and nummulitic limestones that constitute the Hibr Hill and its surroundings. The formation represents the third and last sedimentary carbonate cycle of the Hibr Group and was deposited in an intertidal to inner shelf subtidal, restricted shelf environment. However, the abundance of planktonic foraminiferid remains suggests the past presence of an access to more open water.

Features of the formation are well-documented from drillholes in the Umm Wu'aal North area, and the best surface exposures are found as inliers within the basalt cover of the Al Amud area. Generally thickening towards the northwest, it is some 50 - 250 m thick.

In the Thaniyat Turayf area, the formation is represented by a much deeper lateral facies equivalent (the Hidrij Member). Outcrops form elongate ridges and isolated mesas in an area centered at 30°30'N, 37°47'E.

Northeast of the Wadi as Sirhan area, the best surface exposures of the formation are found in wadis and as inliers within the basalts of the Al Harrah in the Al Amud area, mainly in Wadi Tarbah (Lat. 30°51'N, long. 39°08'E), Wadi Shihyah (Lat. 30°03'N, long. 38°39'E), Wadi U'ayli (Lat. 30°36'N, long. 38°41'E), and Wadi Rushayda. It also occurs north and east of the basalt cover, straddling the Khawr Umm Wu'aal Graben, and extending to the Iraqi and Jordanian borders. The basal contact in this part of the region

(between the Arqah Phosphorite Member and the underlying Sib Limestone Member) is presumed to be a disconformity, but there is some drilling evidence to suggest that the contact may be an angular unconformity in the Umm Wu'aal North area. The contact itself varies from a sharply defined lithological break to a diffused zone of coarse secondary calcite more than 5 m thick. In outcrop, the nature of this possible unconformity is not readily apparent, but pervasive silicification of the underlying Sib Limestone Member of the Bardawil Formation suggests a time gap between the two formations.

Northeast of the Wadi as Sirhan, the formation, together with the Bardawil Formation is cut by faults and prominent lineaments which affect the continuity of its members.

Equivalents of the Turayf Formation in the southern part of the studied area were included into seven distinctive members (from base upwards) as follows :

2.3.1 The Arqah Phosphorite Member :

The Arqah Phosphorite Member in the Al Amud area varies in thickness from 6-17 m and consists of interbedded, finely crystalline limestones, bioclastic limestones, brown phosphatic cherts, chert lenses and carbonate-cemented pelletal phosphorite lenses in the north in Wadi Tarbah. Further south, at Wadi Rushayda, relatively massive, carbonate-cemented to semi-friable upward fining pelletal and finely bioclastic phosphorite unit (with a few barren and silicified phosphorite interbeds) overlies a bioclastic and cross-bedded limestone.

In the Umm Wu'aal North area, the member varies in thickness from 2-27 m and consists of interbedded , finely crystalline limestones, bioclastic limestones, cherts and pelletal phosphorite.

West of the Khawr Umm Wu'aal, the Arqah Phosphorite Member thickens steadily to over 40 m, down-dip to the west, where argillaceous carbonate indicate a deeper water facies. The member's average thickness also increases towards the south, along strike, with an increase in its limestone and chert content; drillholes in the Umm Wu'aal South area indicate the continuity of thin, non-friable, phosphorite beds within the member through to the north end of the Al Amud area.

2.3.2 The AL-Amud Limestone Member :

The AL-Amud Limestone Member is sub-divided into the Ma'da Coquina, the Rushayda Claystone and the Rushayda Coquina Beds.

The Ma'da Coquina bed (0-31.5 m) is confined largely to the Umm Wu'aal area, where it is the sole representative of the member. It comprises an elongate, lenticular, north-northeast-trending bank complex, consisting of medium to finely comminuted bivalves, nummulitic in its upper part, all set in a calcitic matrix.

The Rushayda Claystone Bed (5-20 cm) is a thinly bedded succession of weathered white, pale-yellow to pale-green and gray, porous, fine-grained, silicified claystone, argillaceous thinly bedded limestone, and thin discontinuous bands and lenses of brown to gray cherts. Thin horizons of pelletal phosphorite and calcite geodes are associated with this bed. It is overlain by the Rushayda Coquina Bed (0-10 m) which is

restricted to the vicinity of Wadi Rushayda and contains abundant Nummulitic remains and bivalve fragments.

2.3.3 The Hamad Limestone Member :

The Hamad Limestone Member overlies the Al-Amud Limestone Member, except west of the Khawr Umm Wu'aal where it directly overlies the Arqah Phosphorite Member, the Ma'da Coquina Bed being absent in that area too. The Hamad Limestone Member varies in thickness from 20-80 m.

In the Umm Wu'aal area, the lower part of the Hamad Limestone Member is a slightly argillaceous, poorly phosphatic limestone characterized by red-brown cherts. Its upper part is a buff to off-white well bedded, hard, finely crystalline limestone with thin (1-5 cm) discontinuous interbeds and nodules of gray-brown chert.

West of the Khawr Umm Wu'aal graben the Hamad Limestone Member becomes slightly siliceous, with pale-brown to gray chert interbeds.

In the Amud area, the Hamad Limestone Member is best exposed in Wadi Tarbah and consists entirely of well-bedded gray to buff, hard, fine grained limestones with thin interbeds, lenses and nodular bands of brown chert.

2.3.4 The Tarbah Nummulitic Limestone Member :

Probably through erosion, the Tarbah Nummulitic Limestone Member is now restricted to the west and southwest of the Khawr Umm Wu'aal where it is represented by a 2-18 m thick succession of the chemically pure, recrystallized, bioclastic limestone, with casts of pelecypods, gastropods and some bryozoa near the base while the upper part of

the member has a distinctive nummulitic horizon. It can be traced in drillholes and outcrop along strike for 125 km between Jabal Umm Wu'aal (Lat. 31°50'N, long. 38°55'E) and Wadi U'ayla (Lat. 30°36'N, long. 38°41'E).

North of the Harrah basalts the member is poorly exposed and forms thin sheet-like beds of nummulitic, recrystallized carbonate with some bivalve debris. In the Al Amud area, where the member is well exposed in some of the windows in the basalt, it pinches and swells, varying in thickness from 2-11 m.

2.3.5 The Shihiyah Limestone Member :

The Shihiyah Limestone Member directly underlies most of the flat, undulating plain west of the Khawr Umm Wu'aal. Its outcrop is generally poor and its crystallized limestones and brown cherts are similar to those of the Hamad Limestone Member except that the Shihiyah Member contains a high proportion of caramel-colored chert.

East of the Wadi as Sirhan, the Shihiyah Limestone Member directly overlies the Hamad Limestone Member and although the contact between the two members is not obvious, the deeper water facies that characterizes the Hamad Member there is not represented in the Shihiyah Member.

In Al Amud area, in Wadi ash Shihiyah, outcrops of the Shihiyah Member consists of rhythmically and thinly interbedded laminated buff to white finely crystalline limestones and chert lenses 5-10 cm thick; some of the cherts are phosphatic. Further south, in Wadi Tarbah, the member contains both silicified and slightly phosphatic limestones.

2.3.6 The Jirani Chalky Limestone Member :

The Jirani Member is a thin bedded , distinctively white chalky limestone containing a minor amount of fossil debris and , along bedding planes, some gypsum. Its outcrop is restricted to a small area west of Turayf town, adjacent to the Jordanian border.

2.3.7 The Hidrij Shale Member :

A deeper-water lateral facies equivalent of the Turayf Formation in the Southwestern area was included under the name Hidrij Shale Member (cf. Riddler and others, 1986). The basal part of the member consists of dark yellow, to brown, to green highly fissile shales intercalated with more massive shaly to silty dolomitic beds. These are overlain by massive, variably dolomitic, silty limestones and claystones with pale-gray chert fragments.

CHAPTER FOUR

TECTONIC SETTING AND STRUCTURAL FEATURES OF THE SIRHAN-TURAYF BASIN

4.1 General Discussion :

The long, relatively narrow tract of the earth's crust that includes the area of the present-day Mediterranean Sea and the great ranges of the Alpine-Himalayan chain was one of the world's most extensive geocynclines. Geologists call this ancient tract of water "the Tethys Seaway", or "the Mesogene Seaway".

During the Early Paleozoic time and in its western reaches, this Seaway lay between the African and the Baltic shields; to the east it was open south of the Asian block until the close approach of India in the late Cretaceous time.

During the Late Paleozoic, the "Tethys Seaway" continued to act as a water barrier between lands of the Southern and the Northern Hemispheres. What is now central and southern Europe, the Mediterranean Sea, and North Africa (north of the Sahara) was occupied by a succession of shifting seas, swamps, lakes, and sandy low lands, which received a great variety of sediments. This belt occupied an unstable position between the

rigid Baltic Shield to the north and the African platform to the south and was in a state of constant unrest. By contrast, most of central and southern Africa remained stable and above water.

During the Mesozoic Era, the Tethys was still down-sinking and receiving great thicknesses of sediments. Compared with rocks of similar ages elsewhere, the sediments of the Tethys Seaway are exceptionally rich in carbonate rocks (limestones and dolomites). In the Late Jurassic-Early Cretaceous, fairly intensive phosphorite deposits were laid down at the northern margin of the Tethys (in both the Volga and Aktyubinsk basins, Union of the Russian Republics), culminating with the formation of deposits of nodular phosphorite (cf. Baturin, 1982). The most favorable conditions for phosphorite formation arose later, toward the end of the Cretaceous and the beginning of the Paleogene, on the vast shelf area along the southern margin of the Tethys basin. The Late Senonian-Paleogene time was characterized by exceptionally extensive distribution of numerous phosphorite deposits, particularly in the African-Arabian province. The lower limit of this phosphorite belt coincides with the Campanian-Maastrichtian Boundary, with which the phosphorites of Egypt, Palestine, Jordan, Syria and Turkey - on one side - and, Tunisia, Algeria, Morocco, Mauritania, Angola, Congo, Columbia and Venezuela - on the other side are associated. Occasionally, phosphorite beds occur higher up in the Paleogene with which the phosphorite deposits of both western Iraq and northwestern Saudi Arabia are associated. The upper age limit of these deposits corresponds to the Middle Eocene.

The formation of the phosphorite deposits on the shelves of the Tethys apparently occurred under the influence of a powerful north equatorial trade-wind current flowing from east to west. In its western part, the Tethys Seaway was bounded on both sides by

well-defined continental areas, other sites of Mesozoic marine deposits are mainly marginal to continental masses, bordered by land areas on one side only. During the Cenozoic Era, the Tethys deposits were dramatically elevated into great mountain ranges, including the Atlas, Alps, Apennines, Taurus, Zagros and the Himalayas. It is in these regions that we can read the record of the previous history of the Tethys.

4.2 Geotectonic History of the Study Area :

The earliest recorded structures in the region appear to be at least of post-Devonian age.

The Mesozoic Era (245 m.y. B.C.- 65 m.y. B.C.) lasted for estimated 180 million years during which drastic alterations took place in the distribution of continents and ocean basins. These include the inception of the fragmentation of Gondawana which began to break apart and the beginning of formation of both the Atlantic and the Indian oceans through sea-floor spreading and continental drift. Towards the end of the Jurassic, incipient rifting and large-scale strike-slip faulting were active upon a large part of the west-Tethyan realm, leading to the early stages of the separation of Arabia from Africa.

The movement of the newly-formed Arabian plate was partly accommodated by the sinistral, strike-slip motion along the Gulf of Aqaba-Dead Sea lineament. The most obvious structural features created by these tensional stresses are a tightly spaced set of normal faults and horst and graben structures, sub-parallel to the Red Sea coast. These structural trends have greatly influenced the depositional environment during the Late Mesozoic-Early Cainozoic times, by creating a lobate shoreline of broad embayments with northwest trending axes particularly in the Sirhan-Turayf area of northwestern Saudi

Arabia and its northward extension in Central Jordan. The corrugation of the substrate, caused by these structures, appears to have decreased in amplitude away from the Dead Sea lineament, in what is now an easterly direction.

4.3 Structural Features of the Sirhan-Turayf Area :

Significant NNW-SSE trending structures, such as the Ha'il Arch complex and both the Wadi as Sirhan and the Khawr Umm Wu'aal grabens dominate the region. Parallel lineaments include Ar Riyyatan, Al Busayta and Al Qasa'im fault systems. Numerous parallel and diagonal smaller lineaments (some of which show displacements) have also been recorded. These have N-S or even NNE-SSW trends. Such structures have seriously influenced the distribution of phosphorite accumulations in northwestern Saudi Arabia, and the most important elements of which can be reviewed as follows :

4.3.1 The Ha'il Arch Complex :

The Ha'il Arch Complex is one of the most important structural features in the region. It is a broad, block-faulted, NNW-SSE trending structure, which stretches from Ha'il on the northern tip of the Arabian Shield to the city of Mardin on the Syrian-Turkish borders. It now manifests itself at surface as a broad, doubly plunging anticlinal structure locally displaced by faulting. Based on both surface and subsurface data, it is believed that the Arch Complex started to move in post-Devonian times, at least when it acted as stable positive features surrounded by longitudinal sub-basins throughout the Carboniferous-Middle Cretaceous times. Parallel structures (e.g. the Jalamid syncline and both the Khawr Umm Wu'aal and the Wadi As-Sirhan Grabens) have apparently affected

the pattern of sedimentation at least since the time of deposition of the Late Cretaceous Aruma Group. Subsequent Early Paleogene deposition indicates a separation of sedimentation and faunal assemblages, along these structures, between the Eastern Arabia sub-basin and the Northwestern Arabia (or the Sirhan-Turayf) sub-basin. This has led to the distinction of the phosphoritic / calcareous rocks of the Hibr Group in the northwest from the chronostratigraphically equivalent carbonate and evaporite Hasa Group in the east.

The Ha'il Arch Complex had a regional tectono-sedimentational significance in separating these two sub-basins as a relatively stable marine platform in the east (the Eastern Arabia sub-basin) and a northwestern sub-basin of major tectonic disturbance and volcanism (Sirhan-Turayf sub-basin). Later foldings such as (the Badanah uplift and its parallel structures of N-S, NNE-SSW or even E-W directions) have apparently been superimposed on the older folds during the late Cretaceous time. Similarly, Red Sea and Gulf of Aqaba fault lines clearly dissect the outcropping rocks in the area.

4.3.2 The Badanah Uplift :

Uplift and erosion occurred after the deposition of the Aruma Group in the late Late Cretaceous time. This uplifting movement, commonly known as the Badanah uplift, is reflected by facies variations within both the Aruma and the Hibr Groups (compared to their lateral equivalents in the east), as well as by the angular unconformity between these and older rocks, in the region. The axis of this plunging anticlinal uplift (which trends almost N-S) runs to the east of the Ha'il Arch, and crests along a line somewhere between the town of Hazm-Al-Jalamid and Badanah. The observation that the Badanah uplift post-

dates the lower part of the Aruma Group is based on the fact that these sedimentary rocks thicken across it. The uplift is also reflected in a facies change in younger sedimentary rocks which indicate the creation of a much shallower water environment, with intertidal conditions and little or no deposition in the northeastern parts of the region, over the plunging anticline. These later strata dip gently (0.5°) off either side of the anticlinal axis formed by the Badanah uplift, and thin towards it, reflecting its role as a controlling factor for the deposition of the Hibr Group.

4.3.3 The Wadi as Sirhan Graben :

The Wadi as Sirhan Graben generally strikes NW-SE, extending for more than 300 km, with a width that ranges from 10 to 40 km. It is occupied by extensive deposits of Miocene carbonates, shales and gravels, and is covered by undifferentiated Pleistocene-Holocene deposits including eolian sands. The graben has a downthrow of up to 3500 m in its northwestern part, and is probably hinged where it narrows towards the southeast.

4.3.4 The Khawr Umm Wu'aal Graben :

The Khawr Umm Wu'aal Graben, in the northern part of the region, forms a relatively shallow depression trending $N 30^\circ W$, is 6 to 10 Km wide and 120 Km long, extending from the basalts of Harrat al-Sham near Khabrat Arus, northwestwards to the Jordanian borders.

The graben depression in the flat-lying Al Hamad plain is important as it provides rock outcrops (of each of the Sib, the Arqah Phosphorite, the Tarbah and the Shihyah Members) along its edges. The graben is filled with Miocene and younger deposits.

Faulting probably dates from the Paleocene times, inferred from the thickening of sediments of that age within the graben.

The Khawr Umm Wu'aal Graben gradually narrows southwards into a series of minor graben structures and NW-SE fault lines which terminate just north of al Shuwayhitiyah town.

4.3.5 The Busayta Lineaments :

The Busayta lineaments trend NNW-SSE along the eastern extremity of the Hibr Group outcrop in the southwestern part of the study area. These lineaments represent the western fault boundary of the Wadi as Sirhan graben, while the Wadi as Sirhan fault forms its eastern boundary (fig. 3.3 b). The trace of the latter through the basalt cover is marked by an alignment of volcanic vents.

4.3.6 The Ar Riyyatan Fault Complex :

The Ar Riyyatan fault complex occupies a wadi northwest of the town of Al Jawf and northeast of al Quraymiz, on the southern escarpment, in the vicinity of latitude $30^{\circ} 06' N$, and longitude $39^{\circ} 40' E$. Faults strike NNW-SSE over a distance of approximately 32 km from the escarpment to Khabrat as Sib; the Tawil Formation is faulted against the Jauf Formation towards the south of the complex. It is important to note that to the east of Ar Riyyatan, the regional dip of the Tawil Sandstone and subsequent pre-Paleogene strata is to the east and northeast, up to at least the Hudayb Limestone.

4.3.7 The Qasa'im Fault System :

The Qasa'im fault system is a series of lineaments striking through the southwestern part of the study area in a NNW-SSE direction, extending from the Wadi Hidrij near the Jordanian border southwards to the Thaniyat Turayf escarpment. A marked physiographic change across this lineament from a deeply incised plateau in the west to a broad flat plain in the east, suggests its faulting nature.

4.3.8 Other Lineaments :

Added to the above structures, the Sirhan-Turayf area has numerous other lineaments trending N-S, NNE-SSW, NE-SW and E-W.

4.4 Relationship between Structural Features and Phosphorite Occurrences :

It is assumed that the prime sites for sedimentary phosphorite deposition and accumulation are those where local topographic features are present on gentle sub-marine shelf slopes developed off emergent paleotopographic highs. This assumption is in good agreement with observations made in the Sirhan-Turayf region, where phosphorite occurrences have been greatly affected by the prevailing topographic and structural features during and after deposition. Specific examples are as follows :

1. In Al Amud area, slopes of dome structures, centered on the southern part of Wadi Rushayda and at Wadi Tarbah, controlled the deposition of the Arqah Phosphorite Member and the later distribution of basaltic flows.

2. In the Umm Wu'aal North area (east of the Khawr Umm Wu'aal graben) local doming due to gentle folding, trending NW-SE, created a shoal around which significant lag deposits of phosphorite were deposited, the thickest being on the western side of the paleofeature (Arqah Phosphorite Member). Most faulting in the area is probably related to the development of the Khawr Umm Wu'aal graben and post-dates both the deposition and lithification of the phosphorites.
3. In the Jalamid area, local paleohighs on the slopes of plunging anticlines played an important role in the distribution of the lower and upper beds of phosphorite within the Thaniyat Phosphorite Member. Phosphorites were deposited in a huge synclinal structures (the Jalamid syncline) on the southern and southwestern sides of a huge structure that extends almost parallel to the Ha'il Arch. Post-depositional folding has slightly modified this picture as it brought the thickest part of the phosphorite accumulation (formerly deposited in a sea-bed hollow) nearer to the surface in the northern prospect (fig. 3.4) and as a result, the phosphorite beds were beneficated by weathering (see chapter 8). Based on close-spaced drilling results over the northern prospect, there appears to have been little effect on the phosphorite beds from post-depositional faulting. A NE-SW lineament is in alignment with a possible syn-sedimentary fault line, which has apparently acted as a depositional control in the southern part of the area, and southeast of which phosphorites are not recorded (cf. Van Eck & others, 1984).

4. In the Southwestern area, post-depositional progressive step faulting probably relates to the formation of the Wadi as Sirhan graben, and effectively puts the more significant Thaniyat Phosphorite Member to depths below overburden beyond the reach of surface strip quarrying.

CHAPTER FIVE

PETROGRAPHY OF THE STUDIED

PHOSPHORITE DEPOSITS

5.1 General Discussion :

Phosphorite and phosphoritic sediments are difficult to describe because of their inherent complex nature as they are usually the product of three or more different sedimentary processes, followed by intermixing of numerous pure end members of sedimentation. These end members generally include the phosphorite minerals, the carbonate (both dolomite and calcite) minerals added to terrigenous material, organic matter and siliceous sediments such as the chert and / or the diatomaceous earth.

Most phosphorite deposits are composed of the mineral francolite, a cryptocrystalline or microcrystalline carbonate fluorapatite with highly varied forms (cf. Bushinski, 1935; Cook, 1972; 1976; etc.). Following Cook (1976) marine phosphorite deposits can be classified on the basis of grain size into the following three basic types :

1. Phosphoritic nodules (nodular phosphorite), with grain sizes of > 2 mm in diameter,

2. Phosphoritic grains and pellets (pelletal phosphorite), with grain sizes between 2 mm and 1/16 mm in diameter,
- 3 Fine-grained (predominantly clay-size) non-pelletal (structureless phosphorite) with grain sizes < 1/16 mm in diameter.

Significant differences in the genesis of each of these three basic types of sedimentary phosphorites are believed to exist.

5.1.1 Phosphorite nodules :

Phosphorite nodules measure several millimeters in diameter (between > 2 mm and several tens of centimeters), usually attain various shapes (spherical, lenticular, flattened parallel to the sedimentary bedding plane, etc.) and are formed by chemical or biochemical concretion around one or more centers, most frequently of organic origin (cf. Slansky, 1986).

The internal structure of such nodules is highly variable. Some are comparatively homogeneous and are composed predominantly of structureless francolite, or alternatively silt- and clay-sized terrigenous material in a francolite matrix. Others are layered, or concentrically banded, and have been ascribed to accretion or post-depositional weathering. Other nodules are of a compound nature, i.e. are composed of smaller nodules or angular fragments, cemented together in a conglomeratic or brecciated texture.

Nodular phosphorites are most abundant in both the platform-type deposits (such as those of the Moscow Basin) and the residual deposits (such as those of the Bone Valley Formation of Florida), and can be a relict feature of many disconformity and unconformity surfaces (cf. Cook, 1976).

5.1.2. Phosphorite grains and pellets :

Phosphorite grains range in diameter between 1/16 and 2 mm., being well-rounded to angular, spherical, lenticular or flattened, with or without a nucleus of some kind. Flattened grains are usually described as pellets, regardless of their origin, whether faecal or otherwise.

Phosphorite pellets are generally half-rounded to well-rounded, with a spherical ellipsoidal to a highly squashed and flattened form (fig. 5.1). These are composed of cryptocrystalline or microcrystalline phosphorite minerals and have no radial or concentric structure in general (cf. Pettijohn, 1957). Where the phosphoritic material is angular (figs. 5.2, 5.15) as is the case with some phosphatized fossil fragments, the term grain is preferred to pellet (cf. Cook, 1976).

Pellets may contain various forms of organic remains and / or mineral grains such as : foraminiferal or radiolarian tests, frustules of diatoms, undifferentiated organic matter, fragments of quartz, feldspar, or calcite grains, dolomite rhombohedra, etc. (figs. 5.3-5.7). Abundant organic matter such as carbon, or compounds such as hydrocarbon material commonly imparts a black to dark brown color to unweathered pellets.

In principle, the phosphorite pellet can vary in diameter from 10 μm to 2 mm, but in practice it is usually between 50 μm and 1 mm (cf. Slansky, 1986). Pelletal phosphorites are abundant in both geosynclinal and platform deposits (cf. Cook, 1976).

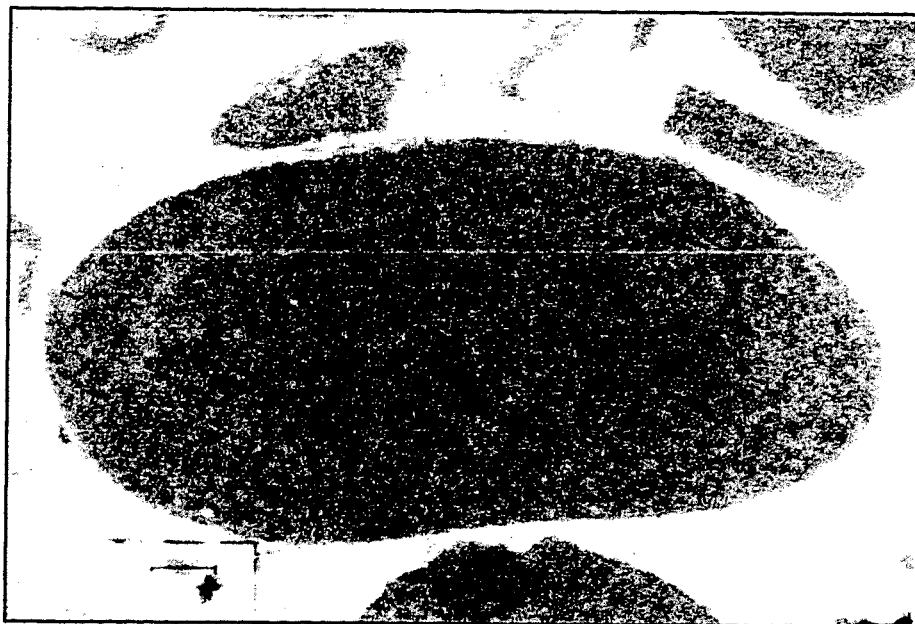


Fig. 5.1 : Photomicrograph showing well rounded, ellipsoidal & homogeneous Pellet . Sample from East Khawr Umm Wu'aal Phosphorite deposit.



Fig. 5.2 : Random section showing angular phosphorite grains , pseudo oolitic ovules with a rim of light colored apatite from where organic carbon has been removed by leaching, chert nodules and planktonic foraminifera, all embedded in a calcareous cement. Sample from East Khawr Umm Wu'aal Phosphorite deposit.



Fig. 5.3 : Photomicrograph showing random sections in phosphorite pellets growing around different mineral grains, fossil fragments or bone lathes, in a dolomitic calcitic cement. Sample from Turayf Phosphorite deposit (al Khatebah tunnel).

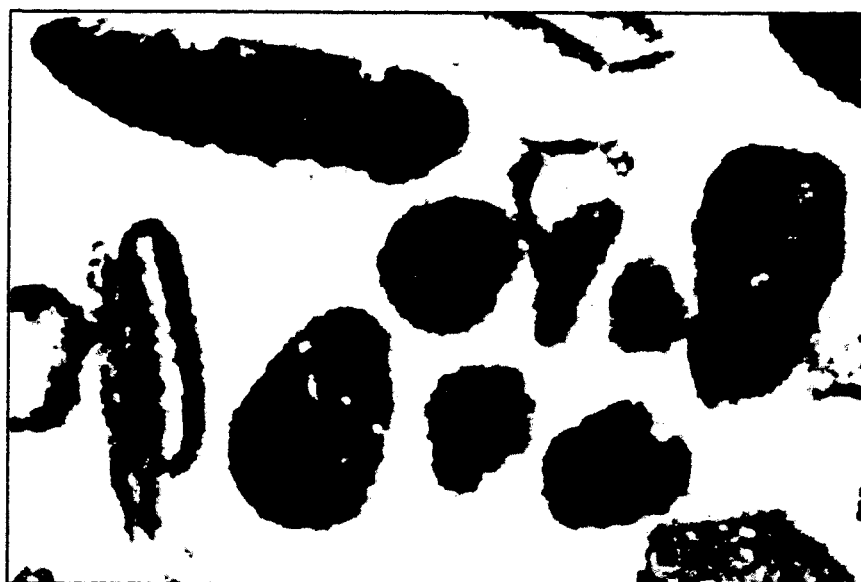


Fig. 5.4 : Photomicrograph showing random sections in phosphorite pellets, coprolith grains and bone lathes in a calcareous cement. The pellets are growing around bone fragments, calcite or quartz grains Sample from Turayf Phosphorite deposit.

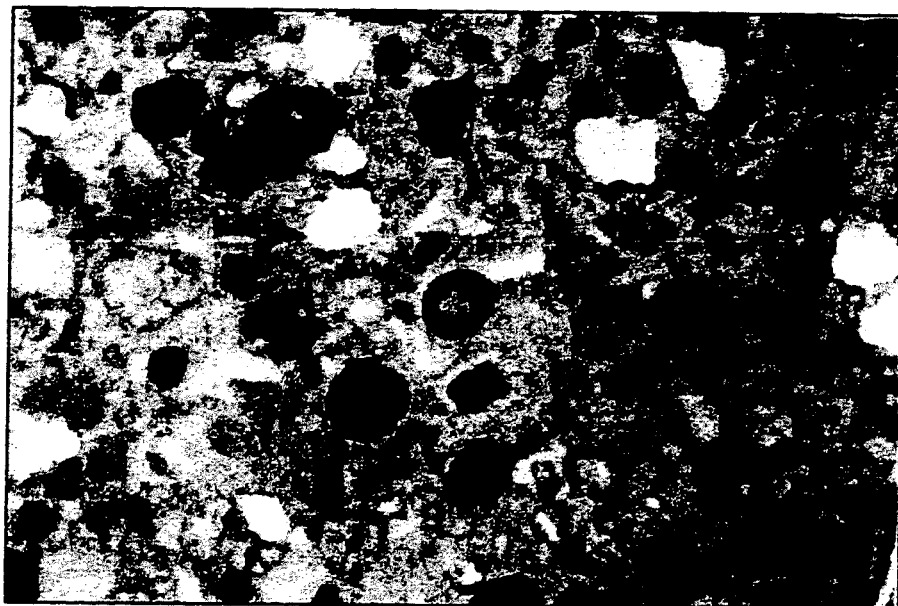


Fig. 5.5 : Photomicrograph showing abundant quartz grains around which phosphorite pellets are growing. Sample from Tubaiq Phosphorite Tunnel.



Fig. 5.6 : Photomicrograph showing an equatorial section in a tooth around which a phosphorite pellets grow. Sample from Turayf Phosphorite deposit.

Mabie and Hess (1964) described more than thirty different textures in phosphorite ores of the Western Phosphate Field (USA) including pelletal phosphorites. A modified version of their classification was used by Cook (1976), and this last version is used here, with further modifications as follows :

a. Ovular pellets or Ovules :

These represent one of the most common types of pellets in phosphorite deposits. Pellets of this type have a rounded to subrounded outline and generally show no internal structure (fig. 5.8). In some instances, weathering may produce a pseudo-oolitic appearance due to the marginal leaching of dark organic material (fig. 5.2).

b. Nucleated Pellets :

These consist of a nucleus of a single mineral grain or fossil fragment, around which precipitation of phosphoritic material has taken place (figs. 5.3-5.7). In some cases the nucleus itself may be completely phosphatized leaving a “ghost” behind, as a reminder of its previous existence at the center of the pellet.

c. Polynucleated Pellets :

Where the nucleus consists of two or more detrital grains or fossil fragments. Many of these pellets form in much the same way as the nucleated pellets except for the fact that the pellet formed around a multiple nucleus. Others are believed to be of intraclastic origin, with abundant detrital grains scattered throughout the pellet. These



Fig. 5.7 : Photomicrograph showing phosphorite pellet with a carbonaceous nucleus surrounded by carbonaceous calcite, then phosphatized rime, together with other pellets, some of which nucleated with calcite while others are not, phosphatized bone lathes and coprolith grains in a dolomitic cement. Sample from al Khatebah tunnel, Turayf area.



Fig. 5.8 : Photomicrograph showing well-rounded phosphorite ovule embedded in a calcareous cement. Sample from East Turayf Phosphorite deposit.

polynucleated pellets probably formed when a lamina cemented by the interstitial precipitation of phosphorite became torn up and rounded to give a pelletal form.

d. Compound Pellets :

These are composed of two or more pellets or fragments of pellets cemented together and coated by an outer layer of phosphoritic material (fig. 5.9). An intraclastic origin is indicated where the pellets were broken then cemented together, and further accreted by outer skin of phosphoritic material around the multiple pellet.

e. Oolites :

These differ from rounded pellets in that they have a clear internal concentric structure (fig. 5.10), that may form by the “snowball” effect (i.e. gentle agitation of pellets resulting in rolling and the incorporation of phosphoritic and other material in the outer skin of the pellet).

f. Phosphoritic fossil fragments :

Phosphoritized fossil fragments (or in some cases, fragments of originally phosphoritic shells) form a significant proportion of some deposits (fig. 5.11).

5.1.3. Non-Pelletal Phosphorite :

This rock consists essentially of dense, light-colored, structureless francolite; that is either bedded or encrusting on siliceous or calcareous sediments, with a variety of terms such as “microsphorite” of Freas (1964), “collophane mudstone” of Trueman (1971) and



Fig. 5.9 : Photomicrograph showing compound pellet. Sample from East Khawr Umm Wu`aal Phosphorite deposit.

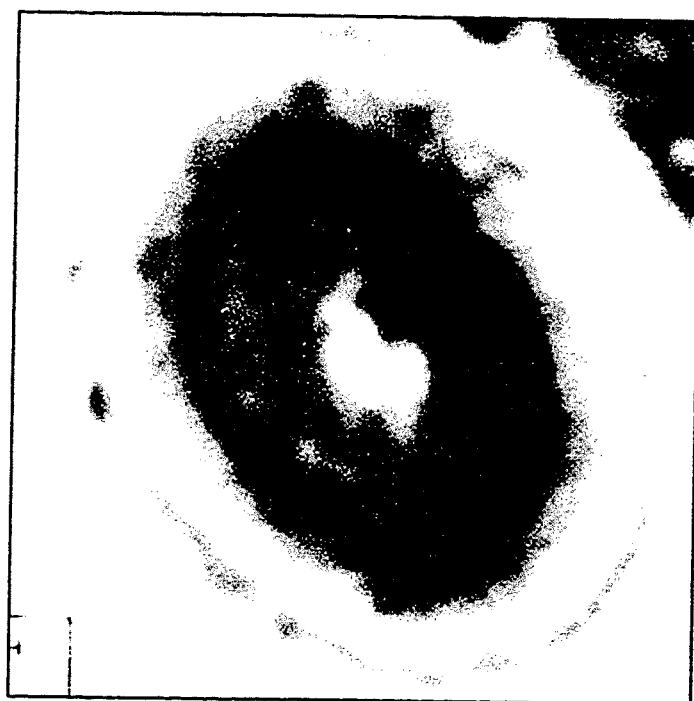


Fig. 5.10 : Photomicrograph showing Oolite with a calcareous nucleus. Sample from East Khawr Umm Wu`aal Phosphorite deposit.

the two terms “phospholutite” and “phoscrete” of Cook (1972). The former term was introduced in analogy with the term “calcilutite” to describe primary deposits of this type and the second in analogy with the term “calcrete” for secondary phosphorite deposits of supergene origin (cf. Cook, 1972).

5.2 Description of the Studied Phosphorite Deposits :

Based on the previous classification, the phosphorite deposits of the Sirhan-Turayf basin, northwestern Saudi Arabia, belong to the pelletal phosphorites (fig. 5.12), with occasional phosphorite nodules and coprolithic materials. They are mostly friable to consolidated, fairly to poorly sorted, fine to coarse grained and rarely granular. The main components are phosphorite pellets, ovules, nodules, coprolithic material, phosphatized fossils (e.g. bone and other fossil fragments, particularly fish remains) with minor oolithes and rare compound pellets.

The pellets occur in a number of widely varying forms, owing to differences in texture, structure, endogangue and diagenetic history.

Certain pellets are homogenous in appearance (fig. 5.1), with practically no endogangue. Others, though almost entirely apatitic, have very clear inclusions such as calcite, dolomite or quartz grains, fossil fragments (e.g. bone fragments, diatomaceous, radiolarian, foraminiferal and other fossil debris) all epigenized with phosphorite (figs. 5.3-5.7). A pellet may contain several grains, but only one generally takes a central position, around which the apatite is distributed in one or more layers.



Fig. 5.11 : Photomicrograph showing random sections in skeletal grains, ostracode valve, gastropode shell and milliolide shells, all are phosphatized and embedded in a calcite cement. Sample from East Khawr umm Wu' aal Phosphorite deposit.



Fig. 5.12 : Photomicrograph showing abundant phosphorite pellets and bone lathes in a dolomitic calcareous matrix. Some pellets are growing around a bone lath or calcite nucleus. Sample from al Khatebah tunnel, Turayf area.

Some pellets show marginal replacement of apatite by calcite, dolomite or silica (fig. 5.13), while the outer edge of others is covered by a cortex of hyaline apatite a few microns in thickness (fig. 5.14). Compound pellets are not uncommon (fig. 5.9).

Ovules are abundant, and show little or no internal structure, but are well rounded (fig. 5.8), with a low degree of sphericity. Oolithes (fig. 5.10) are rather less developed and form mainly around nuclei of foreign materials.

Coprolithes, are common and have different shapes and sizes (Figs. 5.15, 5.16). Indeed, most of the encountered pellets can be of faecal origin, and so are many nuclei. Other biogenic remains are also common, such as : fish scales and teeth, bone fragments, worm tubes, as well as foraminifer, radiolarian, ostracode, diatomaceous, bryozoan, sponge, echinoid and molluscan remains (figs. 5.3-5.7, 5.17-5.20).

The matrix is mainly composed of carbonate minerals (figs. 5.12, 5.17), but clayey matrix cannot be excluded (cf. Berge and Jack, 1982). These authors (op. cit.) recorded this clayey matrix in the Zone 1 Phosphorite of the Thaniyat Turayf area, and described it as mostly composed of montmorillonite, with minor amounts of palygorskite and kaolinite minerals, and significant quantities of the mineral goethite. These authors (*loc. cit.*) also mentioned that the layered nature of the clayey matrix suggests its simultaneous deposition with the pellets. In some cases the matrix is composed of phosphorite pellets (fig. 5.16).

Carbonate (either calcite or dolomite) dominates as a cement (figs. 5.2-5.4, 5.7, 5.11, 5.13, 5.15-5.16, 5.18, 5.20), although silica cement also occurs, in particular, at the

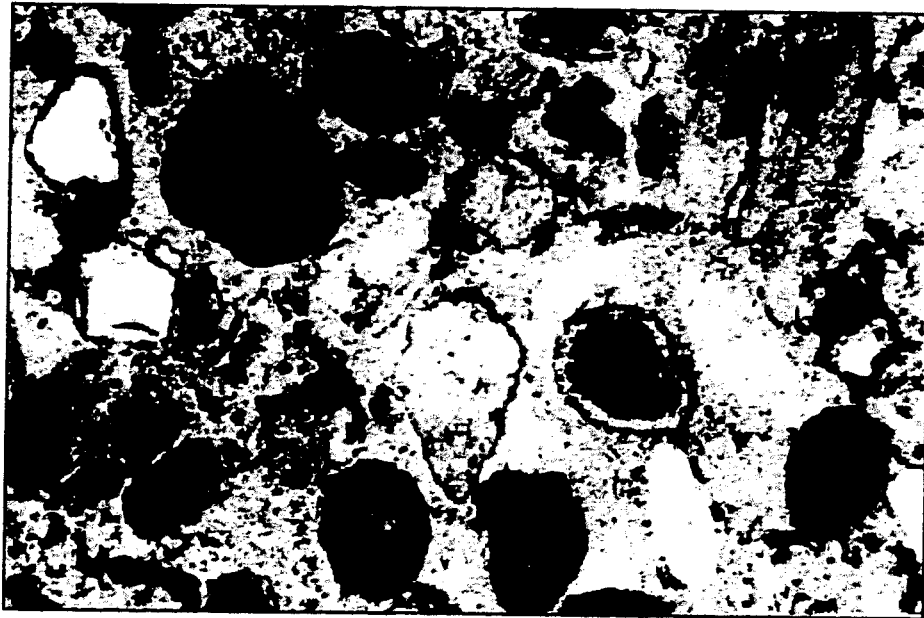


Fig. 5.13 : Photomicrograph showing sharply angular quartz grains with high polarizing colors (1st order), coprolithes, dark colored phosphorite pellets and grains with colored outer periphery being replaced by calcite or dolomite, dolomite rhombus, all embedded in a dolomitic cement. Sample from Tubaiq Phosphorite Tunnel.

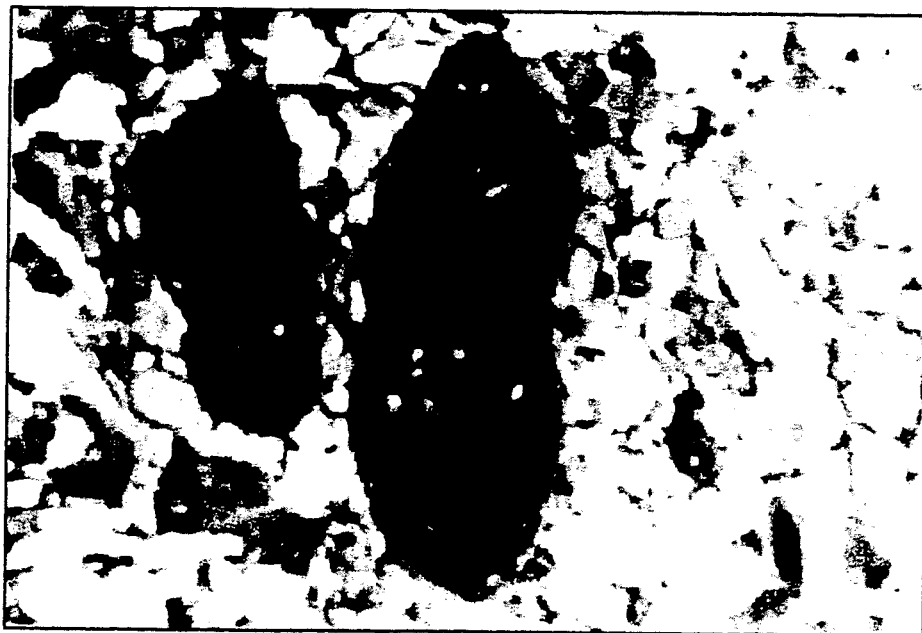


Fig. 5.14 : Photomicrograph showing phosphorite pellet with a cortex of hyaline apatite, bone lathes, angular to subangular quartz grains. Sample from Thaniyat Turayf Phosphorite deposit.

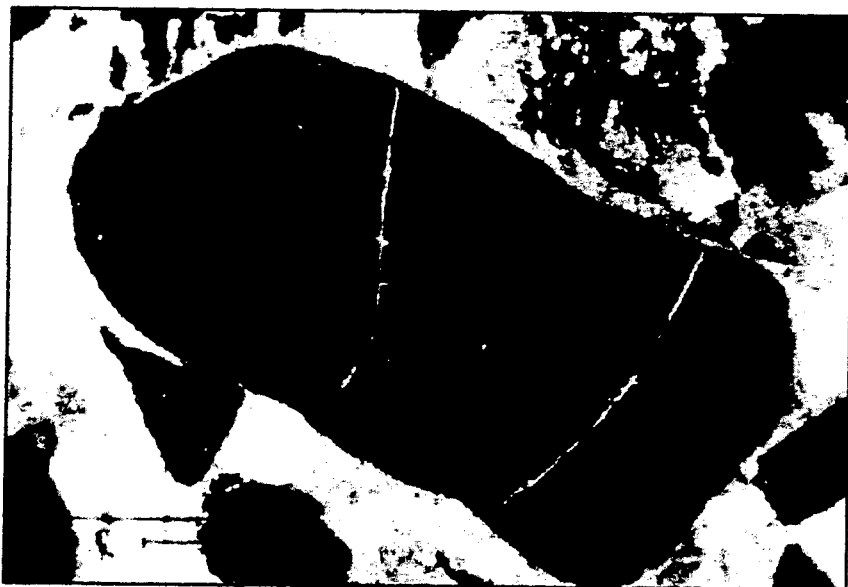


Fig. 5.15 : Photomicrograph showing large coprolith with cracks, angular phosphorite grains, all embedded in a calcareous cement. Sample from East Khawr Umm Wu'aal Phosphorite deposit.



Fig. 5.16 : Photomicrograph showing coprolith grain with phosphatized nucleus and replaced outer rime in a matrix of phosphorite pellets embedded in a calcareous cement.



Fig. 5.17 : Photomicrograph showing random section in fish teeth, coprolith grains, phosphatized pellets, worm tubes and echinoid spine in a dolomitic matrix. Sample from Turayf Phosphorite deposit.

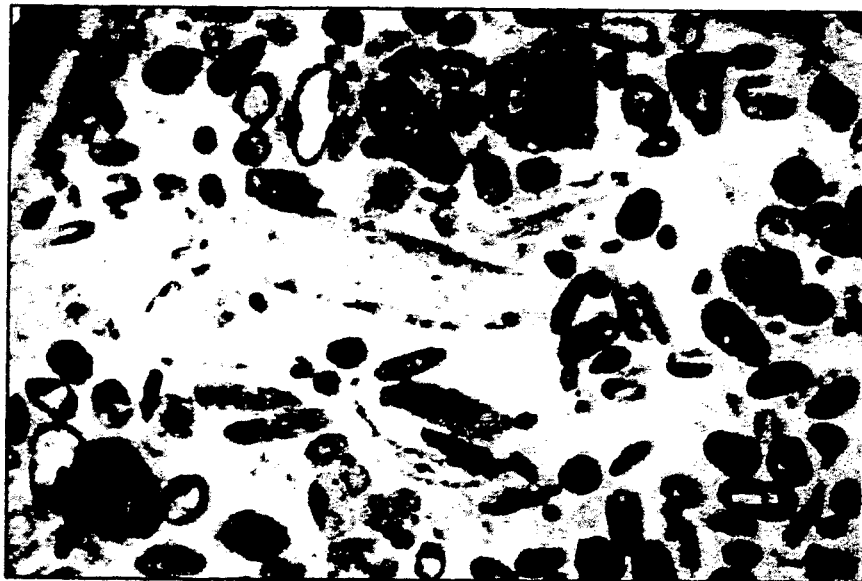


Fig. 5.18 : Photomicrograph showing random sections in sponge spicule, coprolithes, pellets, bone lathes inside phosphorite pellets, in a fine calcareous cement. Sample from al Khatebah tunnel, Turayf Phosphorite deposit.

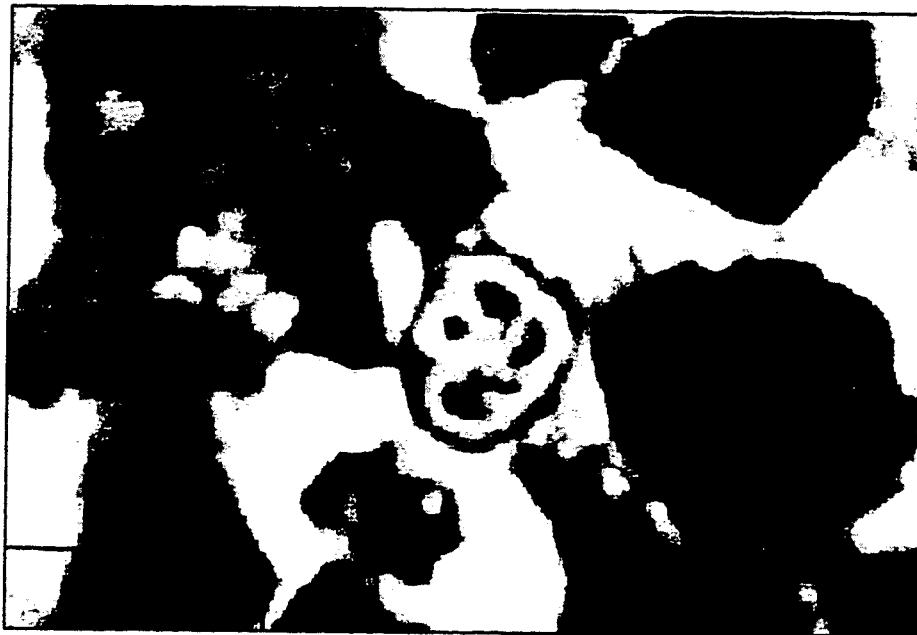


Fig. 5.19 : Photomicrograph showing phosphatized planktonic foraminifer shell with a dominantly calcareous test surrounded by microcrystalline apatite. Sample from East Khawr Umm Wu'aal Phosphorite deposit.

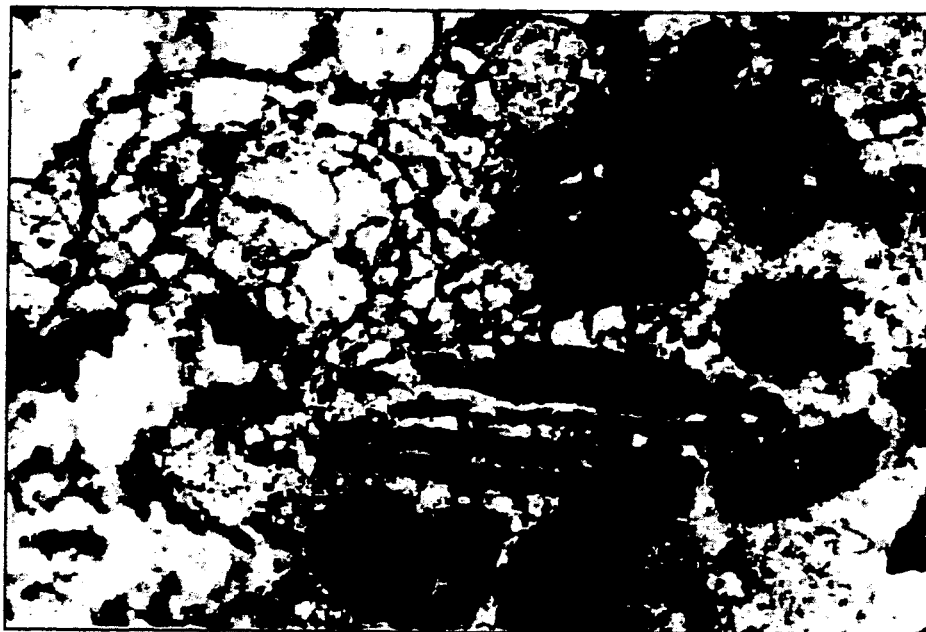


Fig. 5.20 : Photomicrograph showing random sections in phosphorite pellets, bone lathes, worm tubes, in a calcareous cement. Sample from al Khatebah tunnel, Turayf Phosphorite deposit.

Thaniyat Turayf area. Silicification of carbonate cement is also well documented. In some instances due to either winnowing or leaching, there is virtually no matrix, and the rock is composed of a sparsely cemented friable mass of pellets.

As previously noted, the endogangue materials show a wide range of variation, being composed of quartz, calcite or dolomite grains, fossil fragments, or carbonaceous material. Similarly the exogangue materials are also highly variable being either of calcareous or siliceous composition.

A carbonate exogangue is very common in Jalamid phosphorites, being predominantly calcitic, but dolomite is also present and is sometimes the most abundant mineral. Chert is also well recorded in the exogangue (fig. 5.2), particularly where silicification has taken place.

Clastic quartz grains are frequent in the exogangue of the Thaniyat Turayf phosphorites. The grains are angular to subangular (figs. 5.5, 5.13-5.14) suggesting immediate reworking from a nearby source, most probably the underlying Zallum or Tawil Sandstones. In some samples recovered from the contact of the phosphorite with the underlying Zallum Sandstone, some pellets have been observed in disintegrated fractions, suggesting a hiatus or reworking prior to deposition of the phosphorite horizon.

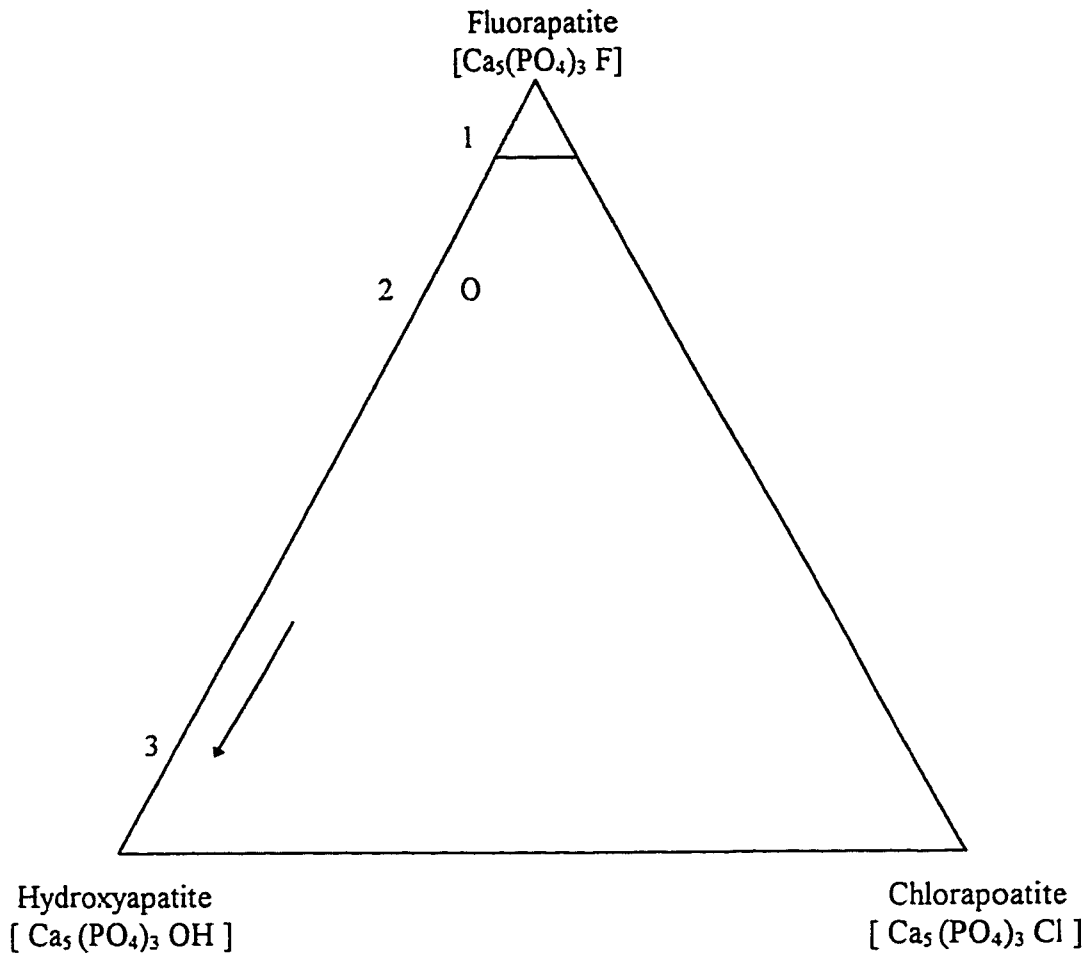
CHAPTER SIX

MINERALOGY OF THE STUDIED

PHOSPHORITE DEPOSITS

The element phosphorus (P) constitutes 0.10 % to 0.12 % of the earth's crust, 0.03 % of the total Earth and 0.11 % of Meteorites on the average. It never occurs as a free element in nature because of its strong affinity to oxygen, and occurs primarily as orthophosphates: PO_4^{3-} and is mainly contained in minerals, in the biosphere and in the ocean waters.

Over 200 mineralogical species have-so far-been identified in natural phosphorites, but many of these minerals are rare and the most widespread ones belong to the apatite family. The most abundant minerals in sedimentary environments are the calcium phosphates (although aluminum phosphates are also known). These can be placed in the apatite series : fluorapatite, chlorapatite and hydroxyapatite (fig. 6.1). However, phosphorites are seldom (if ever) composed of one end member as chlorapatites invariably contain fluorine and hydroxyapatites contain either fluorine or chlorine. The structure of the sedimentary apatite minerals can allow a set of isomorphic substitutions, of which, the most common is that of PO_4^{3-} by CO_3^{2-} and consequently the most frequent



1. Igneous rocks, and stable phase under sedimentary conditions.
2. Authigenic phosphorite in which CO_3^{2-} replaces PO_4^{3-} to a few percent.
3. Modern bones, teeth, etc.

Fig. 6.1 : The apatite mineral series (after Mero, 1966 and Simpson, 1972).

mineral in sedimentary phosphorites is the carbonate fluorapatite (francolite) which is represented by the formula $\text{Ca}_5(\text{PO}_4\text{CO}_3)_6\text{F}$. This mineral was previously named collophane or collophanite (colophanite) and was believed to be amorphous (cf. Slansky, 1986), but modern mineralogical studies have shown it to be cryptocrystalline or microcrystalline and to be made up of minerals of the apatite family. The name "collophanite", is a petrographic rather than a mineralogic term that refers to cryptocrystalline apatitic rocks, but specialists in the field no longer recommend the use of such term (cf. Slansky, 1986).

Phosphorites may also contain a number of non-apatitic minerals, that can be produced by the processes of weathering and diagenesis such as the lateritic alteration of pre-existing deposits of calcium phosphate. This can lead to the formation of aluminum phosphate minerals such as millisite $\{(\text{Na-K})\text{CaAl}_6(\text{PO}_4)(\text{OH})_9\cdot 3\text{H}_2\text{O}\}$, crandallite $\{\text{Ca}_2\text{Al}_6(\text{PO}_4)_4(\text{OH})_{10}\cdot 2\text{H}_2\text{O}\}$, wavellite $\{\text{Al}_3(\text{PO}_4)_2(\text{OH})_3\cdot 5\text{H}_2\text{O}\}$ and turquoise $\{\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8\cdot 4\text{H}_2\text{O}\}$ which are very common in the phosphorite deposits of Senegal, Brazil and Venezuela.

Other phosphorite minerals such as, autunite $\{\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2\cdot 10\text{-}12\text{H}_2\text{O}\}$ or meta-autunite $\{\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2\cdot 2\text{-}6\text{H}_2\text{O}\}$ have been reported in phosphorite deposits such as those at Bakouma, in the Central African Republic (cf. Gony, 1971), metayuyamunite $\{\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2\cdot 3\text{-}5\text{H}_2\text{O}\}$ (a yellow calcium-uranium-vanadate), monazite (a rare earth phosphorite mineral), goyazite $\{\text{Sr}_2\text{Al}_6(\text{PO}_4)_4(\text{OH})_{10}\cdot 2\text{H}_2\text{O}\}$, vivianite $\{\text{Fe}_3(\text{PO}_4)_2\cdot 8\text{H}_2\text{O}\}$, reddingite $\{\text{Mn}_3(\text{PO}_4)_3\cdot 3\text{H}_2\text{O}\}$, strengite $\{\text{FePO}_4\cdot 2\text{H}_2\text{O}\}$, fouchérite $\{\text{CaFe}_4(\text{OH}_8)(\text{PO}_4)_7\cdot 7\text{H}_2\text{O}\}$, monetite $\{\text{CaHPO}_4\}$, variscite $\{\text{AlPO}_4\cdot 2\text{H}_2\text{O}\}$, montgomeryite $\{\text{Ca}_4\text{Mg}(\text{H}_2\text{O})_{12}\text{Al}_4(\text{OH})_4(\text{PO}_4)_6\}$, etc. (cf. Fischer and Jerome, 1973).

It has been a common practice to consider as phosphorite any sedimentary rock with 50 % or more phosphorous minerals. However, as these vary greatly in their phosphorous content, it was found advisable to translate this into a P_2O_5 %.

A sedimentary phosphorite with 50 % fluorapatite, contains > 21 % P_2O_5 , but if this 50 % is represented by carbonate fluorapatite, the P_2O_5 content may be less than 17 %. In case of 50 % crandallite $\{Ca_2Al_6(PO_4)_4(OH)_{10}2H_2O\}$ or augelite $\{Al_2(PO_4)(OH)_3\}$, the P_2O_5 content is of the order of 20 %, while it is greater than 22 % in the case of variscite $(AlPO_4 \cdot 2H_2O)$, and less than 16 % in the case of vivianite $(Fe_3(PO_4)_2 \cdot 8H_2O)$ or goyazite $\{Sr_2Al_6(PO_4)_4(OH)_{10}2H_2O\}$.

In view of this variation, a P_2O_5 content of 18 % has been arbitrarily selected by Slansky (1986), as the borderline between phosphorites and phosphoritic rocks (rocks regarded as having 50 % or more phosphorous minerals and those containing less than 50 %), despite the fact that Pettijohn (1975) had placed that boundary at 19.5 % P_2O_5 .

In the present study, phosphorites with 19 % P_2O_5 (calculated from about 3000 samples, collected from 392 wells drilled over an area of about 800 km²) are found to contain 46.7 % phosphorous minerals, while those with 20 % P_2O_5 are found to contain 49.16 % phosphorous minerals, a figure close to 50 %. Consequently, a P_2O_5 content of 20 % is selected as the borderline between rocks regarded as having 50 % phosphorous minerals and those containing less than that.

6.1 Mineralogy of the Hazm al-Jalamid Phosphorite Deposit.

The Hazm al-Jalamid Phosphorite deposit (31°32' N., 39°56' E.) is located about 800 m above the sea level in a gently undulating, arid desert, 120 km east-southeast of

Turayf and about 25 km north of the Trans.-Arabian Pipeline (TAP Line). The deposit occurs at the base of the Paleocene Hazm al-Jalamid Formation, which is predominantly composed of a phosphorite-bearing carbonate / chert section. Two main phosphorite horizons and a third one of only local importance have been recorded.

The deposit is composed primarily of phosphatic peloids and intraclasts embedded in a well crystallized sparry calcite to dolomitic, finely crystalline matrix and cement. Minor quartz grains, chert fragments, rare gypsum and bassanite as well as minor amounts of metayuyamunite (a yellow secondary calcium-uranium vanadate mineral $\{Ca(UO_2)_2(VO_4)_2 \cdot 3H_2O\}$) have been recorded.

The dominant phosphorite minerals present include francolite (carbonate-fluorapatite), $\{Ca_5(PO_4 CO_3)_3F\}$ and dahllite (carbonate hydroxyapatite), $\{Ca_5(PO_4 CO_3 OH)_3(F,OH)\}$, which is produced by the partial replacement of F by OH in francolite (and hence the amount of fluorine is less than 1 %). As the average grade of the ore is in the range 19-21 % P_2O_5 , it is concluded that the substitution of PO_4^{3-} by CO_3^{2-} could never have been of any important role as the process usually lowers the P_2O_5 to less than 17 %.

Typical phosphorite grains range in diameter from 50 to 300 microns, averaging 215 microns. SEM observations (backscattered electrons) indicate that the grains have highly varying concentrations of elements, and hence are polygenetic and / or have had differing diagenetic histories. SEM observations and physical tests also indicate that the phosphorite grains break cleanly from the matrix, whether this is of sparry calcite, dolomitic micrite, or of mixed character. This can facilitate the liberation of the soft phosphorite pellets upon crushing the ore without destroying them which makes the ore amenable to beneficiation by the process of flotation. This is contrast with other

calcareous phosphorites in the region which fracture across, instead of around the apatite grains; and hence are not amenable to flotation but can only be concentrated by calcination.

The Hazm al-Jalamid Phosphorite deposit may be mineralogically described in terms of three major components : apatite (francolite), dolomite and calcite (tables 6.1-6.3). Figures 6.2-6.17 show iso-tenor maps and three-dimensional views (3-D) for the distribution of these three components in the Zones 1 and 2 Phosphorite of the Hazm-al Jalamid area..

In the Zone 1 Phosphorite, apatite has an average of 46.35 % (with a maximum of 57.2 % and a minimum of 40.21 %), dolomite of 36.69 % (with a maximum of 54.57 % and a minimum of 9 %) and calcite of 13.14 % (with a maximum of 42.82 % and a minimum of 0.5 %). The 3 components together account for an average of 96.18 % of the total minerals present (with a range between 92.53 and 98.31 %) (table 6.1).

These values reflect the dolomitic nature of the Zone 1 Phosphorite and indicate the effect of post-depositional changes (diagenesis), in particular, the leaching of calcite.

In the Zone 2 Phosphorite, apatite has an average of 46.88 % (with a maximum of 59.37 % and a minimum of 40.30 %), dolomite of 22.57 % (with a maximum of 53.22 % and a minimum of 0.98 %), and calcite of 24.48 % (with a maximum of 54.46 % and a minimum of 1.98 %). The 3 components together account for an average of 93.93 % of the total minerals present (with a range between 87.28 and 97.61 %) (table 6.2).

The overall average mineralogical composition of the Hazm al-Jalamid Phosphorite deposit (of 46.56 % apatite, 30.91 dolomite, and 17.78 % calcite, = 95.25 %)

**Table 6.1 : Mineralogical Composition of the Zone 1 Phosphorite
(Hazm Al-Jalamid Area)**

Serial No.	Well No.	Apatite %	Calcite %	Dolomite %	Total %
1	JAL713	44.45	6.34	45.54	96.33
2	JAL714	41.69	8.41	46.19	96.29
3	JAL716	43.10	5.22	47.24	95.56
4	JAL719	50.30	5.85	38.10	94.25
5	JAL720	42.18	6.43	49.70	98.31
6	JAL679B	48.42	6.22	41.69	96.33
7	JAL680	45.20	28.48	20.87	94.55
8	JAL681	49.11	5.30	41.45	95.85
9	JAL685	45.88	8.14	43.41	97.43
10	JAL686	51.04	11.12	35.39	97.56
11	JAL687	52.56	16.66	27.63	96.85
12	JAL690	48.79	8.14	38.10	95.04
13	JAL691	42.52	6.29	47.33	96.14
14	JAL692	40.21	2.34	54.57	97.12
15	JAL696	45.38	0.50	46.65	92.53
16	JAL707	48.74	4.60	42.37	95.71
17	JAL709	42.59	14.02	40.36	96.97
18	JAL725	47.19	10.59	37.79	95.57
19	JAL726	40.38	40.98	15.04	96.41
20	JAL727	44.89	30.16	21.29	96.34
21	JAL763	43.33	6.00	47.39	96.73
22	JAL767	44.48	25.50	26.79	96.77
23	JAL768	45.66	42.82	9.00	97.48
24	JAL769	44.74	9.60	42.73	97.07
25	JAL770	57.20	4.28	34.37	95.85
26	JAL718	54.94	27.76	12.90	95.60
	Maximum	57.20	42.82	54.57	98.31
	Minimum	40.21	0.50	9.00	92.53
	Average	46.35	13.14	36.69	96.18

**Table 6.2 : Mineralogical Composition of the Zone 2 Phosphorite
(Hazm Al-Jalamid Area)**

Serial No.	Well No.	Apatite %	Calcite %	Dolomite %	Total %
1	JAL713	51.80	23.45	20.00	95.25
2	JAL714	46.80	15.51	32.81	95.12
3	JAL715	45.32	12.86	37.14	95.32
4	JAL716	53.57	5.03	38.73	97.32
5	JAL719	40.70	2.43	53.22	96.35
6	JAL720	59.37	1.98	34.80	96.15
7	JAL675A	40.30	19.46	27.81	87.57
8	JAL683	51.19	18.46	22.75	92.40
9	JAL690	46.60	23.71	27.30	97.61
10	JAL691	49.04	25.86	18.93	93.83
11	JAL695	45.50	46.54	1.42	93.46
12	JAL696	46.41	21.88	26.04	94.32
13	JAL707	48.87	16.28	31.46	96.61
14	JAL709	44.48	41.34	1.46	87.28
15	JAL725	45.41	41.91	6.78	94.10
16	JAL768	41.56	54.46	0.98	97.00
17	JAL769	44.37	35.46	12.01	91.84
18	JAL770	42.58	34.00	12.63	89.21
	Maximum	59.37	54.46	53.22	97.61
	Minimum	40.30	1.98	0.98	87.28
	Average	46.88	24.48	22.57	93.93

**Table 6.3 : Mineralogical Composition of the Interval Zone
(Hazm Al-Jalamid Area)**

Serial No.	Well No.	Apatite %	Calcite %	Dolomite %	Total %
1	JAL713	19.3	6.26	68.21	93.77
2	JAL714	18.75	11.41	58.89	89.05
3	JAL715	25.70	7.64	60.08	93.42
4	JAL716	19.75	6.40	61.00	87.15
5	JAL717	20.92	4.44	62.82	88.18
6	JAL719	23.04	17.37	50.44	90.85
7	JAL720	23.22	8.81	60.55	92.58
8	JAL683	29.42	11.91	55.18	96.51
9	JAL685	15.13	11.23	60.96	87.32
10	JAL690	15.94	9.28	63.30	88.53
11	JAL691	15.00	9.31	68.26	92.57
12	JAL695	13.92	23.28	56.45	93.65
13	JAL696	17.12	4.52	68.20	89.84
14	JAL698	13.54	30.50	47.35	91.39
15	JAL705	12.51	16.06	62.57	91.14
16	JAL707	20.81	11.56	62.57	94.94
17	JAL709	20.57	13.46	58.18	92.21
18	JAL725	19.96	11.92	63.57	95.45
19	JAL726	21.67	55.03	14.38	91.09
20	JAL768	31.07	64.54	1.67	97.28
21	JAL769	25.03	15.33	54.79	95.16
22	JAL770	23.31	16.08	50.64	90.03
	Maximum	31.07	64.54	68.26	97.28
	Minimum	12.51	4.44	1.67	87.15
	Average	20.26	16.65	55.00	91.91

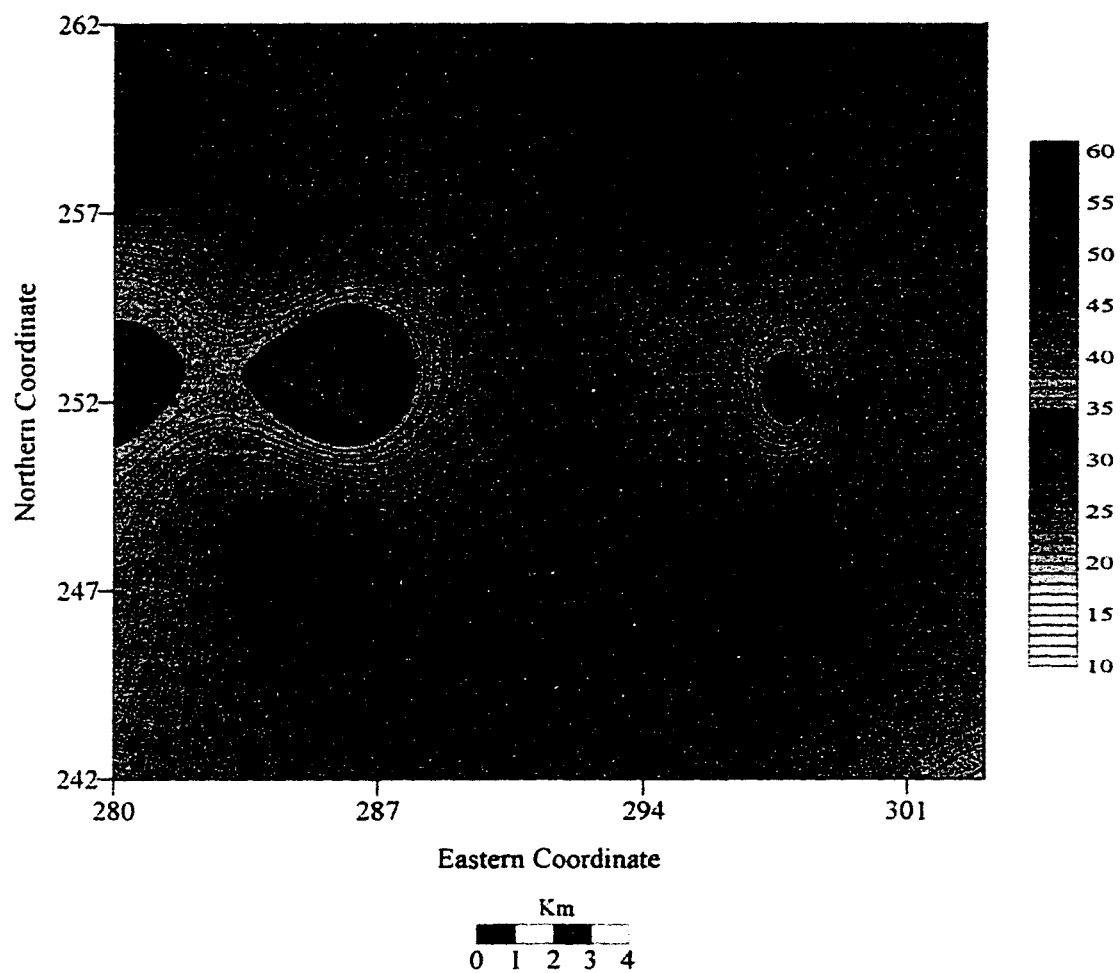


Fig. 6.2 : Distribution of the mineral Apatite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

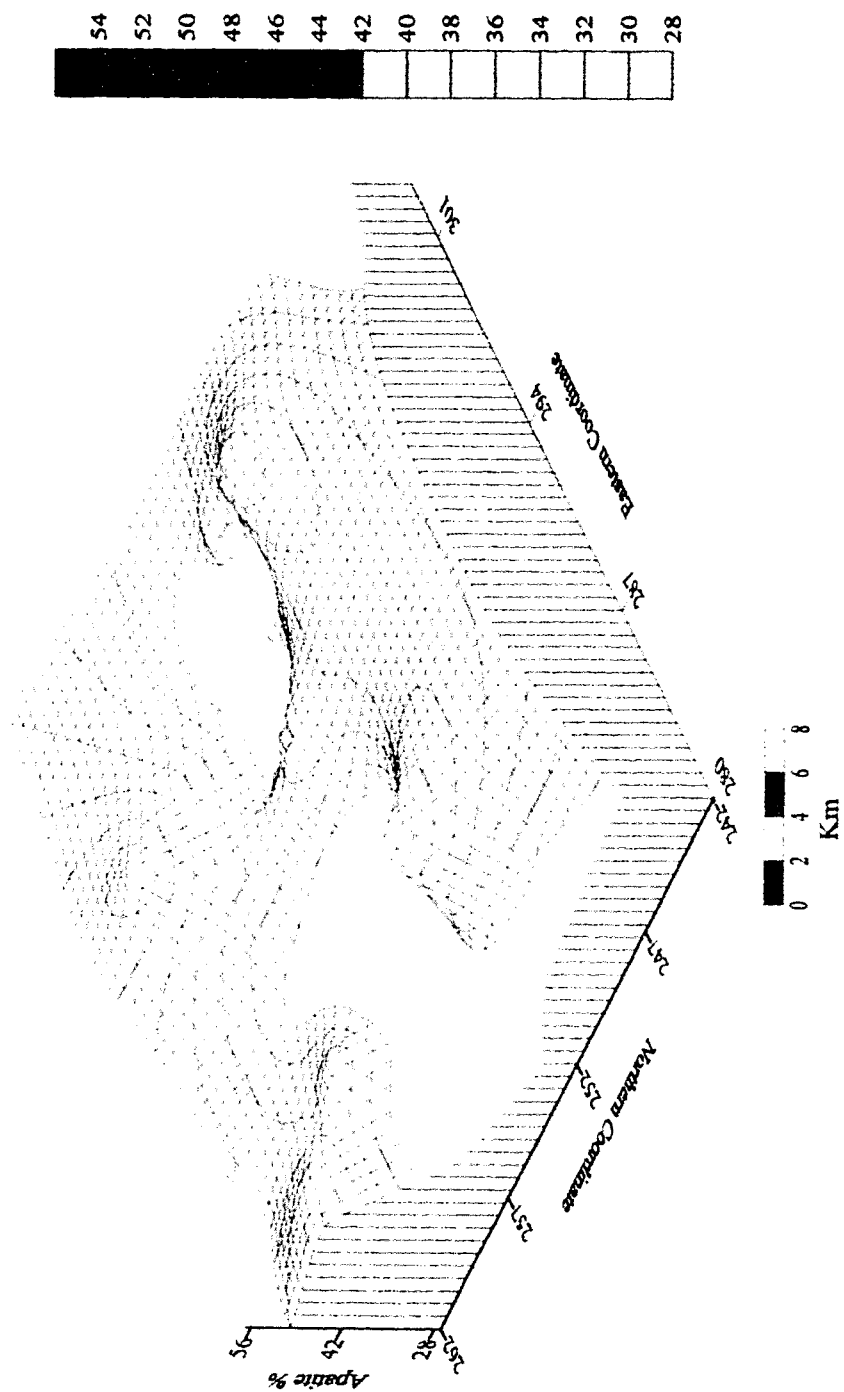


Fig. 6.3 : Three-Dimensional View for the Apatite content in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

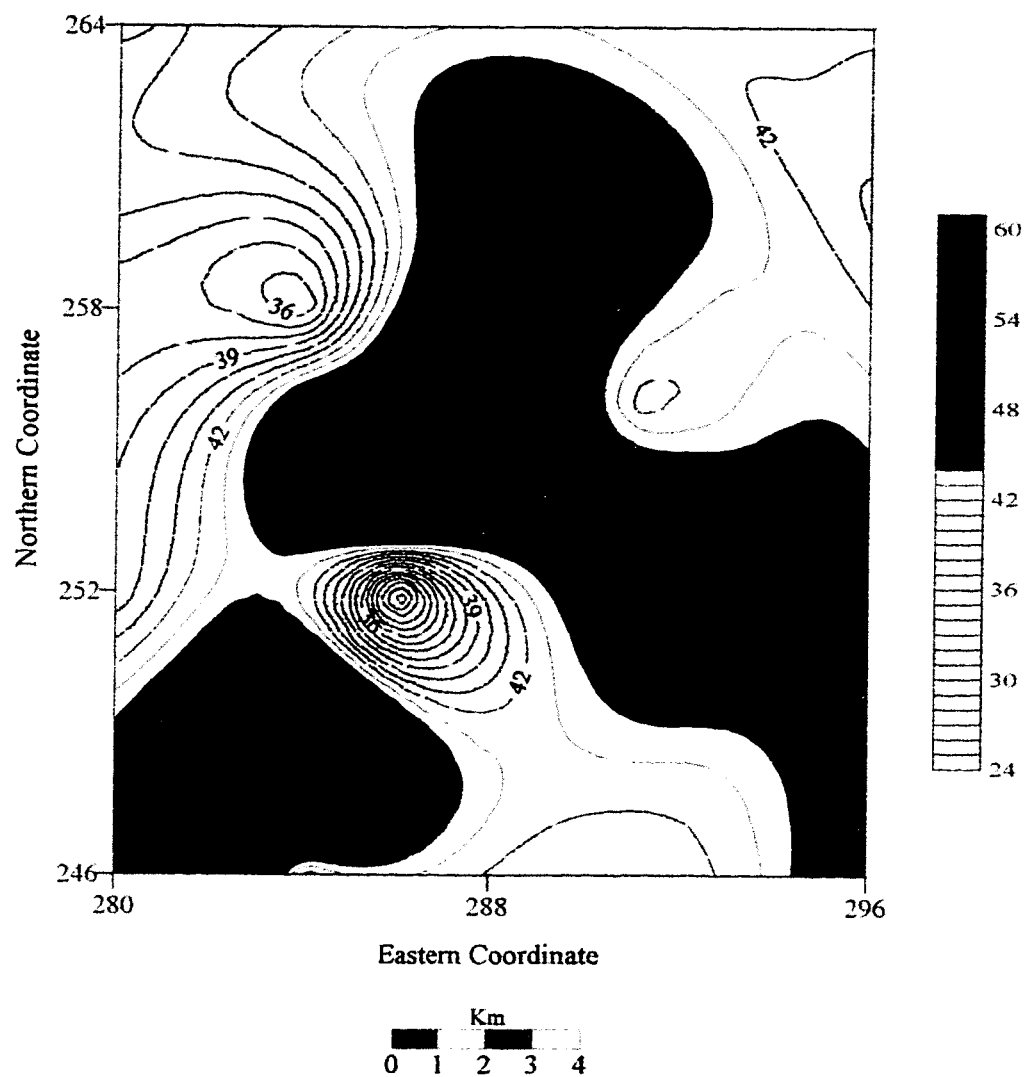


Fig. 6.4 : Distribution of the mineral Apatite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

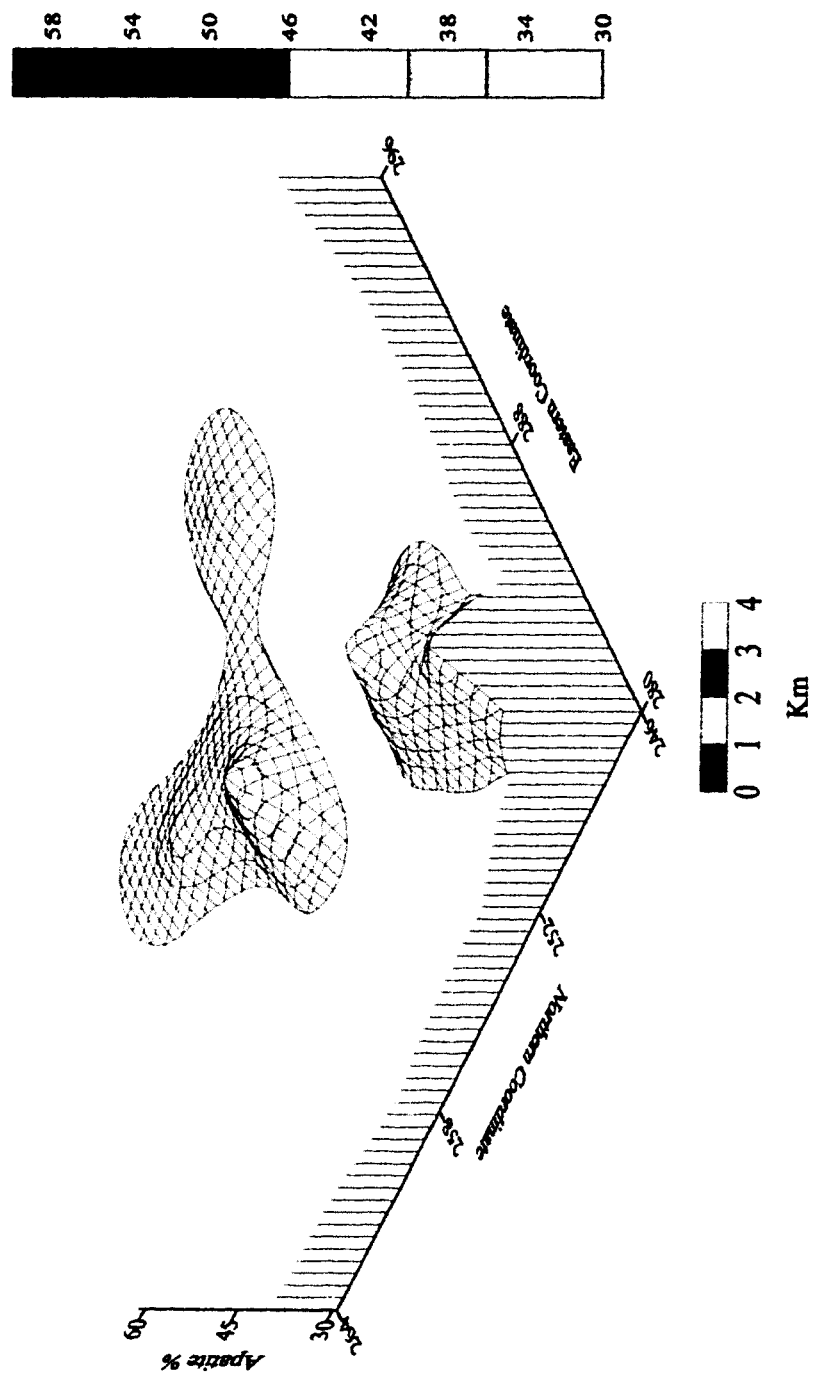


Fig. 6.5 : Three-Dimensional View for the Apatite content in the
Zone 2 Phosphorite of the Hazm Al-Jalamid area.

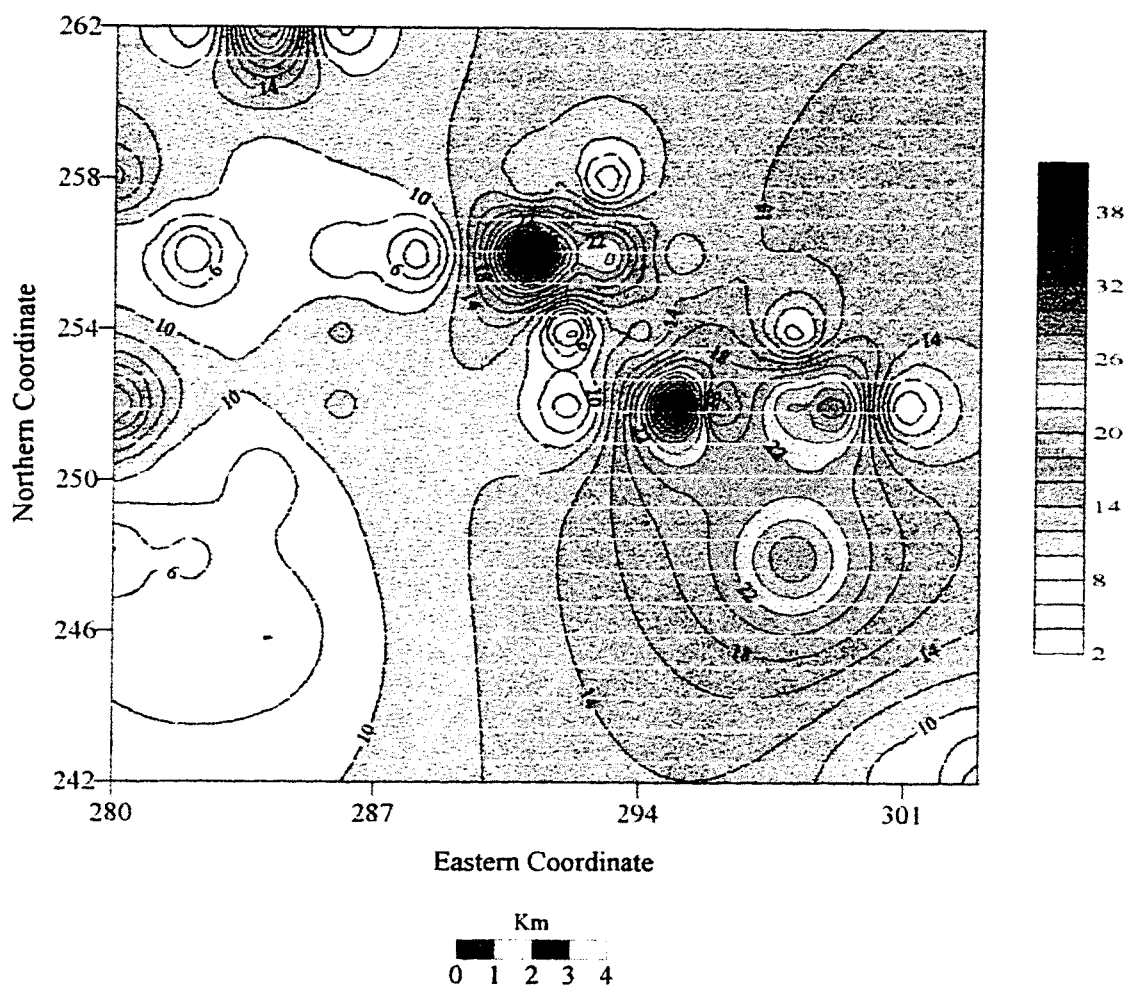


Fig. 6.6 : Distribution of the mineral Calcite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

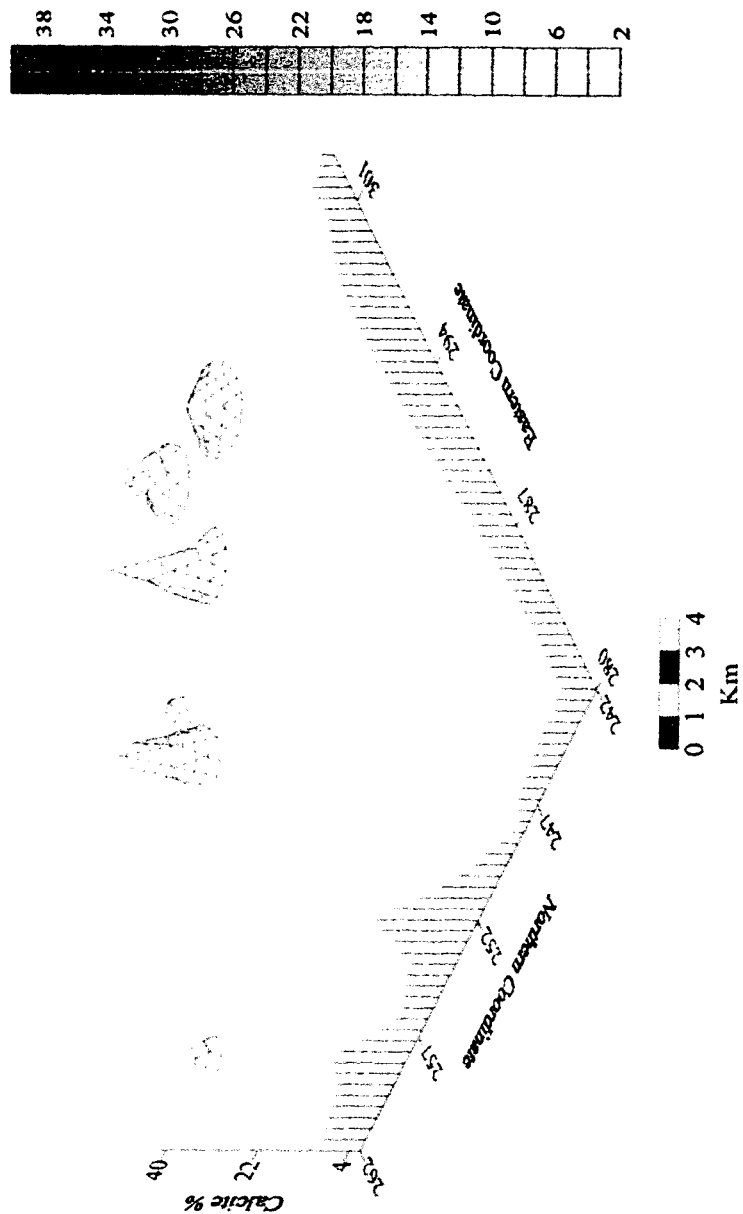


Fig. 6.7 : Three-Dimensional View for the Calcite content in the
Zone 1 Phosphorite of the Hazm-Al-Jalamid area.

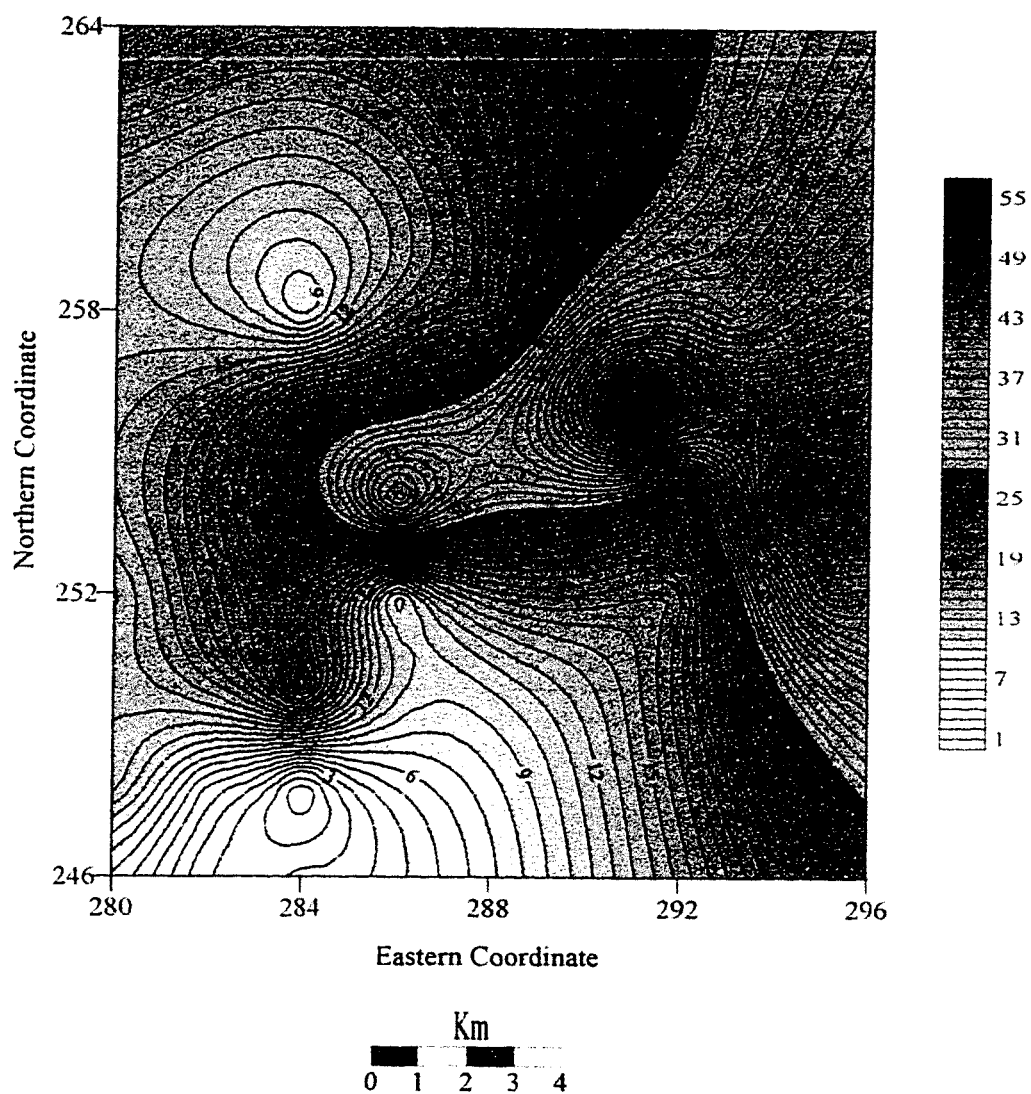


Fig. 6.8 : Distribution of the mineral Calcite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

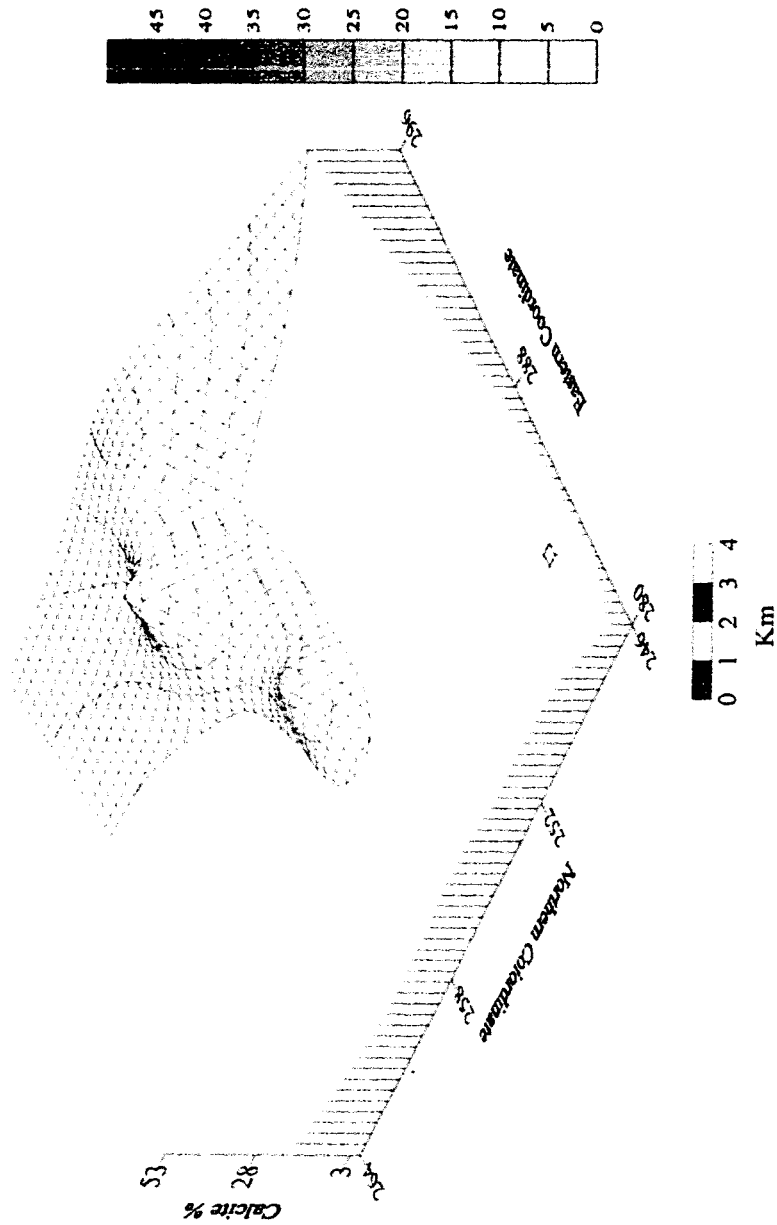


Fig. 6.9 : Three-Dimensional View for the Calcite content in the
Zone 2 Phosphorite of the Hazm Al-Jalamid area.

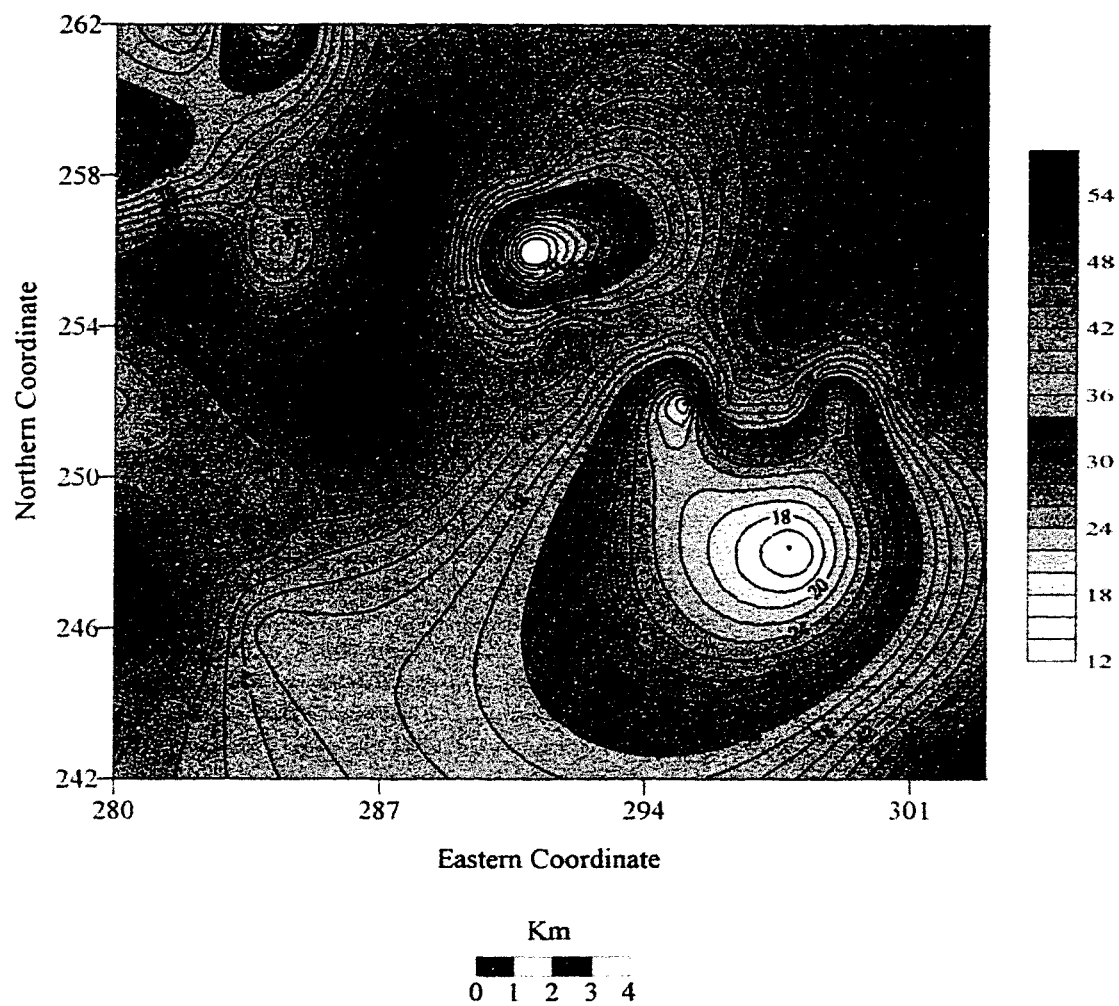


Fig. 6.10 : Distribution of the mineral Dolomite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

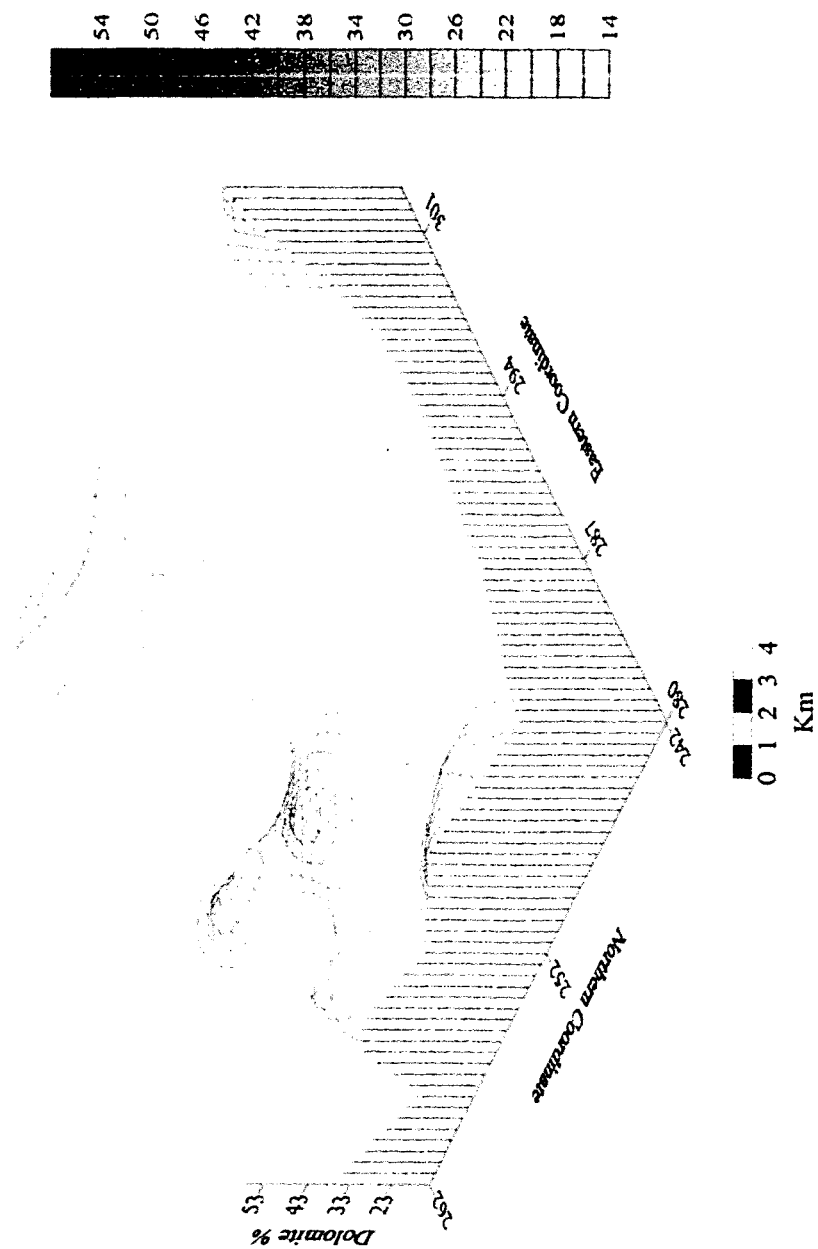


Fig. 6.11 : Three-Dimensional View for the Dolomite content in the Zone 1 Phosphorite of the Hazim-Al Jalamlid area.

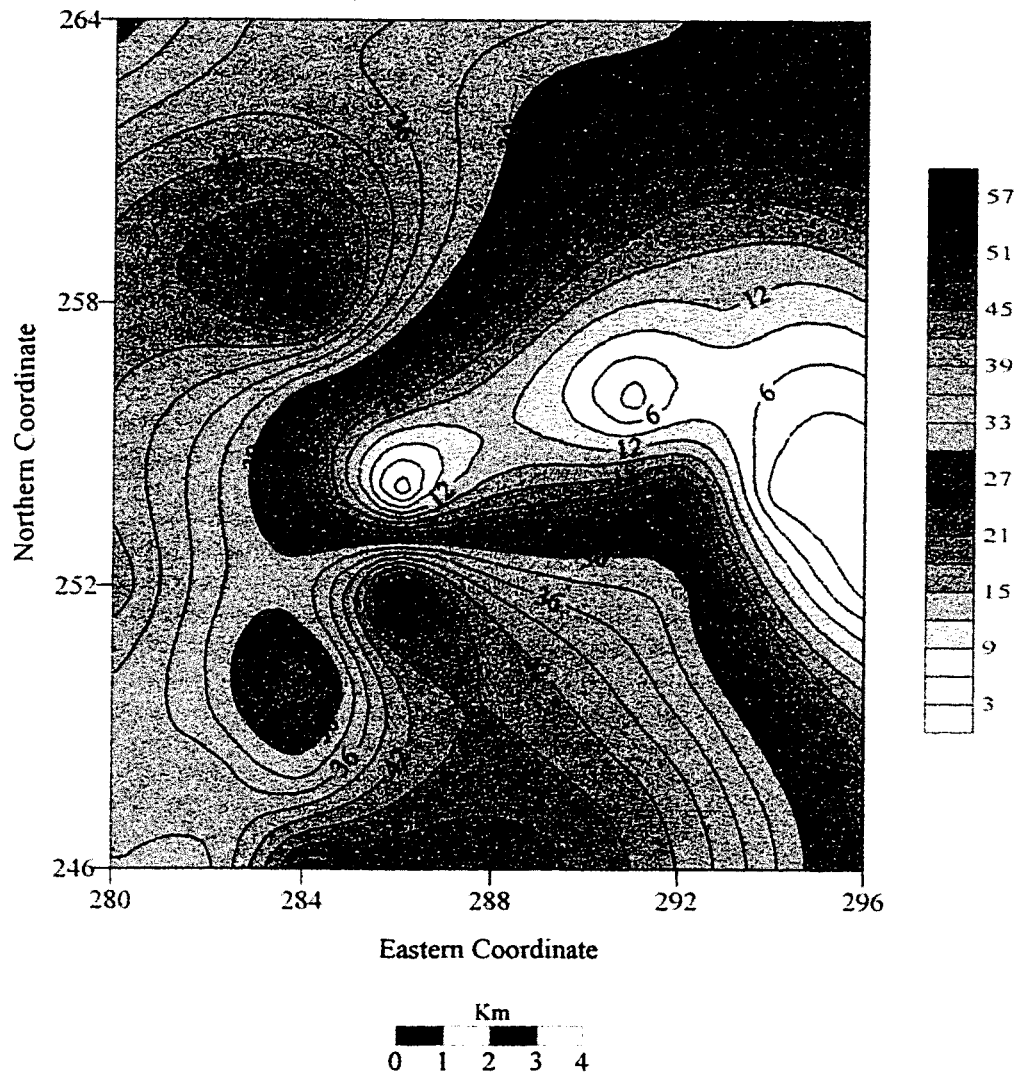


Fig. 6.12 : Distribution of the mineral Dolomite in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

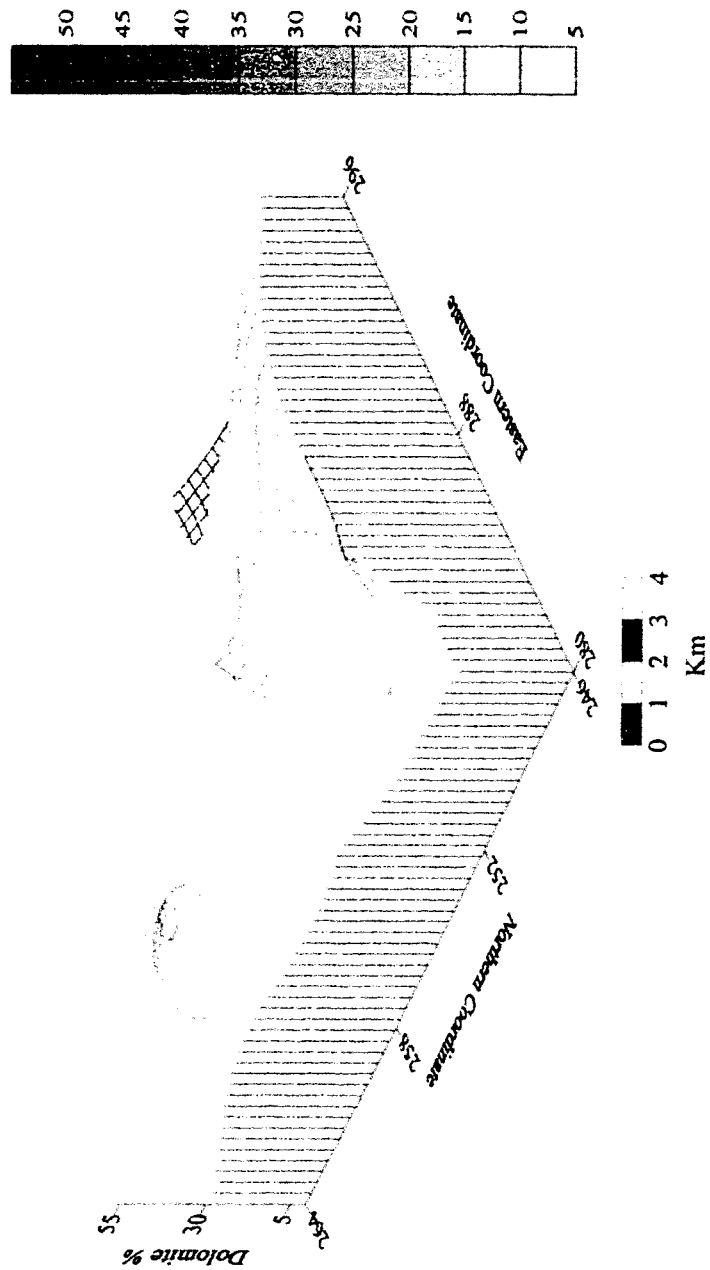


Fig. 6.13 : Three-Dimensional View for the Dolomite content in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

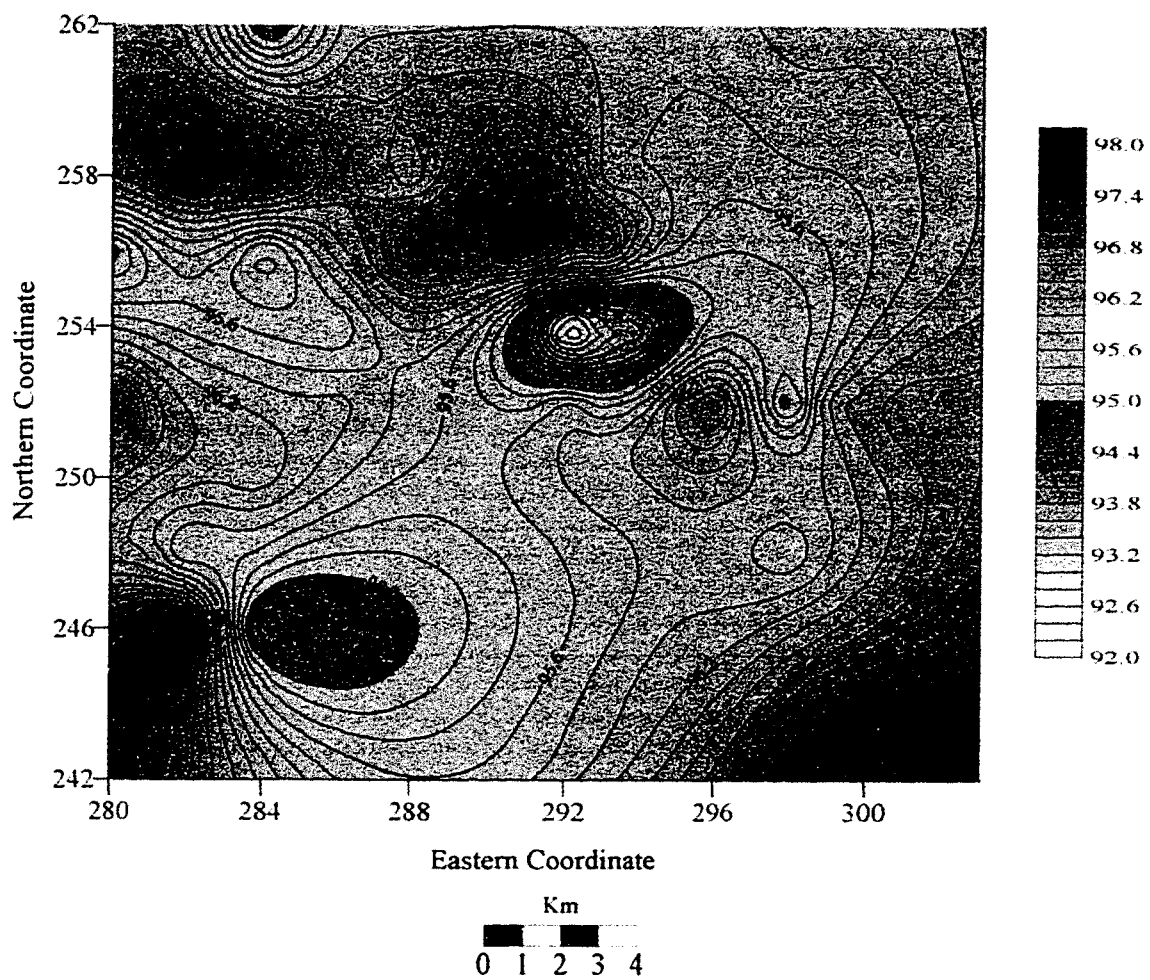


Fig. 6.14 : Distribution of the minerals Apatite + Calcite + Dolomite in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

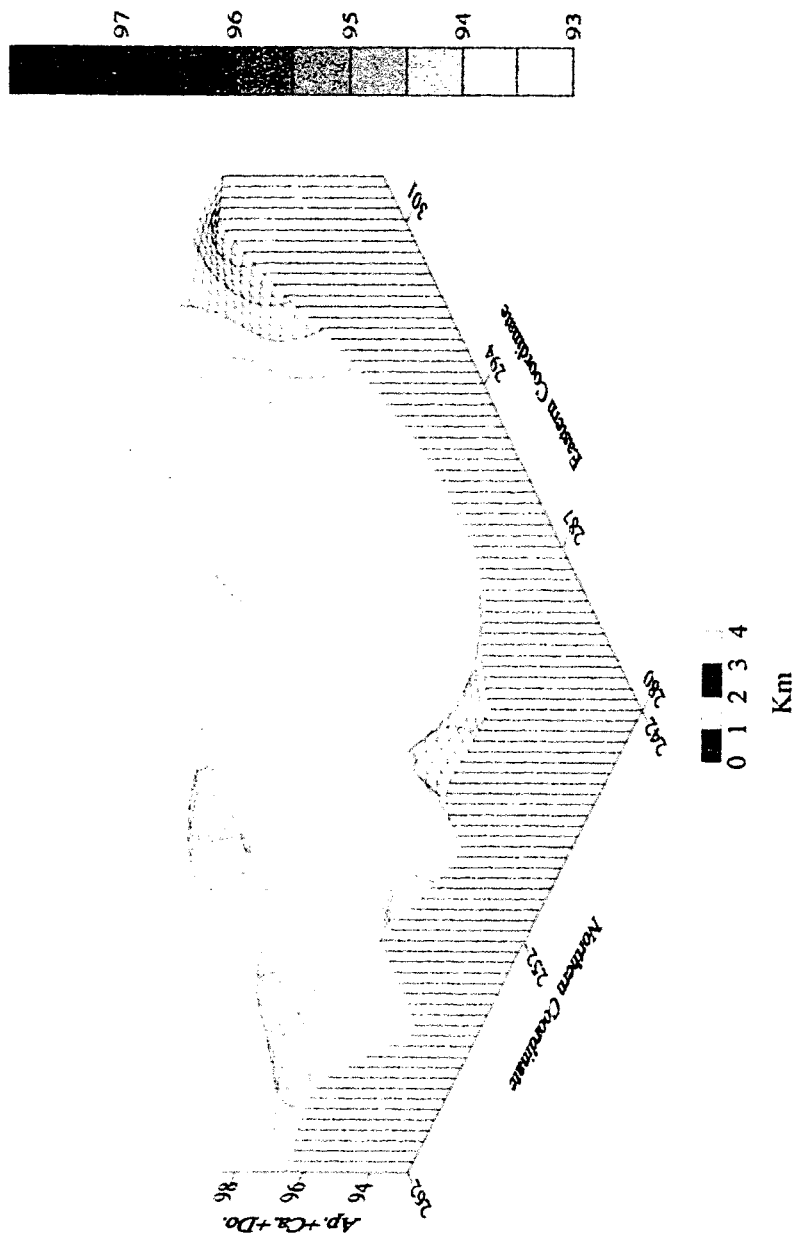


Fig. 6.15 : Three-Dimensional View for the Apatite + Calcite + Dolomite contents in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

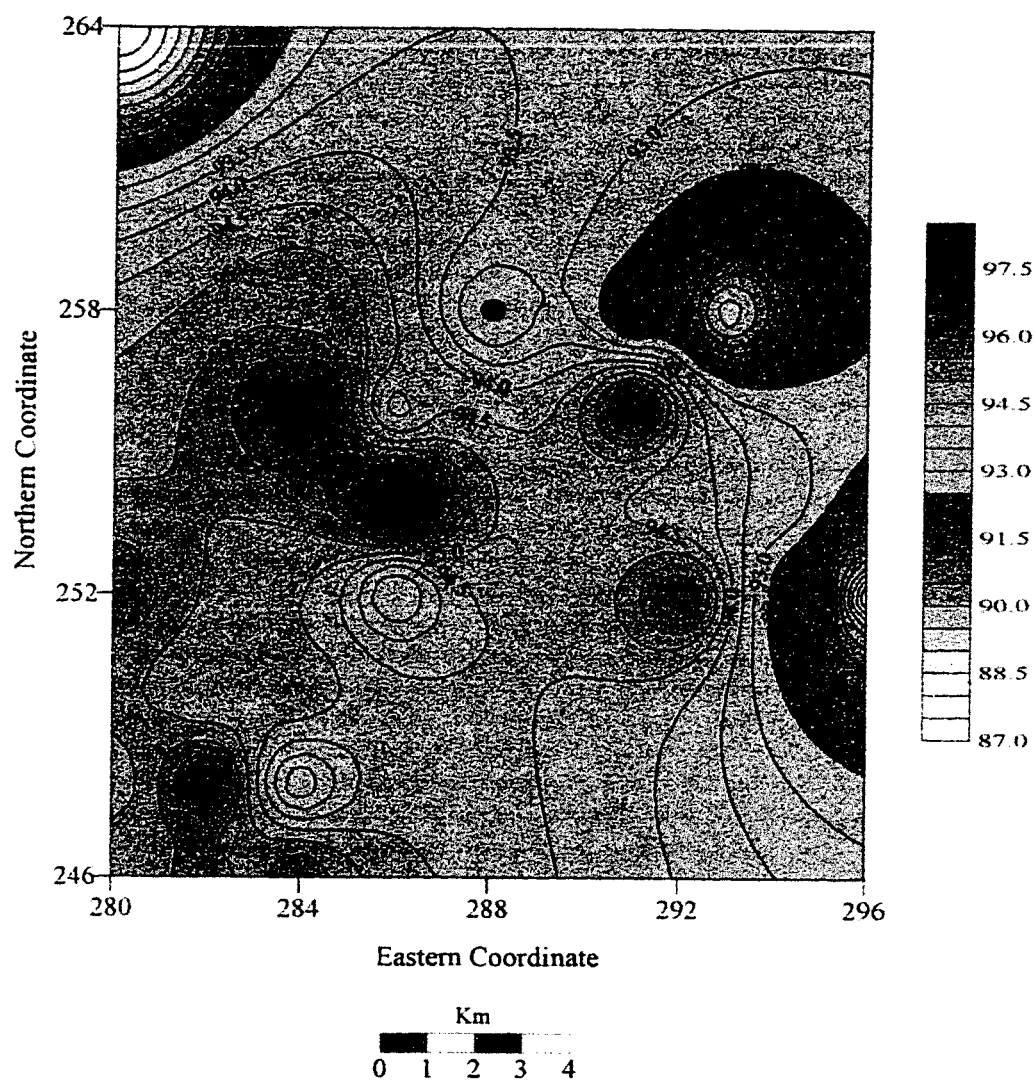


Fig. 6.16 : Distribution of the minerals Apatite + Calcite + Dolomite in the Zone 2 Phosphorite of the HazmAl-Jalamid area.

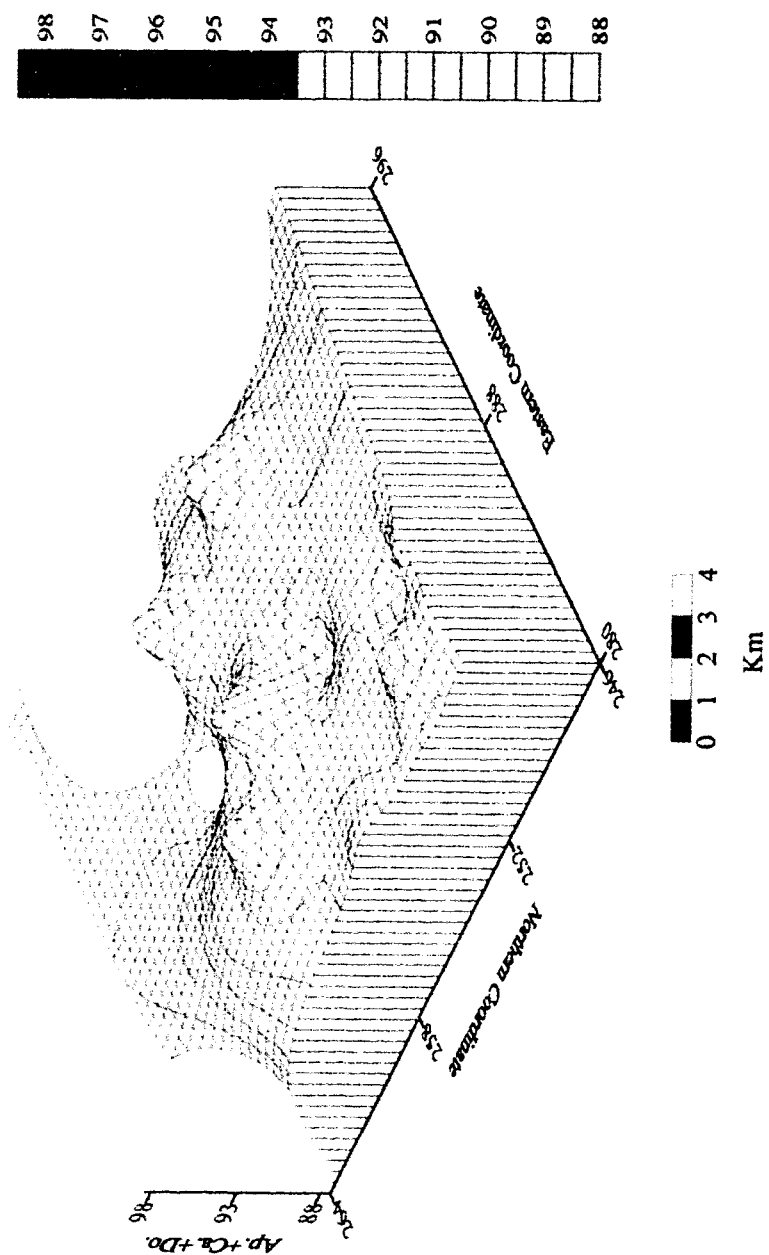


Fig. 6.17 : Three-Dimensional View for the Apatite + Calcite + Dolomite contents in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

reflects the restricted to semi-restricted nature of the basin of deposition. Such environmental conditions of deposition encouraged the high rate of chemical precipitation (carbonate material) and the very little amounts of detrital sediments (< 5 %) which was probably transported to the basin largely by wind. The scarcity of detritus material also reflect the chalky nature of the underlying strata over which the Hazm al-Jalamid Phosphorites were deposited. Reworking here could only produce calcareous material, while in Thaniyat area it could produce quartz grains due to the sandy nature of the underlying units (see 6.2). The average composition also reflects the effect of diagenetic changes (such as surficial weathering) in the enhancement of the phosphorous content via dedolomitization and calcite leaching.

The average mineralogical composition of the Interval Zone (of 55 % dolomite, 20.26 % apatite, 16.65 % calcite, totaling 91.91 %) (table 6.3) supports this view.

6.2 Mineralogy of the Thaniyat Turayf Phosphorite Deposit :

Phosphorite beds occur at several levels in the Thaniyat Turayf Phosphorite Member at the base of the Hazm al-Jalamid Formation. The member consists of phosphorite, sand, chert, shale, and finely crystalline dolomite. Here, the phosphorite beds contain numerous quartz grains which are the principal non-phosphoritic fraction and are sometimes so abundant that the rock can easily be named sandy phosphorites or even phosphoritic sandstone. The majority of the quartz grains are sharply angular to subangular, but some are rounded to sub-rounded, and were formed by the reworking of the underlying sandstone units. Minute quartz grains sometimes form nucleus around which apatite was deposited (fig. 5.5), on the other hand some of the apatite pellets show

peripheral replacement either by silica or calcite (fig. 5.13). Chemical analysis of the Thaniyat Turayf Phosphorites (table 7.4) indicate clearly their siliceous nature (with the silica ranging from 1.88 % to 27.73 %, having an average of 13.33 %). The siliceous nature can also be seen from figures 5.5, 5.13 which show abundant angular to sub-angular quartz grains dispersed (amidst apatite pellets, coprolite grains, bone lathes, dolomitic rhombus) in a dolomitic limestone cement.

6.3 Nomenclature and Classification :

To date there is no general agreement on the nomenclature of phosphorous-rich sedimentary rocks. The term “phosphate”, often used to describe such rocks, is not a good petrographic term, as it belongs strictly to the chemical field (where it is used for salts of phosphoric acid), while the term “phosphorite”, appears to be more suitable. Nevertheless, the users of the term phosphorite are not in full agreement about its exact meaning. Some authors (e.g. Bushinski, 1964; Soviet Geological Directory, 1973; Pettijohn, 1957; etc.) believe that in a phosphorite, the phosphorous content must be the predominant fraction, while others (e.g. Riggs 1979a) describe phosphorite rock to contain a minimum of 10 % by volume of phosphorite grains, and a third group (e.g. Gimmelfarb and others 1959) limit the term to sedimentary rocks that contain only 5 % P_2O_5 . With less precision, Altschuler and others 1964, define a phosphorite as “a rock or specimen containing substantial amounts of sedimentary apatite”. The Glossary of Geology published by the American Geological Institute (1980) has a similar definition : “a sedimentary rock with a high enough content of phosphate minerals to be of economic interest”.

Regarding the mineralogical composition of sedimentary phosphorite deposits, there is no greater measure of agreement. For example, according to McConnel (1973) and Pettijohn (1957), the phosphate fraction must consist of calcium phosphates or even made up only of francolite. However, Cook (1976) and Riggs (1979a) accepted aluminum phosphate minerals within the definition of phosphorites. Slansky (1980) proposed that the term phosphorite should be used for sedimentary rocks consisting mainly of phosphate minerals, which might be phosphates of calcium, aluminum or iron, and this term was later extended to cover any rock having an appreciable phosphate fraction, without attempting to include it in any rigorous petrographic system (cf. Slansky, 1986).

From the previous discussion and based on our data, we attempt here to develop a simple and straightforward mineralogical classification for phosphorite deposits, based on the following :

1. The term phosphate and its derivatives is avoided as it belongs strictly to the chemical field,
2. The term “phosphorite” and its derivatives is adopted here to designate sedimentary rocks with different phosphorus content,
3. The term “collophanite” is also abandoned and the appropriate minerals of the apatite family are used instead,
4. Phosphorite minerals other than the apatite family (e.g. aluminum phosphate, iron phosphate minerals, etc.) are considered within the definition of phosphorites,

5. A P_2O_5 content of 18 % is selected to represent the borderline between phosphorite rocks (with 45 % or more phosphorite minerals) and phosphoritic rocks (having less than 45 % phosphorite minerals),
6. The P_2O_5 content is regarded to be the controlling factor in the classification and nomenclature of the phosphorite rock, regardless of the type and amount of phosphorite minerals present. A minimum of 18 % P_2O_5 is strictly required for a rock to be termed phosphorite. Between 8 % and 18 % P_2O_5 , the primary petrographic term to be used is that of the non-phosphorite fraction, with “phosphoritic” as a qualifier (e.g. phosphoritic limestone, phosphoritic clay, phosphoritic sandstone, etc.). If the P_2O_5 content ranges between 1 % and 8 %, the primary petrographic term to be used is that for the non-phosphorite fraction, with “slightly phosphoritic” as a qualifier (e.g. slightly phosphoritic limestone, slightly phosphoritic clay, slightly phosphoritic sandstone etc.). Below 1 % P_2O_5 was completely ignored. A summary of the classification and nomenclature together with the corresponding percentage of phosphorite mineral in the studied phosphorite deposits is shown in table 6.4,
7. The amount of phosphorite minerals may differ for different deposits having the same P_2O_5 content, hence the content of phosphorite minerals may slightly differ from those recorded here, however, this makes no difference as the P_2O_5 content is regarded as the controlling factor in our classification and nomenclature,
8. The phosphorites are defined here as “any rock of sedimentary origin that contains a minimum P_2O_5 content of 18 %.” A prefix provides a means of

Table 6.4 : Proposed Classification and Nomenclature for Phosphorite Deposits.

P₂O₅ %	Phosphorite Minerals %	Nomenclature
< 1	< 2.5	Ignored
1-8	2.5-20	“Slightly phosphoritic” + non-phosphoritic fraction
8-18	20-45	“Phosphoritic” + non-phosphoritic fraction
≥ 18	≥ 45	Phosphorite

naming rocks with other phosphorite minerals, such as aluminophosphorite, ferriphosphorite, uranophosphorite, etc.,

9. The non-phosphoritic fraction is termed the “endogangue” when it is inside the grains, nodules or other phosphorite particles, and the “exogangue” when it is outside. The siliceous or carbonate coating that more or less encloses certain grains may be called the “epigangue.”
10. The proposed terminology is as descriptive as possible and does not indulge into the disputes of genesis,

The applicability of this classification is indicated by a number of binary and ternary diagrams (figs. 6.18-6.26). These figures represent the most common associations in phosphorites but all other possibilities can also be easily plotted.

Based on this classification, the Hazm al-Jalamid phosphorous-rich ore falls will within the phosphorite category ($\geq 18\%$ P_2O_5 and $\geq 45\%$ phosphorite minerals) with carbonate (calcite and dolomite) as the dominant non-phosphoritic fraction (figs. 6.27-6.29). The dolomitic nature of the Zone 1 Phosphorite is clear from figure 6.27, and hence the name dolomitic phosphorite. The Zone 2 Phosphorite has a mixed nature, calcite + dolomite (fig. 6.28), and hence the name dolomitic calcareous phosphorite. The Interval Zone mostly falls within the phosphoritic or the slightly phosphoritic class (fig. 6.29) and hence the name phosphoritic dolomite. The Thaniyat Phosphorite deposit falls well within the phosphorite category, but some of its beds can be more specifically designated as siliceous or sandy phosphorites, and others as phosphoritic sandstone.

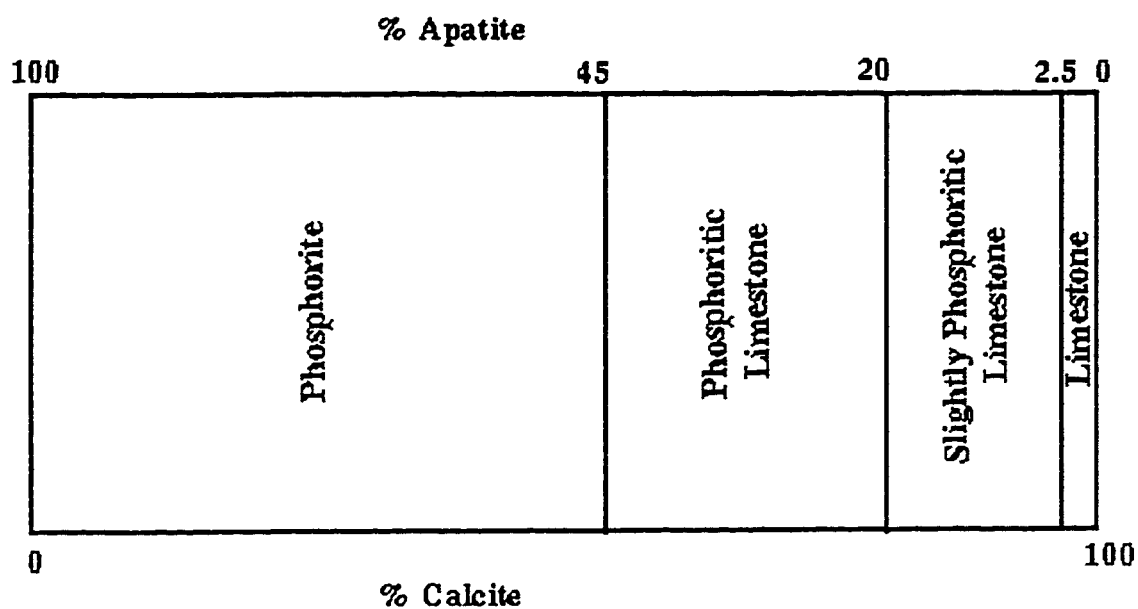


Fig. 6.18 : Binary diagram for phosphorite classification using % apatite and % calcite.

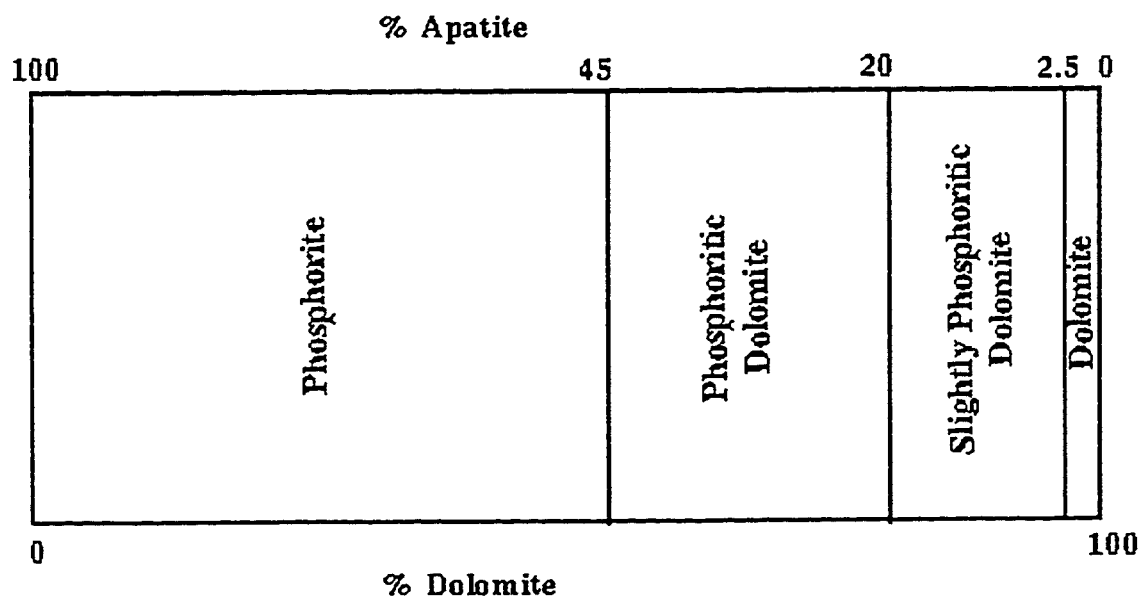


Fig. 6.19 : Binary diagram for phosphorite classification using % apatite and % dolomite.

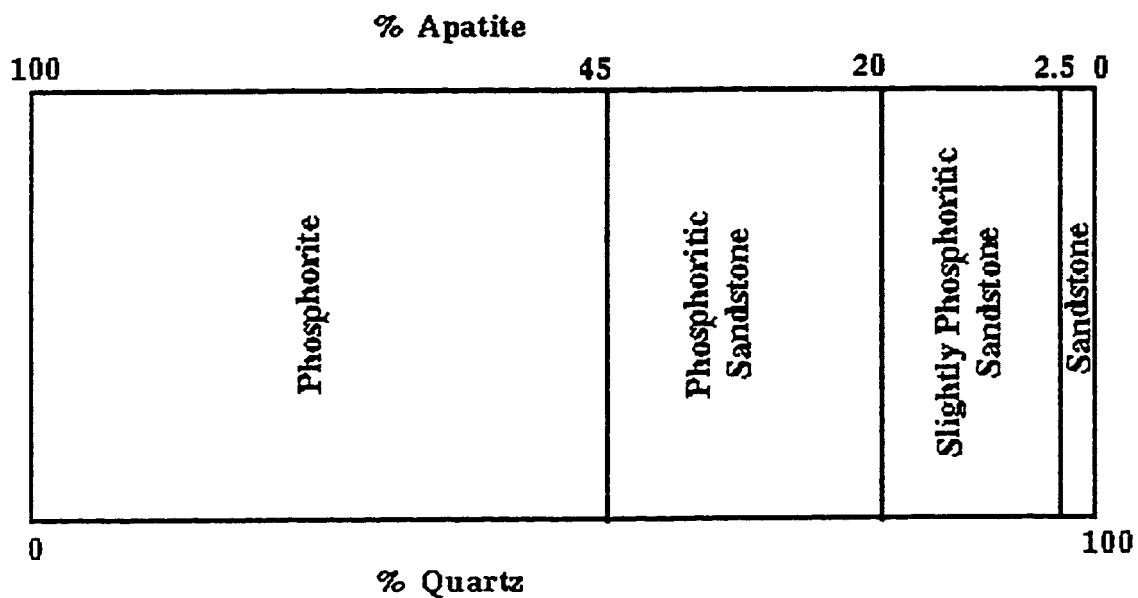


Fig. 6.20 : Binary diagram for phosphorite classification using % apatite % quartz.

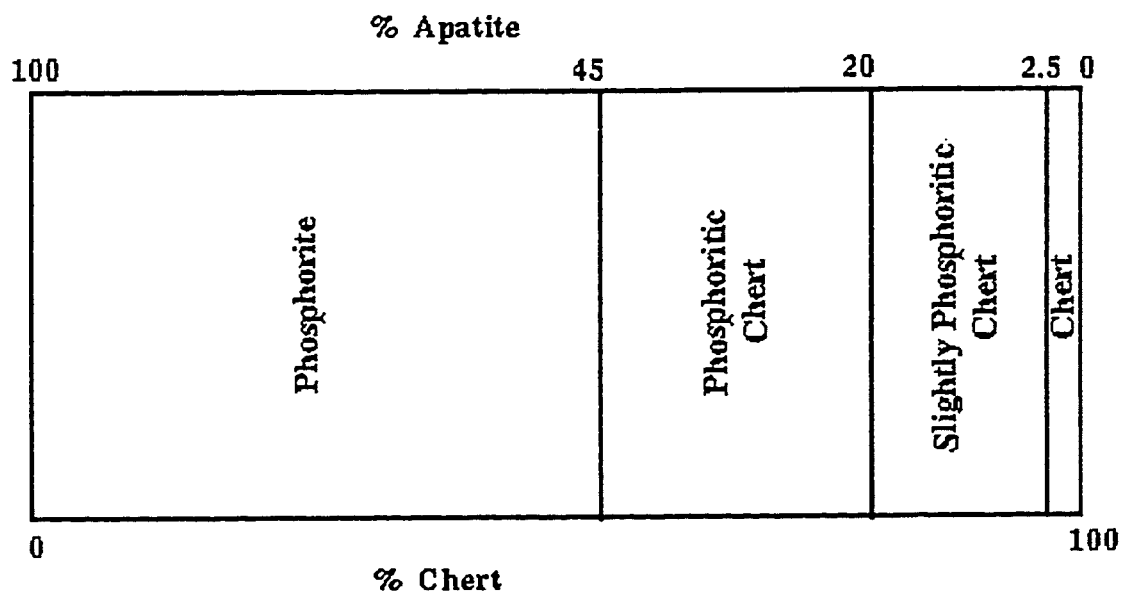


Fig. 6.21 : Binary diagram for phosphorite classification using % apatite % chert.

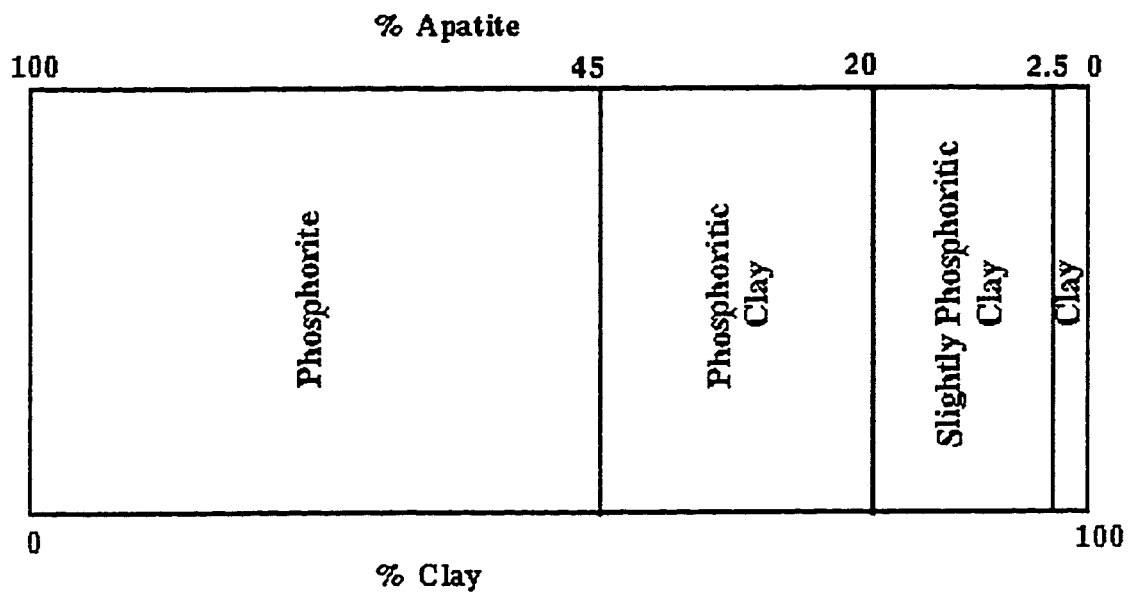


Fig. 6.22 : Binary diagram for phosphorite classification using % apatite and % clay.

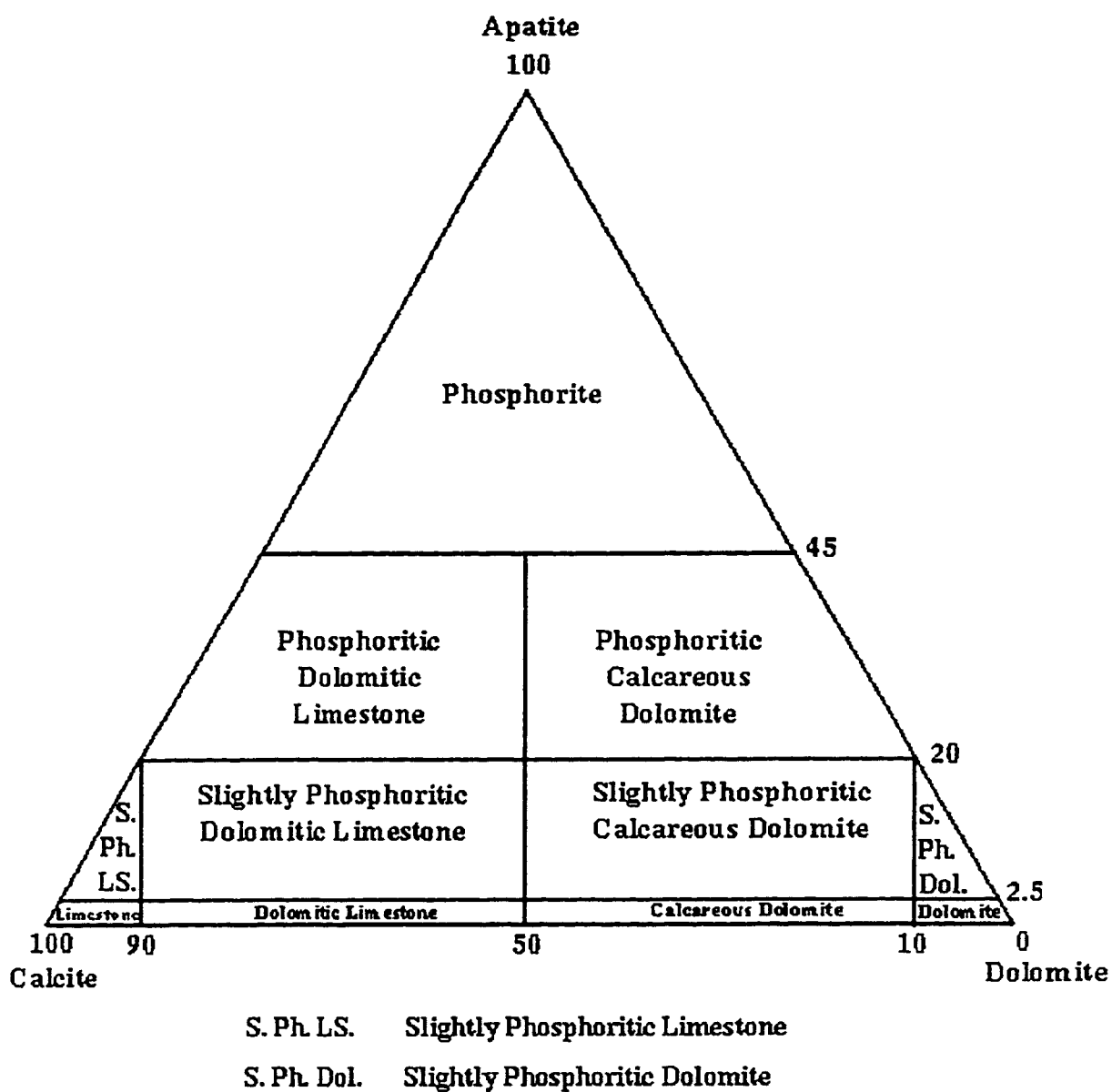


Fig. 6.23 : Ternary diagram for phosphorite classification using % apatite, % calcite and % dolomite.

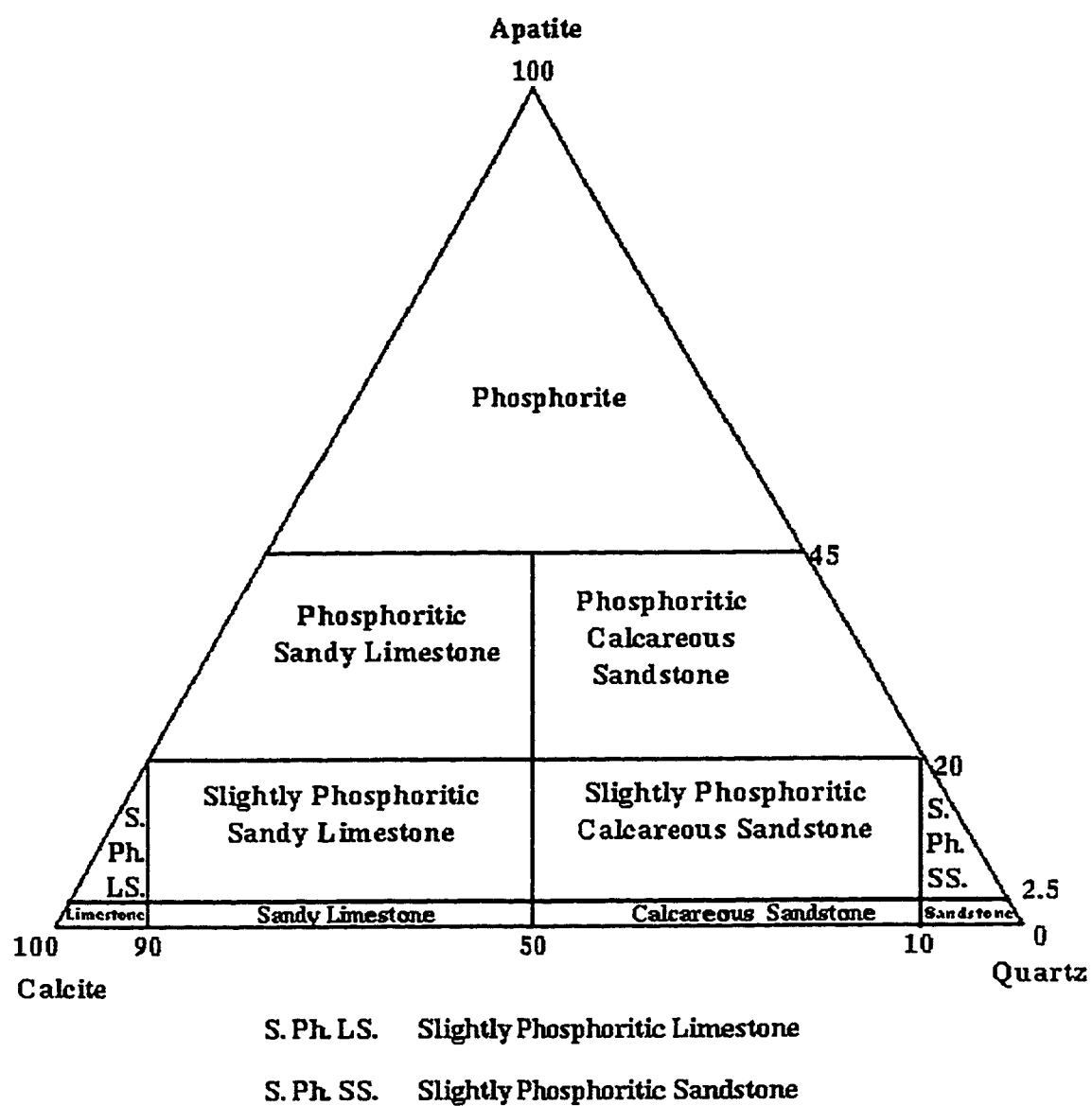
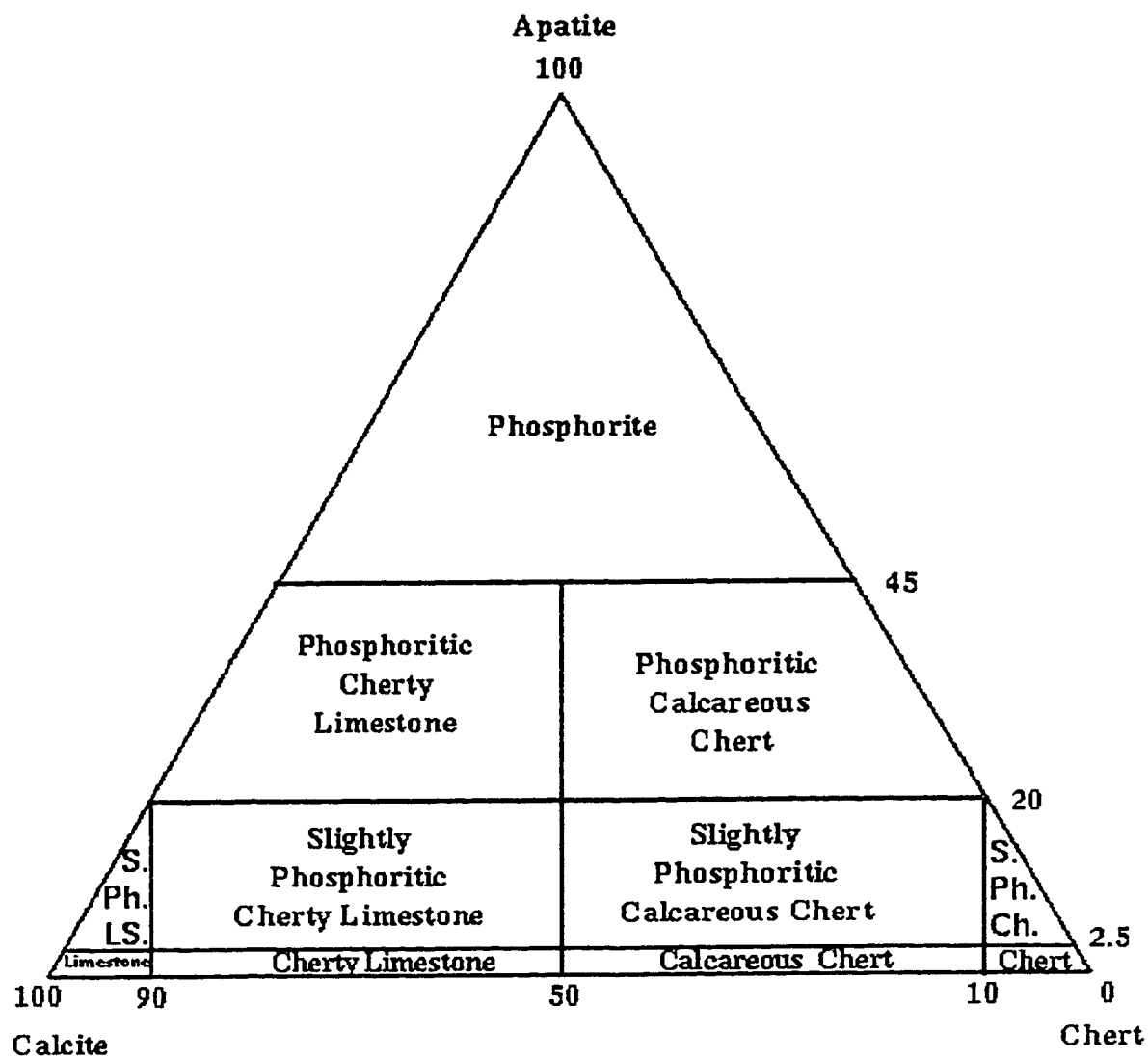


Fig. 6.24 : Ternary diagram for phosphorite classification using % apatite, % calcite and % quartz.



S. Ph. LS. Slightly Phosphoritic Limestone
S. Ph. Ch. Slightly Phosphoritic Chert

Fig. 6.25 : Ternary diagram for phosphorite classification using % apatite, % calcite and % chert.

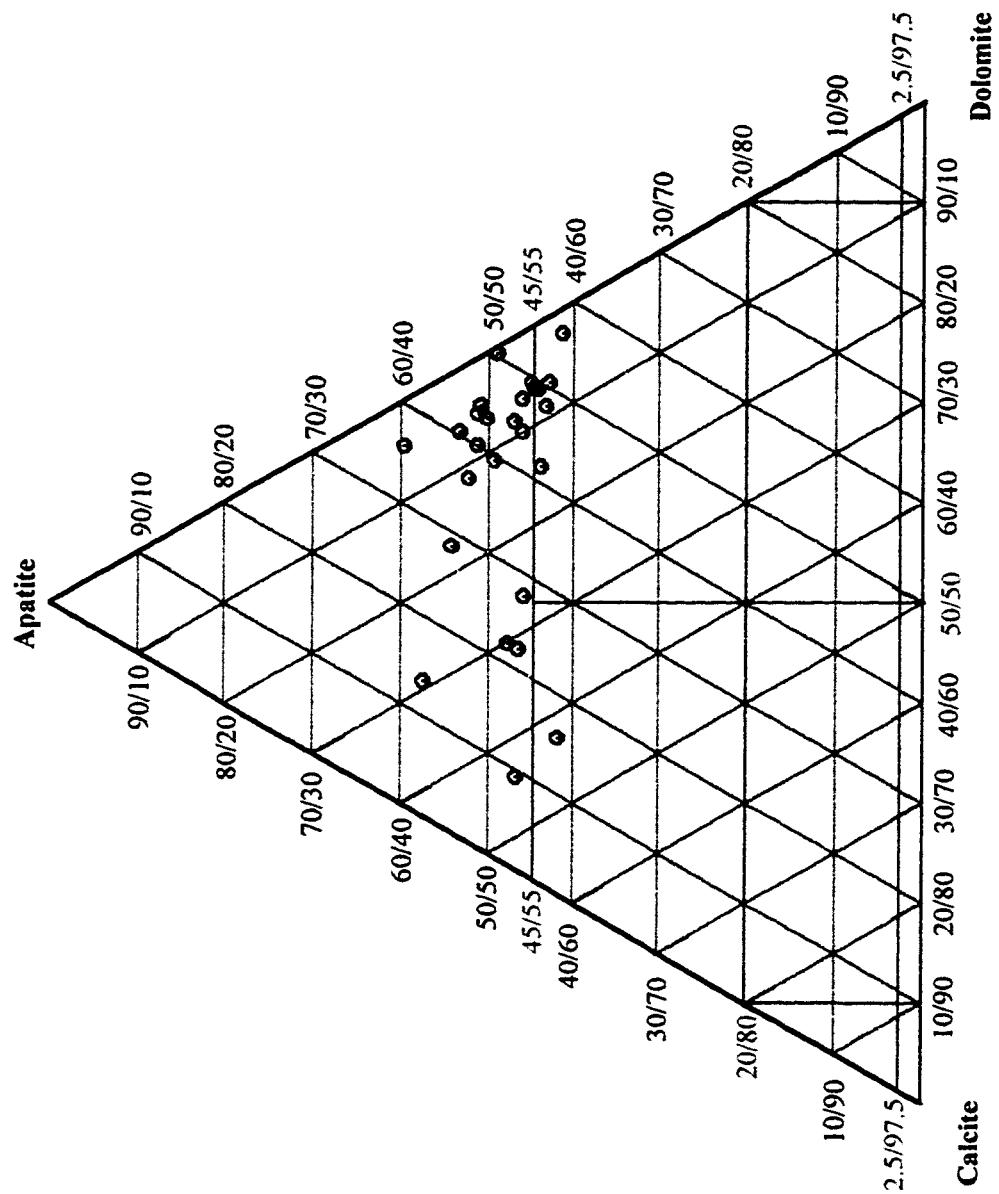


Fig. 6.27 : Plotting of the Zone 1 Phosphorite of the Hazm Al-Jalamid area on the ternary classification.

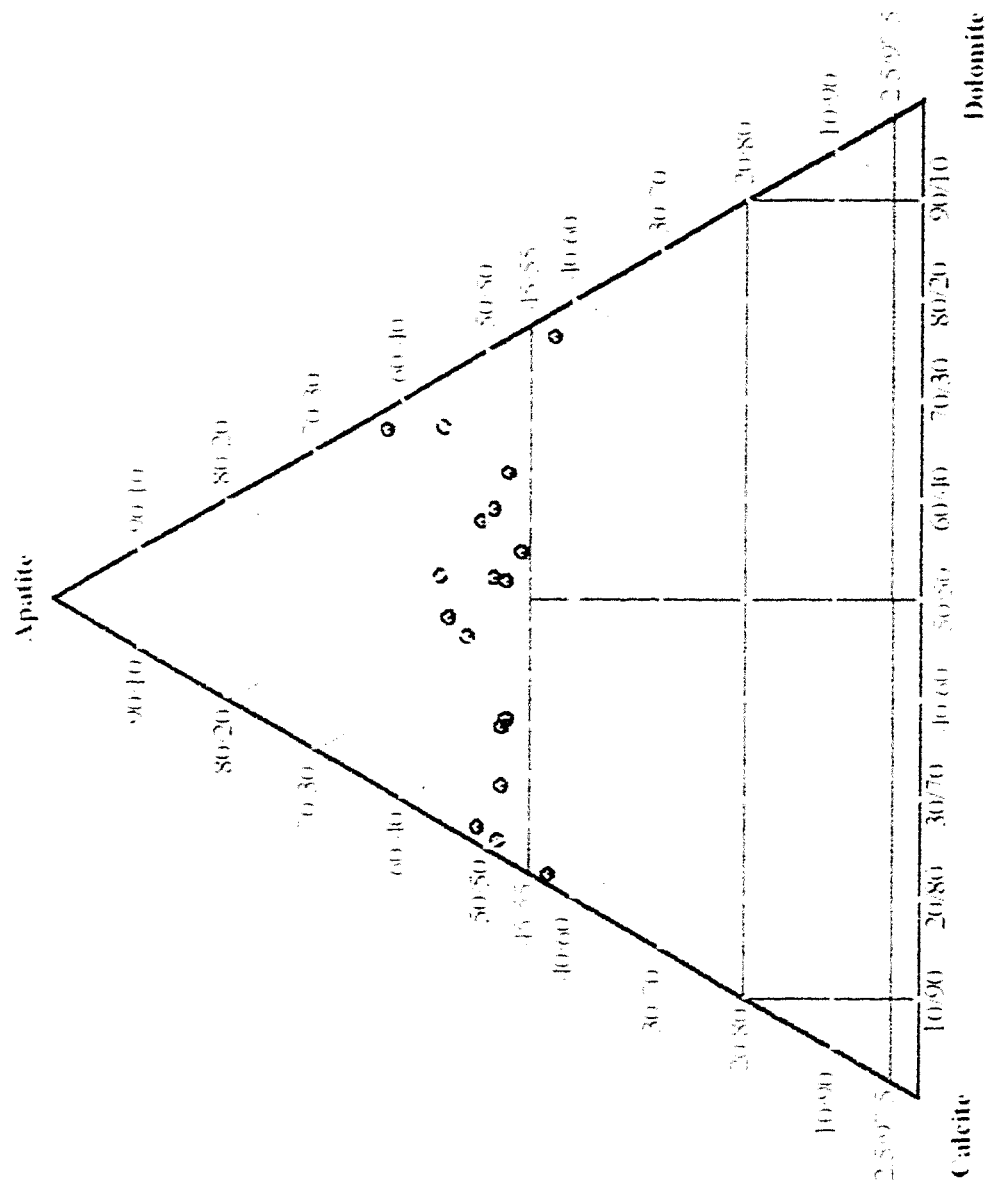


Fig. 6.28 : Plotting of the Zone 2 Phosphorite of the Hazm Al-Jalamid area on the ternary classification.

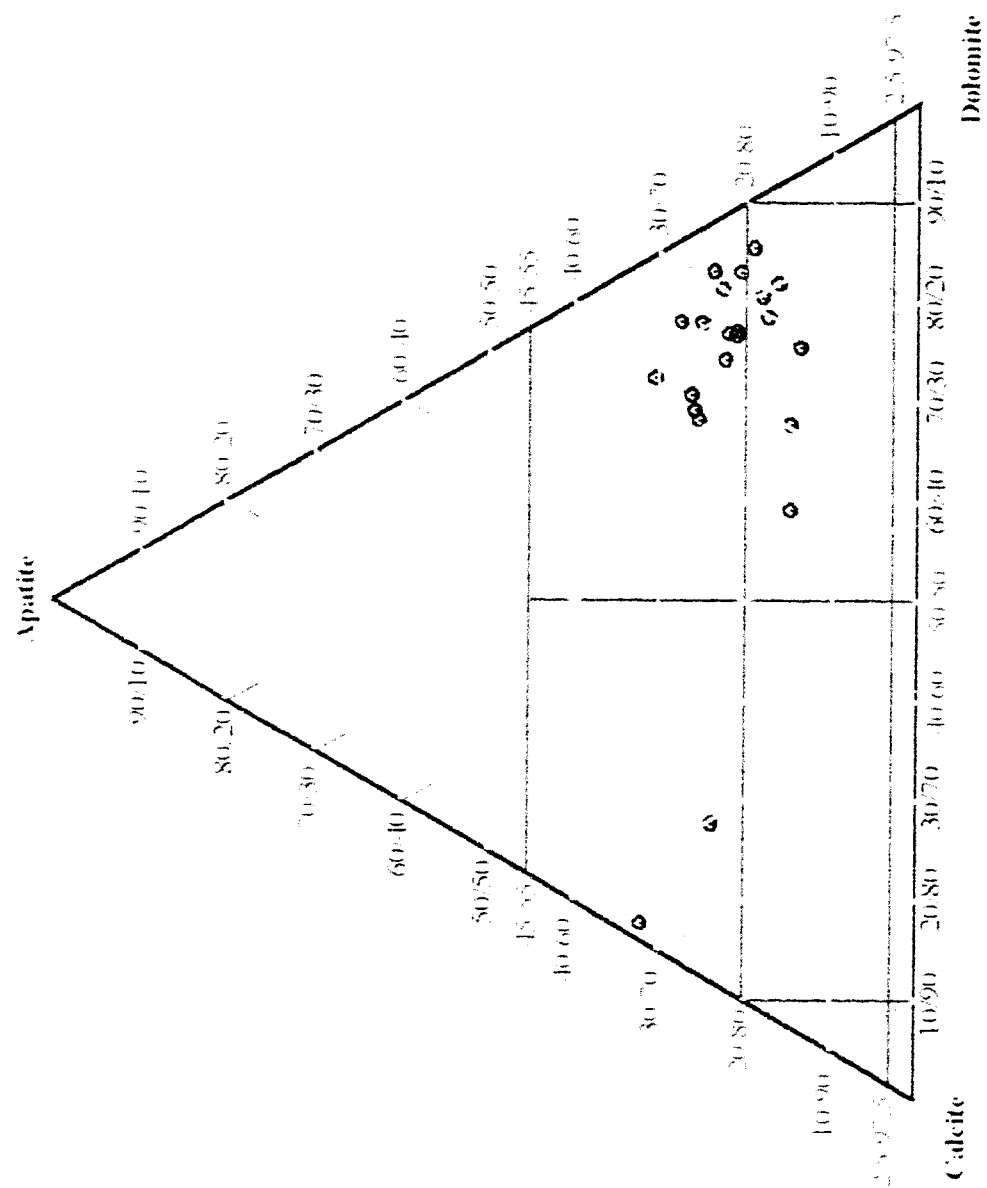


Fig. 6.29: Plotting of the Interval Zone in the Hazm Al-Jahmid area on the ternary classification.

CHAPTER SEVEN

GEOCHEMISTRY OF THE STUDIED PHOSPHORITE DEPOSITS

7.1 General Discussion :

The composition of phosphorite deposits is complex, but dominated by the phosphates of calcium, especially the several varieties of apatite which can be listed as follows :

- a. Fluorapatite, $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$
- b. Chlorapatite, $\text{Ca}_{10}(\text{PO}_4)_6\text{Cl}_2$
- c. Hydroxyapatite, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$
- d. Oxyapatite (Voelckerite), $\text{Ca}_{10}(\text{PO}_4)_6$
- e. Carbonateapatite, $\text{Ca}_{10}(\text{PO}_4)_6\text{CO}_3$

The general formula can be written as $\text{Ca}_{10}(\text{PO}_4, \text{CO}_3)_6(\text{F}, \text{Cl}, \text{OH})_2$ (cf. Pettijohn, 1975).

Sedimentary phosphorite deposits are seldom (if ever) composed of pure end members of the above-mentioned groups, and the predominant minerals are similar to the

fluorapatite mineral of igneous rocks but usually differ from it by a set of partial isomorphic substitutions.

The most common substitution in sedimentary apatites is that of PO_4^{3-} by CO_3^{2-} . The introduction of supplementary F^- ions helps to maintain the electrical neutrality of the crystal, and hence, the most frequent mineral is carbonate fluorapatite (francolite), for which the general formula may be written as $\text{Ca}_{10}(\text{PO}_4)_{6-x}(\text{CO}_3)_x\text{F}_{2+x}$. The value of x is variable and frequently ranges from (0.4 to 1.4), but with notable exceptions in so many deposits all around the world (cf. Slansky, 1986). Numerous other ions can substitute for PO_4^{3-} , particularly SO_2 , SO_4^{2-} , SiO_4 , As_2O_4 or VO_4 ; but the extent to which such substitution may take place is not well known. For example, while Gulbrandsen (*op. cit.*) claims that the SO_4^{2-} ion is as likely to substitute for PO_4^{3-} as is CO_3^{2-} , McClellan and Lehr (1969) claim that it is far less likely to do so.

Another frequent substitution in sedimentary apatites is that of Ca^{2+} by both Na^+ and Mg^{2+} . Na^+ has an ionic radius similar to that of Ca^{2+} , and consequently can readily be admitted into the apatite lattice, substituting some of the Ca^{2+} ions. Gulbrandsen (*op. cit.*) and Smirnov (1958) have found high sodium values in phosphorite deposits. Similarly, Lehr and others (1967) have shown that the substitution of Ca^{2+} by Na^+ and Mg^{2+} is directly connected with that of PO_4^{3-} by CO_3^{2-} . When the molar $\text{CO}_3 / \text{PO}_4$ ratio reaches 0.3 (x in the above structural formula then being approximately 1.4), about 6 % of the Ca^{2+} ions are replaced by both Na^+ and Mg^{2+} (cf. Slansky, 1986). Therefore, these two elements (particularly Na^+ which is more abundant and also monovalent) combine with F^- to preserve the electrical neutrality of the apatite crystal when PO_4^{3-} is replaced by CO_3^{2-} .

Other substitutions which have been suggested for calcium include Sr^{2+} , K^+ , Ba^{2+} , Al^{3+} , Fe^{2+} , Mn^{2+} , Pb^{2+} , Th^{4+} , U^{4+} , Ce^{4+} and Y^{3+} and other Rare Earth Elements (REE).

The partial replacement of F by OH is also frequent in sedimentary apatites, with variable degrees. When the proportion of F by weight is below 1 %, the apatite is called Dahllite or carbonate hydroxyapatite, the structural formula of which may be written as $\text{Ca}_{10}(\text{PO}_4, \text{CO}_3, \text{OH})_6(\text{OH}, \text{F})_2$. It is this substance that provides the mineral content of bones and teeth (with very low fluorine content). The mineral is very common in phosphorites derived from guano, but it is also found, combined with carbonate fluorapatite, among phosphorites of marine origin. The fluorine position may also be partly or completely occupied by chlorine (cf. Cook, 1976).

Such substitutions can explain the anomalously high concentrations of many trace elements in sedimentary phosphorite deposits such as those of the Phosphoria Formation in the U.S.A., where Gulbrandsen (1977) recorded selenium, cadmium, silver, uranium, antimony, molybdenum, arsenic, rhenium, chromium, zinc, thallium, mercury, vanadium, rare earths and tin. These elements are enriched several times their natural abundance in the continental crust (from 600 times for selenium down to 5 times for tin) which can warrant their exploitation as by products. Vanadium, for example averages 800 ppm and has been recovered as a by-product since 1941 (cf. Gulbrandsen, *op. cit.*). Other 17 elements, plus the Rare Earths were reported by the same author as enriched enough to be of economic value.

Altschuler (1973) also lists Ag, I, La, Mo, Sb, Se, Sn, Sr, U and Y as being enriched in world phosphorites by a factor of 2 over crustal abundances (cf. Tooms and others, 1969).

In the present work, vanadium values up to 1.54 % (15400 ppm) were measured, but this is exceptionally high and the average content although much less is still in the economic range. The same reasoning applies for chromium, where values up to 5600 ppm were measured, and for a number of other elements which will be discussed in the following pages.

As pointed out by Tooms and others (1969), the previously mentioned substitution patterns are dependent on two main factors : the geochemical factor (i.e. the availability of the substituting elements in the environment of apatite formation) and the crystal chemistry factor (i.e. the capacity of the apatite lattice to accept foreign ions).

In crystal chemistry, substitutions obey the usual rules of diadochy which include : similar ionic radii and maintenance of electrical neutrality. For example, Ca^{2+} (ionic radius $0.99 \text{ \AA}$) can be replaced more easily by Na^+ ($0.97 \text{ \AA}$), U^{4+} ($0.97 \text{ \AA}$), Mn^{2+} ($0.80 \text{ \AA}$) or Mg^{2+} ($0.66 \text{ \AA}$) than by larger ions such as Sr^{2+} ($1.12 \text{ \AA}$), Ba^{2+} ($1.32 \text{ \AA}$) or K^+ ($1.33 \text{ \AA}$). Similarly, the F^- , OH^- and Cl^- ions have sufficiently similar ionic radii (estimated at 1.36 , 1.40 and $1.81 \text{ \AA}$, respectively) to allow replacing each other. On the other hand, iodine is an element easily available in the environment of marine phosphorite deposition, but not accepted by apatite due to its large ionic radius ($2.16 \text{ \AA}$).

Because of the wide variety and ranges of possible substitutions, the admixtures of non-phosphoritic materials, (such as, calcite, dolomite and chalcedony) and the occasional abundance of detrital contaminants, (such as, quartz and clay) chemical analysis of phosphorites are highly variable.

7.2 Chemical analysis and Geochemical Significance :

Selected samples were analyzed for their mineralogic composition, P_2O_5 content, major, minor and rare elements, as well as for their natural radioactivity (U, Th, and radioactive K). The samples were chosen from both surface and subsurface sections of different localities, but, with more concentration on both the Hazm-Al-Jalamid and the Thaniyat Turayf areas, which are the best known localities - so far - for phosphorite mining in the whole Sirhan-Turayf basin.

The results of the analyses, have been used to draw isopach , isotenor and 3-D views for the main components of the Hazm-Al-Jalamid Phosphorite deposits, to draw X-Y plots among various components for the Zones 1 and 2 Phosphorite of the Hazm-Al-Jalamid area, for the Zone 1 Phosphorite of the Thaniyat Turayf area , for the Arqah Phosphorite Member of Al-Amud and Umm Wu'aal North areas and for the Thaniyat Phosphorite Member of Soutwestern area. Added to these, elemental distribution maps, line scans, spot analysis and micrographs for the most important features of the ore have also been constructed, and the following conclusions have been drawn :

- 1 The phosphorite grade varies from one area to another. The highest P_2O_5 content (39.1 %) was measured in a sample from the Thaniyat Phosphorite Member of the Hazm-Al-Jalamid area (table 7.10), but, this is an exceptionally high value and the average P_2O_5 content for the area is between 18.5 % for the Zone 1 and 19.5 % for the Zone 2 phosphorite (tables 7.1, 7.2, respectively). However, the friable phosphorite variety, with less carbonate cement in the area, contains 26-31 % P_2O_5 .

In the Thaniyat Turayf area, the P_2O_5 content varies from 22.2 to 31.6 % with an average of 28 % for the Zone 1 outcrops (table 7.9), and between 17.67 and 27.51 % with an average of 22.93 % in the subsurface (table 7.4).

In the Turayf area, the P_2O_5 content of the Zone 2 Phosphorite (drill hole samples) varies from 14 to 19.25 %, averaging 17.25 % (table 7.5), while, the uppermost phosphorite horizon (named Zone 5) in the same area has an average grade of 18.58 % P_2O_5 (table 7.6).

In the Umm Wu'aal North area, the P_2O_5 content of the Arqah Phosphorite Member ranges between 16.1 % and 33.2 % with an average of 21.97 % (table 7.7), while in Al-Amud area, it varies from 18.2 to 24.5, averaging 20.13 % (table 7.8).

2. Phosphorus is mainly concentrated in both grains (mainly featureless or nucleated pellets) and intraclasts (tables 7.11-7.18), but in the matrix and / or cement, its value is much more less (tables 7.11, 7.14). This feature is obvious in the microscopic examination of the thin sections, but is more clearly demonstrated in the elemental distribution maps (figs. 7.1-7.4) where phosphorus is obviously confined to the grains, while calcium, for example is more or less uniformly distributed throughout both the grains and the matrix. Similarly, the line scans (figs. 7.5-7.6) show phosphorus peaks that coincide with the grains.

SEM observations (backscattered electrons) indicate that the grains have different P concentrations (tables 7.11-7.18) and possibly are polygenetic and / or have had different diagenetic histories. Moreover, spot analysis, has clearly indicated that the P content varies within one and the same grain, particularly those that had been

subjected to diagenetic changes (such as replacement or dissolution) and those which have a non-phosphoritic nucleus.

- 3 No relationship could be established between the P_2O_5 content of the phosphorite deposits and most of the other chemical components (particularly those which are regarded as replacing elements such as K^+ , Mg^{2+} , Ba^{2+} , Al^{3+} , Fe^{2+} , Mn^{2+} , Th, U, Ce, etc.) as most of the X-Y plots clearly indicate (figs. 7.34, 7.44-7.48). The absence of correlation is attributed to post-depositional changes, such as leaching in particular. However, the P_2O_5 content shows some relationship with the thickness of the phosphorite bed ($r = 0.6$) which can be easily observed from the similarity of their isotenor and isopach maps and of the 3-D views of their distribution (figs. 7.7-7.14). Other relationships are somewhat weak between P_2O_5 % and SO_3 %, Cl %, Ti ppm, Na_2O % with the correlation coefficient $r = 0.56, 0.55, 0.65$ and 0.65 , respectively (figs. 7.15-7.18). However, the P_2O_5 content shows a strong direct correlation with the concentrations of some elements such as Sr, Cr, F and Y, with correlation coefficient $r = 0.97, 0.90, 0.99$ and 0.83 , respectively (figs. 7.19-7.22). On the other hand, the P_2O_5 content correlates highly negatively with the CO_2 %, with a correlation coefficient $r = -ve 0.97$ (fig. 7.23).
4. The CaO / P_2O_5 ratio averages 2.46 % and 2.49 % for the Zones 1 and 2 Phosphorite, respectively of Al-Jalamid area (tables 7.1, 7.2), 2.39 % for the Arqah Phosphorite Member of Al-Amud area (table 7.8), 2.71 % for the Zone 2 Phosphorite of the Turayf area (table 7.5), 3.12 % for the Zone 5 Phosphorite of the Turayf area (table 7.6), 1.43

% for the Zone 1 Phosphorite of the Thaniyat Turayf area (table 7.4) and 1.37 % for the Thaniyat Phosphorite Member of the Southwestern area (table 7.9).

In the fluorapatite mineral the $\text{CaO} / \text{P}_2\text{O}_5$ ratio is 1.31 % (cf. Slansky, 1986), but it is higher in the carbonate apatites (i.e. in most phosphorites), due either to the substitution of the PO_4 molecule by CO_3 group in the apatite lattice, or to the presence of the mineral calcite or dolomite in the phosphorite. Both effects may act together, up to a certain level at least, as previously demonstrated by Gulbrandsen (1970), and observed in the present study, but in our case it is mostly attributed to the presence of free carbonate minerals (calcite and / or dolomite). Indeed, the highest average $\text{CaO} / \text{P}_2\text{O}_5$ ratio (3.12 %) is associated with the highest average CaO % (55.73 %) (table 7.6), and the lowest average ratio (1.37) is obtained from the mostly clayey / sandy Thaniyat Phosphorite Member in the Southwestern area (table 7.9).

5. Similar reasoning also applies to the $\text{CO}_2 / \text{P}_2\text{O}_5$ ratio, which can reach up to 0.18 % due to both the composition of apatite itself and to the presence of free carbonate (cf. Slansky, 1986). In the present study, this value is sometimes as high as 0.7 % (table 7.8), reflecting the abundance of the free carbonates in the phosphorites.
6. The concentration of SiO_2 is essentially due to the presence of either biogenic (colloidal) silica or free quartz. Feldspars (if present) are generally rare and clays seem not to be of a big deal. The SiO_2 type and content vary considerably from one area to another, reflecting the nature of the basin of deposition. At Al-Jalamid area, the SiO_2 content varies from 0.31 to 4.46 % with an average of 1.18 % for the Zone 1 Phosphorite (table 7.1) and from 0.6 to 11.03 % with an average of 3.09 % for the

Zone 2 Phosphorite (table 7.2). This is mainly in the form of biogenic (colloidal) silica and reflects the restricted to semi-restricted nature of the basin of deposition which received very little amount of detritus. The low SiO_2 content of Al-Jalamid Phosphorite beds is also attributed to the nature of the underlying rock unit (the Ar'âr Chalk), the reworking of which has only contributed carbonate material (calcite and dolomite). Contrary to this, the SiO_2 content of the Zone 1 Phosphorite of the Thaniyat Turayf area is very high, averaging 13.33 % and maximizing at 22.73 % (table 7.4). This is mainly due to the abundant presence of free quartz grains (the principal non-phosphoritic fraction). The sharp angular nature of the quartz grains, and the restricted to semi-restricted nature of the basin of deposition led to the conclusion that, the quartz grains were formed in situ (authigenic) , mostly by reworking of the underlying Tawil (or Zallum) Sandstone, over which the phosphorite deposition has taken place. Similar reasoning also applies to the high SiO_2 content of the Thaniyat Phosphorite Member of the Southwestern area (table 7.9). In general, the SiO_2 content has a weak to moderate negative relationship with the P_2O_5 content ($r = -0.28, -0.35, -0.62$) (figs. 7.24-7.26, respectively).

7. Usually, one or more fluorine atoms are bound to the apatite molecule, and hence the $\text{F} / \text{P}_2\text{O}_5$ ratio, which is taken as characteristic of the mineral, varies between 0.08 and 0.12, or even exceeding 0.14 (cf. Slansky, 1986). Fluorine may also rarely occur in marine phosphorite deposits in a form independent of apatite (usually fluorspar).

In the present study, the average $\text{F} / \text{P}_2\text{O}_5$ ratio varies from 0.08 to 0.11 (tables 7.4, 7.7) with a maximum of 0.16 (table 7.7). Wherever this ratio is less than normal,

leaching and secondary dissolution of apatites can be expected. In the Arqah Phosphorite Member of the Umm Wu'aal North area, fluorine has a moderate direct relationship with the P_2O_5 content with a correlation coefficient equal to 0.53 (fig. 7.27), while in the Thaniyat Phosphorite Member of the Hazm Al-Jalamid area, the relationship is stronger ($r = + 0.99$) (fig. 7.21).

8. Marine phosphorite deposits are usually very poor in chlorine, which is the case here. Average values of 0.027 % have been recorded for the Thaniyat Phosphorite Member of Al-Jalamid (table 7.10), and < 0.02 % for the Arqah Phosphorite Member of Al-Amud (table 7.8). Higher chlorine values (tables 7.5, 7.6) are generally attributed to secondary concentrations of sodium chloride and / or potassium chloride outside the apatite lattice and hence, can be reduced by fresh water washing. This is easily observed from the similarity of the elemental distribution patterns of both Na and Cl (figs. 7.5-7.6).
9. Sodium can substitute for calcium in the apatite structure, with higher concentrations in the phosphorite grains than in the matrix (tables 7.11, 7.14). The amount of Na varies considerably from one area to another (tables 7.4-7.18). Some spots show high Na concentrations (1.11 %) (table 7.12), while others contain less than 0.01 % (table 7.7). This can be attributed to either leaching or partial replacement of Ca by Na, or to both.
10. Sulfur in marine phosphorite deposits can be present in the form of sulfides, sulfates or associated with organic matter. Sulfides are generally found as pyrites, both in the

exogangue and the endogangue, indicated by the corresponding values of iron. The most common sulfate in marine phosphorites is gypsum, which is present only in the exogangue. Sulfur inside the phosphorite pellets is associated with the apatite lattice, where it replaces calcium. This can be concluded from the relatively high concentrations of sulfur (up to 0.94 %) in the phosphorite grains, compared with its concentrations in the matrix and cement (down to 0.07 %) as shown in tables 7.11 and 7.14. Tables 7.4-7.18 show the concentration of sulfur in phosphorites from different areas.

11. Aluminum and iron, expressed either as oxides (tables 7.1-7.10) or as elements (tables 7.11-7.18) show a very close association (fig. 7.28) with a strong correlation coefficient ($r = 0.88$) (fig. 7.29). These two elements are principally associated with clays and to a lesser extent with sulfides, and play a significant role in processing the phosphorite ore, with the maximum allowable content varying from 3 % to 5 % (cf. Notholt, 1994). Their content in the studied phosphorite deposits is generally well below 0.5 % (tables 7.1-7.2, 7.6-7.8, 7.10), except for the Zone 1 Phosphorite of the Thaniyat Turayf area and the Thaniyat Phosphorite Member of Southwestern area, which have average values of 3.31 % and 2.27 %, respectively (tables 7.4, 7.9).

12 MgO is an undesired component in the phosphorite ore, and should not exceed 1 %. The average MgO content of the studied phosphorite deposits is generally below 0.9 % (Zone 1 Phosphorite of Thaniyat Turayf area) (table 7.4) or even below 0.4 % (tables 7.6-7.9, 7.19), but in Al-Jalamid area, it is much higher (tables 7.1, 7.2, 7.10) as it reaches 8.31 % in the Zone 1 Phosphorite, 4.76 % in the Zone 2 Phosphorite.

Beneficiation tests have still to be carried out to determine if the MgO content can be reduced to an acceptable level.

In areas which have little or no free carbonates (e.g. the Thaniyat Turayf area), the percentage of MgO in the ore is very low (table 7.4) and its presence is mainly attributed to replacement of the calcium ion by the magnesium ion in the apatite structure. Nevertheless, calcareous phosphorites with abundant free carbonates (e.g. Al-Jalamid deposit) have higher MgO content (tables 7.1, 7.2), due to the replacement of calcium by magnesium, both in the free carbonate (dolomitization) and in the apatite structure. Calcium replacement by magnesium might have been an important process in the genesis of the ore, as it led to the reduction of magnesium concentration in the medium of deposition and hence reduced the Ca / Mg ratio to the extent that direct precipitation of apatite was made possible (cf. Bentor, 1980). In the Zones 1 and 2 Phosphorite of Al-Jalamid area, the negative relationship between MgO and CaO with correlation coefficient $r = - 0.89$ and $- 0.91$, respectively (figs. 7.30, 7.31) is indicative of dolomitization, and reflects the effect of the nature of the basin of deposition on the genesis of the ore.

13. The general low K content of the studied phosphorite deposits (tables 7.4-7.7, 7.10) reflects its deficiency in clay minerals, but as the K content of the phosphorite grains (0.56 %) is higher than that of the whole rock (0.32 %) (table 7.19), the possible replacement of Ca by K in the apatite structure is inferred.
14. Phosphorite deposits usually contain a number of trace elements including Mn, Pb, Cr, V, As, U, Th, Se, Cd, Hg, Sr, Cu, Zn, Mo, Ni and Rare Earth Elements. (tables

7.4-7.10, 7.21-7.22). The presence of such elements in phosphorites can be attributed to either their association with organic matter, or to the integration of such elements into the apatite lattice or to both (cf. Gulbrandsen, 1966). Concentrations of As, Mo, Ni, V, Zn, Cr, Cu, Se, and Cd are principally associated with organic matter, while those of Sr, U, Th and the rare earths are associated with the apatite lattice, but vanadium can be associated with the apatite lattice, and uranium can occur in organic matter (cf. Slansky, 1986). There is also a possibility for the association of rare earths with organic matter (cf. Prevot and Lucas, 1979).

The most important trace elements in the studied phosphorite deposits can be listed as follows :

a. Vanadium :

The close relationship between the phosphates and the vanadates is well-known and because of this vanadium is often enriched in phosphorites, either by phosphorus replacement or by the formation of secondary minerals. Such enrichment can sometimes reach commercial concentrations (cf. Prevot and Lucas, 1979).

The average percentage of V in the studied phosphorite deposits varies between 48 and 2174 ppm (tables 7.10, 7.5). Such erratic values have been observed in the same trench or borehole. Variations from 168 to 1681 ppm (table 7.4) or from 672 to 2801 ppm (table 7.5) have been recorded. Much higher values of 1.54 % (15400 ppm) in a sample from East Khawr Umm Wu'aal (fig. 7.32) and 1.03 % (10300 ppm) in a sample from bore hole 1 (fig. 7.33) have been obtained by spot analysis. The very close association of these exceptionally high vanadium values with high values of iron (33.8 % and 28.03 %,

respectively), of chromium (5600 ppm and 4000 ppm, respectively) and of aluminum (> 1 %) was observed (figs. 7.32, 7.33). Knowing that vanadium averaging 800 ppm in the Phosphoria Formation has been recovered as a by product since 1941 (cf. Gulbrandsen, 1977) enhances the economic importance of the vanadium concentrations in the studied phosphorite deposits.

Vanadium does not show a marked regular positive correlation either with any phosphorite mineral or with the grade of the phosphorite ore (fig. 7.34), its best partners are other trace elements, such as Cr, Zn, Ni and Fe (figs. 7.32-7.33, 7.35-7.36), with which V forms a constant, positively correlated group. This association is considered to be typical of organic matter (cf. Gulbrandsen, 1966), and hence the direct relationship between such matter and phosphorite deposition.

b. Chromium :

Cr is enriched in the studied phosphorite deposits to values of 80 to 373 ppm (tables 7.10, 7.21), with exceptionally high values of 4000 ppm and 5600 ppm (figs. 7.32, 7.33). It is in positive correlation with P_2O_5 (fig. 7.20). Other factors such as the presence of clay minerals may interfere Cr distribution. According to Prevot and Lucas (1980), Cr though primarily carried by apatite, is further fixed in or on clays, when these are present. The most striking feature of chromium, however, is its association and positive correlation with V, Zn, and Fe (figs. 7.32-7.33, 7.35-7.38).

c. Zinc and Cadmium :

According to Altschuler (1980), phosphorites are sinks for certain elements which are normally members of coherent pairs or groups. Zinc and cadmium, both enriched in phosphorites, are such a pair.

Zinc is enriched in the studied phosphorite deposits to values of 71 to 203 ppm (tables 7.7-7.9 and 7.20-7.21), while average phosphorites have a Zn content of 195 ppm, twice that of average shales (95 ppm) (cf. Altschuler, *op. cit.*). Nevertheless, zinc has a haphazard behavior in phosphorites, its dominant control is its belonging to the group V, Cr, Zn and Fe as previously noted (figs. 7.35-7.37).

Average cadmium enrichment in phosphorites (18 ppm) is more than in shales (0.3 ppm) by a factor of 60 (cf. Altschuler, *op. cit.*). In the present work the average Cd content of the studied phosphorite deposits was found to range between 6 and 19 ppm (tables 7.6 , 7.9). Such values are even erratic from one sample to another in the same trench or borehole, varying from 9 to 30 ppm (table 7.8), and from 4 to 32 ppm (table 7.7).

Cadmium is virtually never found independently in common rocks, and, in most large classes of rocks, the abundance of zinc exceeds that of cadmium by a factor of several hundreds ($Zn / Cd = X00$) (cf. Altschuler, 1980). In phosphorites, however, cadmium is differentially enriched over zinc, very substantially. It seems that this is an instance of crystallo-chemical favorability, as the ionic radii of Cd and Ca are almost identical (0.97 Å and 0.99 Å, respectively), whereas the Zn ion is almost 20 percent smaller (0.74 Å). Whereas Zn and Cd both substitute in apatite, Cd is preferentially

fixed. In the present work the Zn / Cd ratio is generally around 10 (tables 7.7-7.9) with two exceptionally high values (32 and 28 ppm), but, the commutative average ratio is 12.6 ppm which is in agreement with the average worldwide ratio (cf. Altschuler, *op. cit.*).

d. Nickel :

Despite its low abundance, Ni in phosphorite deposits behaves almost like V. It is however, a less evident substitute in apatites (owing to its small ionic radius, = 0.62 Å⁺). Its concentration increases when phosphorites contain glauconite and / or iron oxides (cf. Lucas and others, 1978). The striking absence of glauconite in the studied phosphorite samples, may explain the low average Ni content (28 ppm) (tables 7.7-7.8, 7.21-7.22) of these phosphorites when compared with average world phosphorites (53 ppm), as determined by Altschuler (*op. cit.*).

e. Strontium :

Sr is usually concentrated in phosphorites (cf. Prevot and Lucas, 1980), and in the studied deposits, its concentration averages between 326 and 940 ppm (tables 7.7-7.10). Such values are highly erratic in the same bed and in the same trench or bore hole, varying from 451 to 1070 ppm (table 7.7), 230 to 440 ppm (table 7.10) and from 870 to 1010 ppm (table 7.8).

Sr correlates positively with P₂O₅ (fig. 7.19) indicating its replacement to the calcium ions in both the apatite lattice, and in the free calcite grains, matrix and cement if present. Consequently, the concentration is not strictly proportional, i.e. the sample highest in P₂O₅ is not necessarily the richest in Sr (table 7.7).

Sr accompanies phosphorus in sufficient amounts in sea water, and the relationship between the two elements becomes even closer, if one believes in the hypothesis that apatite forms by the transformation of biological calcium carbonate. It is well-known that phosphorus concentrates in soft parts of microorganisms and in bones of macroorganisms; while strontium concentrates in tests and shells which can contain up to 1 % Sr (cf. Kulp and others, 1952). On weathering, strontium is quickly lost to the apatite lattice (cf. Lucas and others, 1980) and hence to the totality of the phosphorite deposits.

f. Titanium :

Ti usually occurs in relatively stable and insoluble minerals such as ilmenite and rutile and hence, is richer in highly detrital shales (4600 ppm on the average) than in largely chemogenic phosphorites (640 ppm on the average) (cf. Altschuler, 1980). In the studied phosphorite deposits, the Ti content varies from only 18 ppm to 300 ppm (table 7.7) and the mean value for the whole area is 102 ppm (tables 7.7-7.10), which is about one sixth of the Ti value of average phosphorites. This may suggest leaching of Ti, among other elements, from the studied phosphorite deposits.

g. Mercury :

The average Hg content of phosphorites is 55 ppb and of shales is 400 ppb (cf. Altschuler, 1980), suggesting the leaching of Hg from phosphorites. The Hg content measured in the present work is less than 50 ppb, (table 7.10). The presence of Hg in phosphorite deposits seems readily explained by organic complexing, as it is known to be

notably concentrated in carbonaceous matter and can substitute for Ca in the apatite lattice, but its depletion is not fully understood.

h. Manganese :

The Mn content of the studied phosphorite samples varies from 155 to 1007 ppm with an average value of 542 ppm (table 7.4), but, in some areas it is less than 75 ppm (tables 7.7, 7.10). Mn (expressed as MnO) correlates negatively with P (expressed as P_2O_5), the correlation coefficient $r = -0.65$ (fig. 7.39).

Mn is known to be generally enriched in average phosphorites (1230 ppm) relative to average shales (850 ppm) (cf. Altschuler, *op. cit.*), but, in the present study, the average Mn content (542 ppm) is about half that of average phosphorites and even less than that of average shales, suggesting leaching of the studied phosphorite deposits. Indeed, compared with average crustal abundances Mn is considered to be depleted in average phosphorites (cf. Tooms and others, 1969).

i. Other Trace Elements :

The concentrations of other trace elements in the studied phosphorite deposits such as, Se, Mo, Cu, Pb and As, are attributed to organic complexing and / or absorption, as the enrichment of elements of this group in bituminous shales has been well established. Again, the concentration of such elements, individually or collectively in the Phosphoria Formation in samples which are significantly richer in organic matter is a further evidence (cf. Gulbrandsen, 1966). Indeed, many of the elements of this largely

chalcophile group occur as sulfides or are co-precipitated within pyrite in organic-rich sediments (cf. Fleischer, 1956), which is the case with the studied deposits.

The average concentrations of 9 ppm and 3.5 ppm for Mo and Se, respectively (tables 7.7-7.10) matches well with their concentrations in the average phosphorites (9 and 4.6, respectively), while that of lead (143 ppm) is much higher than that of average phosphorites (50 ppm), and that of Cu (25 ppm) is well below that of average phosphorites (75 ppm) (cf. Altschuler, 1980).

k. Rare Earth Elements (REE) :

Y is the only recorded rare earth element in the present work, other elements are either absent or below our detection limit. The average content of Y in the studied samples varies from 55 to 128 ppm (tables 7.7, 7.8), with extremes ranging from 40 to 200 ppm (table 7.8). These values are well below the worldwide phosphorite average (260 ppm), but, are higher than the worldwide shale average (26 ppm), which indicates the preferential enrichment of phosphorites in yttrium (which is known to replace apatite) from sea water which shows a marked enrichment of yttrium (cf. Altschuler 1980).

From the previous discussion, it becomes obvious that the quantity of an element in a rock and its partition between different minerals of that rock are affected by numerous factors, such as the availability of the element in the environment of deposition of the rock and the possibilities offered to it to find accommodation in the lattices of the forming minerals. The genetic environment of sedimentary phosphorites, though leading always to the formation of the same apatitic mineral (carbonate fluorapatite), can produce various accompanying minerals.

As mentioned above, the relationship between the concentration of these trace elements and the P_2O_5 content of the studied phosphorite deposits is never strictly proportional, even when the correlation is good, the scattering of the data values may be significant. Likewise, the existence of an intercorrelated group of elements without tie with any major element or mineral phase can lead to the assumption that these elements, (which have no special affinity for each other) must have been collected by their common affinity for another substance which had already disappeared. The known association of such elements as V, Ni, Cr and Zn with organic matter, together with the abundant signs of biological activity of macro- as well as microorganisms (cf. Doubinger, 1978) indicate that organisms, especially planktons, played an important role in the genesis of phosphorites, and that the described trace element associations show that the first trap for these elements was a biological one, becoming then biochemical. Only the final arrangement of the trapped elements in a very specific environment is chemical (cf. Prevot and Lucas, 1980).

A preconcentration of most of the trace elements characteristic of sedimentary phosphorites in proportions that are dissimilar to their ranges of concentration in sea water can support the above-mentioned argument. If they were formed in apatite by direct chemical precipitation from sea water, there should exist a relation between these two concentration ranges. Such a relation has, so far, not been found, whereas a relation between phosphorite and organic matter does appear. The rate of concentration by organisms also depends on the sea water concentration, but the micro-nutrients here considered are available in sufficient quantities in sea water, so that they are not a limiting factor of organism growth.

These biologically concentrated elements, released upon the decomposition of organic matter must have found in the phosphorite sediment host structures sufficiently accommodating to fix and preserve them. Fixation may occur by simple adsorption on minerals, mainly on clays and apatite, but is stronger when the elements enter the lattices. The complex lattice of apatite, which allows many coupled substitutions, easily accepts various elements; thus, strontium prefers this host to any other. The sites available in apatite are more or less suitable also for other elements, to which clays are more attractive. It appears that apatite is in many cases an intermediate host, as no clays appear to have been present at the time of phosphorite deposition (cf. Prevot and Lucas, 1980).

7.3 Natural Radioactivity :

Natural gamma-radiation in the earth comes from the decay of three radioactive isotopes : Potassium-40 (^{40}K), Thorium-232 (^{232}Th) and Uranium-238 (^{238}U). Though, the concentration of these 3 radioisotopes is highly variable in different rock types and even within the same rock type, they show preferable concentrations in certain lithologies.

Phosphorites have long been known to have relatively high concentrations of these three elements, especially uranium, to make its exploitation economic in some cases. Phosphorites typically contains between 50 and 200 ppm uranium, which is 15 to 90 times greater than the normal crustal abundance of that element (cf. Kolodny and Kaplan, 1970). Although the concentration of uranium in marine phosphorites can reach up to 2000 ppm, it is normally between 100 ppm and 200 ppm, or even below that level, as can be seen from the following survey :

- a. In the Late Cretaceous Egyptian Phosphorite deposits, uranium values of 30-100 and 98-190 ppm have been recorded for the Red Sea deposits (cf. Zaghloul and Mabrouk, 1964). For those of the Nile Valley Phosphorite deposits, various authors mention 82, 97, 68, 150 and 130 ppm (cf. Slansky, 1986).
- b. In the Late Cretaceous Phosphorite deposits of Jordan, 26 samples distributed among the three deposits of Ruseifa, Al-Hasa and Al-Shadya contain between 14 and 156 ppm of uranium for between 5 and 34.3 % P_2O_5 . The U (ppm) / P_2O_5 (%) ratio varies from 1.4 to 12, with an average close to 3 ppm uranium for every 1 % P_2O_5 , except for a group of samples for which it is as high as 9 (cf. Bashir, 1977).
- c. In Syria, the Late Cretaceous Phosphorite deposits have a uranium content similar to that of the Jordanian deposits. The highest U content is sometimes associated with the highest P_2O_5 % (e.g. 130 ppm for rock with 35 % P_2O_5); but the reverse can some other times be true, as a sample with 35 % P_2O_5 showed only 60 ppm of uranium. The U (ppm) / P_2O_5 (%) ratio may vary from 1.7 to 3.7 (cf. Slansky, 1986).
- d. In the Paleocene-Early Eocene Phosphorite deposits of Tunisia, the uranium content does not exceed 60 ppm in the Gafsa Basin but reaches about 100 ppm in deposits further north (cf. Sassi, 1974). The U (ppm) / P_2O_5 (%) ratio varies from 0.6 to 1.3 for P_2O_5 concentrations exceeding 20 %.
- e. In Turkey, the ore of the Mazidagi region shows a uranium content that only reaches or slightly exceeds 100 ppm in six of the 228 samples analyzed. The U (ppm) / P_2O_5 (%) ratio averages about 2.5 (cf. Arda and others, 1976).

f. In Florida, Miocene and Pliocene Phosphorite deposits have yielded a uranium content of 61 ppm for Pellets of the Hawthorn Formation, 90 ppm for Pellets of the Bone Valley Formation and 160 ppm for Pebbles of the Bone Valley Formation (cf. Altschuler and others, 1958).

g. In the Permian Phosphoria Formation of the Rocky Mountains (U.S.A), the average uranium content for 62 samples is 90 ppm, with a maximum of 210 ppm, for an average of 30.5 % P_2O_5 , i.e. an average of 3 ppm uranium for every 1 % P_2O_5 (cf. Gulbrandsen, 1966).

Certain phosphorite deposits contain much higher uranium concentrations than those considered so far. In the Eocene deposit of Bakouma (Central African Republic), 15 samples studied by Gony (1971) contain from 1660 to 5600 ppm for a P_2O_5 concentration between 8.75 and 33.58 (average, 20.37 %). The U (ppm) / P_2O_5 (%) ratio varies from 81.7 to 392.9, with an average of 155.7 (cf. Slansky, 1980). The Uranium content of the apatite is therefor between 10 and 100 times greater in this deposit than in most others.

The Paleozoic Mussoori deposits of India also contain unusually high amounts of uranium, although lower than that of Bakouma. Uranium contents vary from 25 to 831 ppm (average, 408 ppm) for between 7.19 and 23.62 % P_2O_5 (average, 15.34) and the U (ppm) / P_2O_5 (%) ratio varies from 2.2 to 50.5 (average, 29) (cf. Sarswat and others, 1970). Other high uranium concentrations are reported from different parts of the world.

40 phosphorite samples and 6 associated non-phosphoritic samples from northwestern Saudi Arabia were measured for their radioelement contents (U, Th and K) and the results are given in table 7.22. The geochemistry of these radioelements, factors

affecting their concentration, and their relationship with P_2O_5 and with each other are briefly discussed under the following headings :

7.3.1 Geochemistry of Uranium :

The average concentration of uranium in the Earth's crust is about 3 ppm (cf. Serra and others, 1980), with three natural isotopes which are all radioactive : ^{234}U , ^{235}U and ^{238}U . Their respective proportions are 0.0057 %, 0.72 % and 99.27 %, respectively. In sea water the relative concentration of ^{234}U is higher because ^{238}U ions are selectively fixed on $CaCO_3$. The half-lives of uranium isotopes are : 2.5×10^5 years for ^{234}U , 7.1×10^8 years for ^{235}U and 4.4×10^9 years for ^{238}U . What is measured here is ^{238}U .

The main geochemical characteristic of uranium is that it is easily oxidized into the uranyl ion UO_2^{2+} by bacterial action. This ion is very soluble and uranium therefore is very mobile. This mobility played an important role in the concentration and redistribution of uranium in phosphorites and associated sediments.

Uranium exists under two states of valence : 4^+ and 6^+ as follows :

a). Uranium Salts of Valence 4^+ :

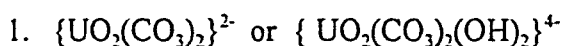
The ion U^{4+} is generally insoluble and exists only in sulfurous hydrothermal waters ($Eh < 0$, $pH < 4$). In reducing and acidic setting ($Eh < 0$, $pH < 4$), U^{4+} gives the insoluble uranium oxide UO_2 or uraninite by dissociation. By oxidation, however, U^{4+} passes easily to the valence 6 as UO_4^{2-} or $U_2O_7^{2-}$.

b). Uranium Salts of Valence 6⁺ :

U⁶⁺ does not exist in solution but immediately gives a complex uranyl ion UO₂²⁺, which is relatively stable under low values of pH (Eh > 0 and pH < 2) and is very soluble. At low pH (< 2.5) and an excess of sulfates, it gives sulfate complexes as {UO₂(SO₄)₃}⁴⁺.

An increase of the pH can induce hydrolysis of the uranyl ion and the formation of U₂O₅²⁺ for 2 < pH < 5, U₃O₈²⁺, or more ionic complexes as {UO₂(OH)₂UO₃}_n. A hydrolysis with precipitation of schoepite for pH = 5, (4 UO₃, pH₂O).

Under neutral conditions the uranyl ion forms various ionic complexes with carbonates :



which are stable for 7.5 < pH < 8.5



Under reducing conditions (Eh < 0), the ion UO₂²⁺ forms numerous complexes with organic compounds (e.g. with humic acids), which facilitate its fixation by organic matter.

The oxide UO₃ is amphoteric (i.e. having both basic and acidic properties) : with acids it gives uranyl salts which are very soluble, and with basic oxides it gives insoluble uraninite.

7.3.2 Uranium Content of the Studied Phosphorite Deposits:

In the studied phosphorite deposits, the uranium content of 40 samples (measured in this work) ranged from 9 ppm to 127 ppm, with an average of 42 ppm, for between

11.46 and 24.71 % P_2O_5 , with an average of 16.75 % (table 7.22). An exceptionally high uranium value of 200 ppm was measured for a surface sample of 33 % P_2O_5 from Darb-Al-Mizhamah surface section, Thaniyat Turayf area. The U (ppm) / P_2O_5 (%) ratio varies from 1.31 to 4.44, with an average of 2.34 ppm uranium for every 1 % P_2O_5 , except for one surface sample for which it is as high as 6.06. Considering the overall range and mean concentration in all samples, the values are at the lower end of the worldwide range (50 to 300 ppm compiled by Mckelvey, 1956 and 8 to 1300 ppm, by Tooms and others, 1969).

The uranium content of the Hazm-Al-Jalamid Phosphorite deposit was measured as U_3O_8 . In the Zone 1 Phosphorite, U_3O_8 ranged from 39 ppm to 123 ppm with an average of 25 ppm for between 14.95 and 25.5 % P_2O_5 , with an average of 18.48 %. The U_3O_8 (ppm) / P_2O_5 (%) ratio varies from 0.79 to 2.52, with an average of 1.33 U_3O_8 ppm for every 1 % P_2O_5 (table 7.1).

In the Zone 2 Phosphorite, U_3O_8 ranged from 14 ppm to 49 ppm with an average of 22 ppm for between 15.05 and 26.5 % P_2O_5 , with an average of 19.5 %. The U_3O_8 (ppm) / P_2O_5 (%) ratio varies from 0.71 to 2.4, with an average of 1.18 U_3O_8 ppm for every 1 % P_2O_5 (table 7.2). Isotenor maps for U_3O_8 in Zones 1 and 2 were constructed (figs. 7.40, 7.42), and 3-D views for its distribution over the same two zones, were also drawn (figs. 7.41, 7.43).

The highest uranium content is apparently associated with the highest P_2O_5 concentration (e.g. 200 ppm U for a sample with 33 % P_2O_5), but this apparent relationship does not seem to be constant. A sample with 11.7 % P_2O_5 was found to contain 52 ppm uranium, while, another sample with 24.71 % P_2O_5 contains only 37 ppm. Other samples with 11.46 % and 19.25 % P_2O_5 were found to contain 36 ppm and 37 ppm

uranium, respectively (table 7.22). These examples show that there is no direct correlation between U concentration and the P_2O_5 content of the studied phosphorite deposits, despite the clear preferential association of uranium with phosphorites in general. The absence of a direct correlation between U concentration and P_2O_5 % is also indicated by the wide range of the U (ppm) / P_2O_5 (%) ratio (1.31 to 6.06) and by the scattered X-Y plots between U_3O_8 and P_2O_5 (figs. 7.44, 7.45) and U and P_2O_5 (fig. 7.46).

7.3.3 Factors affecting Uranium Concentration in the Studied Phosphorite Deposits:

The lack of a direct relationship between U and P_2O_5 in the studied phosphorite deposits warranted the search for factors other than the phosphorite grade which might have controlled the primary concentration and the later distribution of uranium in such deposits. These might have included the amount of organic matter present, the rate of sedimentation, the grain size, the bacterial action and finally the diagenetic changes (cf. Slansky, 1986).

7.3.3.1 Factors affecting the Primary Concentration :

It is now generally accepted that sea water is the original source of uranium in the form of dissolved U^{6+} linked to carbonate complexes. Uranium is integrated into the apatite lattice or adsorbed onto the surface of its crystals by processes that are currently taking place in zones favorable to phosphorite sedimentation. Sediments on the sea floor are rich in organic matter, which can concentrate the U^{6+} in sea water by several factors of ten, while reducing some of the hexavalent forms to U^{4+} which can then be incorporated into the carbonate fluorapatite lattice during its formation; while some of the remaining

U^{6+} can be adsorbed onto the surface of the apatite crystals (cf. Sheldon, 1959; Veeh and others, 1974).

If this is the case, the amount of uranium coming into association with apatite must depend on the amount of the available organic matter in the environment of phosphorite deposition. The more plentiful the organic matter, the greater the uranium content in the interstitial water and the greater the amount of U^{4+} that can be available for incorporation into the apatite lattice. Furthermore, abundant organic matter can limit the growth, and hence the dimensions of the apatite crystallites, which will therefore be more numerous, increasing the specific surface of apatite and the possibilities for adsorption of U^{6+} (cf. Slansky, 1986). It is therefore likely that the uranium content of finer grained phosphorites can be higher than that of the coarser type. This is confirmed by the relatively higher U concentrations in the fine grained phosphorite samples of the Tubaiq Tunnel, compared with other coarser grained samples (table 7.22). For the same reason, bone debris which are highly porous tend to be far richer in uranium than compacted particles of the same size, such as coprolithes or nodules.

The role of organisms (which reflect the amount of organic matter present) in the primary concentration of uranium in the studied phosphorite deposits is also supported by the following observations :

- a. Their evident role in the formation of the studied phosphorite deposits,
- b. Their role in concentrating the other two radioactive elements (Th & K) which have a strong relation with U and no relation with the phosphorite grade,
- c. Their role in concentrating other trace elements and heavy metals such as V, Cr, As, Sr and Zn,

- d. The common association of U with organic matter in the unweathered phosphorites encountered in the few deep boreholes drilled outside the Jalamid area, and its higher concentration in these unweathered phosphorites than in the weathered ones which have lesser amount of organic matter due to oxidation,
- e. The universal strong correlation between uranium and organic carbon (correlation coefficient of 0.86 (cf. Hassan and others, 1976).

The rate of sedimentation can also be a factor affecting the primary concentration of uranium : as low sedimentation rates increase the time during which phosphorite particles are in contact with interstitial waters which increases the chances of uranium integration into apatite. The same effect may be produced if the deposits on the sea floor were periodically set in motion by currents.

7.3.3.2 Factors affecting the Secondary Concentrations :

It has been observed that weathering and ground water circulation have negatively affected U concentration in most of the weathered phosphorite deposits. This can easily be proved by comparing the U content in weathered phosphorites (e.g. in the Jalamid area) and unweathered ones. The Jalamid deposit is close to the surface and the phosphorite beds have been beneficially modified by weathering. Examination of the few deep boreholes that penetrated unoxidized rocks beyond the Al-Jalamid area, showed that unweathered phosphoritic rocks of the Thaniyat Member are organic-rich and dolomitic. Much of Al-Jalamid ore, in its original unweathered state, probably contained less than 10 % P_2O_5 , well below the present ore grade material, and U concentration well above the present content. Surficial weathering resulted in oxidation of the organic matter, partial to

complete dedolomitization, differential leaching of both uranium and calcite, which enhanced the grades to between 15 and 27 % P_2O_5 , and depressed the uranium content. This might be a reasonable explanation for the lack of coherence between P_2O_5 and most of the other components, including radioactive elements in general, and U in particular. It could also enhance the view that organisms have played an important role in the precipitation of phosphorites and the concentration of U within its interstitial spaces.

On the other hand, bacteria might have played an important role in the leaching of U due to its ability to oxidize the uranium ion to the uranyl ion UO_2^{2+} which is very soluble and hence, might have been leached out from the phosphorite deposits.

On the other hand, both weathering and bacteria could have increased the uranium content of the phosphorite ore if it were redeposited in higher concentrations or if it were not associated with organic material that were subsequently subjected to oxidation, but no evidence to such an effect was observed in the present study.

7.3.4 Geochemistry of Thorium :

The average concentration of thorium in the Earth's crust is about 12 ppm. There is only one long-lived thorium isotope : ^{232}Th which is the parent of a long decay chain ending at ^{208}Pb . Other thorium isotopes (^{234}Th and ^{231}Th) are found in nature as transitional daughters of ^{238}U , but they are relatively short-lived and therefore very rare. ^{231}Th and ^{227}Th also occur naturally as a result of their production in the ^{235}U chain.

Thorium exists only at valence 4^+ . It has a very stable degree of oxidation. All its compounds are insoluble : its solubility product, expressed as $Th(OH)_4$, is close to 10^{-42} . During alteration or weathering, thorium is easily hydrolyzed and therefore has limited

mobility and a tendency to concentrate in residual minerals, such as clay minerals. Significant concentrations are also found in heavy minerals, such as monazite.

Owing to its large ionic radius, Th^{4+} is likely to be fixed by absorption on clay minerals (between platelets). The amount probably depends on the pH and on the abundance of other cations (cf. Serra and others, 1980).

Forty phosphorite samples from northwestern Saudi Arabia have been found to contain between 3 ppm and 28 ppm of thorium, with an average of 10 ppm, for between 11.46 and 24.71 % P_2O_5 , with an average of 16.75 %. This range of the thorium content of the studied phosphorite deposits is high, compared to the world range of 1 to 5 ppm quoted by Wedepohl (1969), but, it is within the range of 5 to 100 ppm quoted by Tooms and others (1969). The Th (ppm) / P_2O_5 (%) ratio varies from 0.26 to 0.9, with an average of 0.49 ppm Th for every 1 % P_2O_5 (table 7.22).

Similar to uranium, thorium concentrations in the studied phosphorite deposits have no relationship with their P_2O_5 content. Samples of widely different grades have very close thorium values (table 7.22) (fig. 7.47). This can be attributed to diagenetic changes such as leaching by post depositional weathering and ground water circulation which differentially upgrade phosphorites by the leaching of calcite and other soluble components, while thorium was not equally affected due to its stability and insolubility.

7.3.5 Geochemistry of Potassium :

There are three natural isotopes of potassium : ^{39}K , ^{40}K and ^{41}K with the respective distribution of 93.1 %, 0.0199 % and 6.88 %. ^{40}K is the only radioactive isotope and it is the one being measured here. The ratio ^{40}K / total K is very stable and constant on the

Earth, so, the determination of the ^{40}K content provides a direct indication of the total amount of potassium present. Potassium emits gamma-rays at a single energy of 1.46 MeV.

Forty phosphorite samples from northwestern Saudi Arabia have been found to contain between 0.18 and 2.42 % of potassium 40, with an average of 0.8 %, for between 11.46 and 24.71 % P_2O_5 , with an average of 16.75 %. The K (%) / P_2O_5 (%) ratio varies from 0.03 to 0.08, with an average of 0.04 % K for every 1 % P_2O_5 (table 7.22).

Similar to uranium and thorium, potassium concentrations in the studied phosphorite deposits have no relationship with the grade of the ore and samples of widely different grades were found to have very close potassium values (table 7.22) (fig. 7.48).

7.3.6 Relationship among Uranium, Thorium and Potassium in the Studied Phosphorite Deposits:

Concentrations of the three elements U, Th and K in the studied phosphorite deposits show strong positive relationship. U ppm and Th ppm have a strong correlation coefficient of 0.93 (fig. 7.49). The U (ppm) / Th (ppm) ratio varies from 1.77 to 6.26, with an average of 4.34 ppm U for every 1 ppm Th (table 7.22) which is much lower than the worldwide average ratio of > 10 ppm (cf. Wedepohl, 1969). This lower ratio can be another indication of diagenetic changes which leached uranium from the system due to its mobility, while thorium was not equally affected due to its relative insolubility.

A strong correlation between U ppm and K % was observed in the studied phosphorite deposits, with a correlation coefficient of 0.88 (fig. 7.50). The U (ppm) / K

(%) ratio varies from 13.62 to 109.71, with an average of 55.13 ppm U for every 1 % K (table 7.22).

Similarly, a strong correlation between Th ppm and K % was observed in the same deposits, with a correlation coefficient of 0.92 (fig. 7.51). The Th (ppm) / K (%) ratio varies from 5.28 to 20.86, with an average of 12.73 ppm Th for every 1 % K (table 7.22).

Table 7.1 : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
1	JAL269A	21.01	46.04	2.19	1.31	0.16	0.33	0.49	7.46	26	1.24	10.50
2	JAL359	17.20	42.25	2.46	0.65	0.12	0.15	0.27	10.53	21	1.22	1.00
3	JAL367A	23.48				0.11	0.18	0.29	6.20	30	1.26	2.50
4	JAL370	18.78	43.38	2.31	0.71	0.11	0.38	0.49	9.29	20	1.09	5.00
5	JAL371	19.70	44.46	2.26	0.94	0.11	0.37	0.48	8.94	29	1.48	7.00
6	JAL446	18.11	43.24	2.39	0.80	0.10	0.28	0.37	9.46			4.00
7	JAL449	21.93	46.98	2.14	0.48	0.09	0.30	0.39	7.05			2.00
8	JAL452	18.51	44.03	2.38	2.18	0.11	0.40	0.51	9.12			2.00
9	JAL453B	20.44	46.6	2.28	0.72	0.14	0.04	0.18	8.25			2.50
10	JAL454	19.70	44.30	2.25	0.80	0.10	0.30	0.40	9.81			1.00
11	JAL455	17.76	45.70	2.57	0.82	0.25	0.28	0.53	8.66			2.50
12	JAL465	17.68	43.58	2.47	0.43	0.18	0.23	0.40	10.19			2.00
13	JAL466	16.97	30.00	1.77	0.67	0.13	0.33	0.46	10.18			1.00
14	JAL467	20.60			0.40	0.12	0.20	0.32	7.92			0.50
15	JAL470	16.67	43.40	2.60	0.54	0.12	0.26	0.38	10.86			2.50
16	JAL475	20.53	46.58	2.27	1.32	0.10	0.26	0.36	6.95			11.50
17	JAL479A	16.08	43.85	2.73	0.70	0.09	0.25	0.34	10.88			1.00
18	JAL480	18.30	45.60	2.49	1.07	0.10	0.30	0.40	7.80			1.50
19	JAL481	18.80	46.50	2.47	0.50	0.20	0.08	0.28	7.26			0.50
20	JAL491	17.30	46.00	2.66	1.20	0.09	0.40	0.49	8.40			0.50
21	JAL494	17.92	45.18	2.52	1.03	0.11	0.26	0.37	8.93			5.00
22	JAL495	20.03										1.50
23	JAL498	18.71	44.36	2.37					9.01			4.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
24	JAL499	15.53										1.50
25	JAL503	18.85	43.17	2.29	0.68	0.14	0.33	0.47	9.68			3.00
26	JAL505	17.60	41.35	2.35	0.60	0.13	0.35	0.48	11.35			1.00
27	JAL550	20.58	45.24	2.20	0.96	0.11	0.19	0.29	8.58			4.00
28	JAL568	18.58	53.19	2.86	0.31		0.39		0.88			2.00
29	JAL570	24.68	48.18	1.95	0.45	0.12	0.13	0.25	5.55			2.00
30	JAL575	17.23	43.80	2.54	1.44	0.13	0.33	0.46	9.16			8.00
31	JAL578	19.85	45.18	2.28	2.13	0.09	0.24	0.33	7.07			13.50
32	JAL579	18.07	46.06	2.55	0.75	0.08	0.30	0.38	7.73			7.00
33	JAL581	21.84	45.54	2.09	0.68	0.1	0.3	0.40	8.68			2.50
34	JAL582	18.64	43.04	2.31	1.17	0.08	0.23	0.31	10.33			3.50
35	JAL584	20.70	46.00	2.22	0.58	0.10	0.25	0.35	9.00			2.00
36	JAL605	16.04	42.96	2.68					10.6			2.50
37	JAL606	17.60	43.33	2.46					8.65			2.00
38	JAL607	19.25	41.85	2.17					9.75			1.00
39	JAL608	16.10	42.40	2.63	0.65	0.10	0.20	0.30	10.90			1.00
40	JAL609	19.80	45.40	2.29					8.77			1.50
41	JAL610	18.39	46.80	2.54					6.61			6.50
42	JAL611	18.13	46.65	2.57					7.08			2.00
43	JAL612	18.87	46.37	2.46					7.80			3.00
44	JAL614	19.12	47.89	2.50					5.83			7.50
45	JAL615	16.20	41.10	2.54					12.30			0.50
46	JAL616A	19.88	46.17	2.32					7.65			6.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
47	JAL617	14.95	40.85	2.73					9.55			1.00
48	JAL619	20.13	46.27	2.30					7.57			1.50
49	JAL620	18.40	45.47	2.47					9.37			1.50
50	JAL621	17.35	45.43	2.62					9.13			2.00
51	JAL622	16.90	45.44	2.69					8.78			2.50
52	JAL623C	21.68	49.15	2.27					6.85			2.00
53	JAL624	19.23	41.66	2.17					8.84			5.50
54	JAL625	18.01	44.87	2.49					8.46			6.00
55	JAL655	18.41	46.05	2.50					8.03			6.00
56	JAL656	18.58	44.62	2.40					8.02			2.50
57	JAL659	15.60	46.65	2.99					7.90			1.00
58	JAL667	19.21	44.57	2.32					8.80			3.00
59	JAL668	20.80	44.43	2.14	1.13	0.20	0.10	0.30	9.40			1.50
60	JAL669B	19.19	44.60	2.32					9.03			1.50
61	JAL670	19.68	44.40	2.26					9.13			1.50
62	JAL671	16.69	43.10	2.58					9.60			2.00
63	JAL672	15.74	41.68	2.65					11.00			2.00
64	JAL673	18.17	44.64	2.46					8.83			4.50
65	JAL674	19.35	44.67	2.31					8.47			1.50
66	JAL754	17.28	42.80	2.48					9.86			2.50
67	JAL345	17.20								21	1.21	2.50
68	JAL360	24.53										1.50
69	JAL362	20.04								24	1.22	4.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
70	JAL363	21.00								24	1.13	3.50
71	JAL364	17.43								26	1.49	2.00
72	JAL365	17.52								19	1.07	5.00
73	JAL368	23.65								38	1.59	1.00
74	JAL369	19.20								29	1.49	1.50
75	JAL374	18.65								23	1.21	5.50
76	JAL375	17.58								23	1.29	2.50
77	JAL376	17.14								24	1.43	3.50
78	JAL434B	19.13										3.00
79	JAL435	18.00										3.50
80	JAL437	18.26										5.50
81	JAL438A	20.39										6.50
82	JAL439	17.84										4.50
83	JAL440	19.31										4.50
84	JAL442	19.40										1.50
85	JAL443A	16.40										1.00
86	JAL444A	15.39										3.50
87	JAL445	17.35										4.00
88	JAL447	18.46										4.00
89	JAL448	21.33										4.00
90	JAL450A	21.20										1.50
91	JAL451B	19.68										2.50
92	JAL456	17.18										2.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
93	JAL457	17.26										2.00
94	JAL458	16.71										2.00
95	JAL459	17.48										2.00
96	JAL464	17.77										1.00
97	JAL468	20.23										1.50
98	JAL471	18.60										2.50
99	JAL472E	21.22										2.50
100	JAL473	19.67										1.50
101	JAL476B	18.47										3.00
102	JAL477	19.14										4.50
103	JAL478	16.52										1.50
104	JAL492	21.69										3.50
105	JAL497	16.25										2.50
106	JAL500	19.28										2.00
107	JAL501	18.63										1.50
108	JAL502A	19.99										4.00
109	JAL511	16.00										0.50
110	JAL512	15.00										0.50
111	JAL513	17.67										3.00
112	JAL514	16.88										1.00
113	JAL515	18.66										3.00
114	JAL542A	18.90										3.00
115	JAL571	18.04										4.50

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
116	JAL572	20.03										4.50
117	JAL597	17.43										3.00
118	JAL598	17.46										4.00
119	JAL599	16.98										3.00
120	JAL601	17.70										1.50
121	JAL192	20.45								20	0.98	1.00
122	JAL270	19.90								21	1.06	2.50
123	JAL329	17.70								30	1.71	2.00
124	JAL330	15.80								26	1.65	0.50
125	JAL713	16.60	42.15	2.54	1.35	0.10	0.23	0.33	10.10			1.00
126	JAL714	15.60	41.97	2.69	1.77	0.11	0.21	0.32	10.23			1.50
127	JAL716	16.10	41.28	2.56	1.97		0.48		10.47			3.00
128	JAL717	21.72	41.40	1.91	1.48	0.11	0.24	0.35	10.40			4.50
129	JAL719	18.80	42.90	2.28	2.58	0.10	0.12	0.22	8.50			4.50
130	JAL720	15.75	42.20	2.68	0.90	0.12	0.22	0.34	11.00			0.50
131	JAL171	17.15								21	1.25	4.00
132	JAL259	16.25										3.50
133	JAL271A	19.33								24	1.26	6.00
134	JAL325	21.56								22	1.00	4.50
135	JAL326	18.13								23	1.29	1.50
136	JAL327	17.40								14	0.80	2.00
137	JAL328	20.33					0.18		10.22	22	1.10	4.50
138	JAL358A	16.40								23	1.37	1.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
139	JAL377A	20.78								29	1.39	6.50
140	JAL651	16.41	43.67	2.66					9.87			3.50
141	JAL654	19.85	47.57	2.40					7.26			4.50
142	JAL657	17.61	43.60	2.48					10.03			4.00
143	JAL658	18.00	43.73	2.43					9.74			3.50
144	JAL186	19.30										0.50
145	JAL187	17.50								37	2.13	2.00
146	JAL188	18.16					0.27		12.29	28	1.57	3.50
147	JAL189	19.81								22	1.11	3.00
148	JAL190	15.45								39	2.52	0.50
149	JAL193	15.10								19	1.26	0.50
150	JAL332	19.00								18	0.95	0.50
151	JAL334A	19.45								24	1.23	1.00
152	JAL336	18.04								26	1.46	2.50
153	JAL337	17.85								21	1.16	4.00
154	JAL338	17.17								22	1.26	3.50
155	JAL339	17.50								20	1.11	2.00
156	JAL340	15.79								18	1.15	2.50
157	JAL341	16.53								21	1.24	1.00
158	JAL342	18.76								23	1.23	2.50
159	JAL344	17.00								21	1.21	1.00
160	JAL346	18.83								16	0.84	2.50
161	JAL347	17.80								21	1.18	0.50

Blank Areas = Not Determined

Table 7.1 (Cont.): Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
162	JAL348	20.13								24	1.19	1.50
163	JAL350	20.36								23	1.12	3.50
164	JAL351	19.65								29	1.45	3.00
165	JAL352	17.10								27	1.58	0.50
166	JAL353A	18.80								38	2.02	0.50
167	JAL354	18.00								33	1.81	1.50
168	JAL355	19.30								31	1.59	4.00
169	JAL356	17.87								27	1.49	3.50
170	JAL357	19.96								39	1.95	3.50
171	JAL279	16.23								13	0.79	2.00
172	JAL378	17.67								25	1.43	1.50
173	JAL379	20.20								24	1.19	1.00
174	JAL381	15.72								21	1.34	1.50
175	JAL679B	18.08	43.12	2.38	2.37	0.11	0.17	0.28	9.27			0.50
176	JAL680	16.88	47.47	2.81	2.20	0.15	0.31	0.46	4.71			0.50
177	JAL681	18.34	42.91	2.34	1.28	0.05	0.05	0.10	9.22			1.50
178	JAL683	15.33	39.57	2.58	1.04	0.16	0.18	0.34	12.17			0.50
179	JAL685	17.21	43.31	2.52	1.20	0.14	0.12	0.26	9.64			4.50
180	JAL686	19.06	45.41	2.38	0.74	0.13	0.12	0.25	7.90			2.50
181	JAL687	19.63	47.00	2.39	0.88	0.10	0.10	0.20	6.21			2.00
182	JAL690	18.22	43.32	2.38	2.65	0.14	0.15	0.29	8.49			2.50
183	JAL691	16.43	42.50	2.59	1.10	0.20	0.27	0.47	10.83			1.00
184	JAL692	15.02	40.30	2.68	1.12	0.14	0.13	0.27	12.06			1.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
185	JAL696	16.95	39.74	2.34	4.46	0.16	0.18	0.34	10.35			1.00
186	JAL707	18.20	42.60	2.34	1.06	0.11	0.07	0.18	9.42			0.50
187	JAL709	15.91	43.84	2.76	0.55	0.12	0.10	0.22	8.96			1.00
188	JAL725	17.62	43.70	2.48	1.24	0.18	0.17	0.35	8.42			1.00
189	JAL726	15.08	50.02	3.32	2.15	0.16	0.20	0.36	3.42			0.50
190	JAL727	16.80	48.37	2.88	2.57	0.30	0.36	0.66	4.80			1.50
191	JAL763	16.18	41.90	2.59	2.70	0.16	0.49	0.65	10.50			0.50
192	JAL767	16.61	47.20	2.84	0.60	0.17	0.10	0.27	6.00			0.50
193	JAL768	17.05	52.15	3.06	1.32	0.18	0.23	0.41	2.12			0.50
194	JAL769	16.71	43.29	2.59	0.78	0.11	0.13	0.24	9.49			2.00
195	JAL770	21.36	44.70	2.09	1.30	0.10	0.17	0.27	7.70			0.50
196	JAL196	18.00								29	1.59	1.50
197	JAL199	23.70								24	1.02	2.00
198	JAL460	15.58										1.00
199	JAL461	22.93										1.50
200	JAL462	18.33										1.50
201	JAL484	25.50										1.00
202	JAL485	23.16										4.00
203	JAL506	20.37										5.00
204	JAL510	15.15										1.00
205	JAL541A	20.02	45.7	2.28	0.71	0.15	0.10	0.25	8.33			2.50
206	JAL592	15.90										1.00
207	JAL594	21.90										1.00

Blank Areas = Not Determined

Table 7.1 (Cont.) : Chemical Composition of the Zone 1 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ +Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
208	JAL595	21.03										3.50
209	JAL596A	16.05										1.00
210	JAL632B	19.26	46.60	2.42					3.32			2.50
211	JAL636	21.34	50.44	2.36					2.88			2.50
212	JAL637	22.90	49.35	2.16					4.60			2.00
213	JAL638	17.10	40.60	2.37					9.20			0.50
214	JAL639	18.02	49.98	2.77					2.62			2.50
215	JAL641	15.90	54.10	3.40					0.65			1.00
216	JAL644	20.53	50.03	2.44					0.45			2.00
217	JAL718	20.52	50.07	2.44	0.52	0.13	0.48	0.61	3.00			3.00
	Maximum	25.50	54.10	3.40	4.46	0.30	0.49	0.66	12.30	39	2.52	13.50
	Minimum	14.95	30.00	1.77	0.31	0.05	0.04	0.10	0.45	13	0.79	0.50
	Average	18.48	44.75	2.46	1.18	0.13	0.23	0.36	8.31	25	1.33	2.58
	Counts	217	102	102	62	61	65	61	106	59	59	217

Blank Areas = Not Determined

Table 7.2 : Chemical Composition of the Zone 2 Phosphorite (Hazmi-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
1	JAL359	19.95	45.13	2.26	1.28	0.14	0.20	0.34	7.85	20	1.02	2.00
2	JAL361	20.13					0.21	0.21	0.28	20	1.00	8.00
3	JAL367A	17.58	44.67	2.54					0.15	19	1.08	1.50
4	JAL370	20.84	44.52	2.14	1.95	0.12	0.27	0.39	7.87	25	1.20	5.00
5	JAL371	20.30	46.30	2.28	1.20	0.11	0.30	0.41	7.80	26	1.26	1.00
6	JAL446	15.43	46.38	3.01	5.28	0.26	0.30	0.56	6.29			3.00
7	JAL449	22.74										4.50
8	JAL452	21.95	53.04	2.42	2.99	0.16	0.36	0.53	0.81			5.50
9	JAL453B	23.80	51.77	2.18	2.74	0.24	0.08	0.32	2.41			3.50
10	JAL454	19.44	52.26	2.69	1.09	0.08	0.21	0.29	2.84			7.00
11	JAL455	18.40	53.77	2.92	2.13	0.17	0.43	0.61	0.56			1.50
12	JAL465	17.80	44.27	2.49	3.10	0.21	0.30	0.51	8.16			1.50
13	JAL466	18.70	44.40	2.37	0.65	0.15	0.55	0.70	8.76			1.00
14	JAL467	20.65			2.63	0.14	0.28	0.42	6.57			6.00
15	JAL470	20.22	48.74	2.41	3.61	0.13	0.20	0.33	4.24			6.00
16	JAL479A	21.54	48.85	2.27	3.90	0.18	0.48	0.65	3.52			6.50
17	JAL480	20.70	53.52	2.59	3.41	0.13	0.29	0.42	0.49			4.50
18	JAL481	18.95	46.70	2.46	1.45	0.15	0.11	0.26	6.69			1.00
19	JAL490	18.30	47.14	2.58	5.94	0.13	0.28	0.41	4.60			2.50
20	JAL491	21.29	48.21	2.26	1.61	0.12	0.25	0.37	5.29			8.00
21	JAL493	20.15	47.62	2.36	1.99	0.11	0.29	0.39	5.68			7.50
22	JAL494	20.52	50.42	2.46	1.83	0.18	0.30	0.48	3.66			3.00
23	JAL495	23.45										2.00

Blank Areas = Not Determined

Table 7.2 (Cont.) : Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
24	JAL496	19.40	48.20	2.48					5.90			2.50
25	JAL498	26.50	48.48	1.83					4.08			2.00
26	JAL499	18.91										4.00
27	JAL503	16.95	41.85	2.47	1.05	0.10	0.20	0.30	10.35			1.00
28	JAL504	17.48	45.53	2.60	2.37	0.11	0.15	0.26	7.71			3.00
29	JAL505	21.07	46.24	2.19	3.04	0.15	0.23	0.38	6.09			3.50
30	JAL550	21.25	46.99	2.21	3.33	0.16	0.26	0.42	5.88			6.50
31	JAL568	20.25	53.58	2.65	1.96	0.28	0.35	0.63	0.32			8.50
32	JAL570	20.52	47.41	2.31	3.26	0.12	0.12	0.24	6.02			6.50
33	JAL575	17.33	44.01	2.54	5.28	0.18	0.23	0.41	7.64			5.00
34	JAL578	16.70	37.04	2.22	5.57	0.06	0.43	0.49	13.56			3.50
35	JAL579	19.53	49.25	2.52	2.41	0.14	0.16	0.30	1.07			5.50
36	JAL581	22.24	48.53	2.18	2.51	0.10	0.23	0.34	2.44			9.00
37	JAL582	22.61	49.56	2.19	2.06	0.07	0.26	0.33	4.02			9.50
38	JAL584	22.01	55.30	2.51	1.55	0.08	0.23	0.31	0.22			7.50
39	JAL602	20.18	48.12	2.38	2.34	0.16	0.20	0.36	4.68			6.00
40	JAL603B	17.95	51.99	2.90	3.32	0.14	0.28	0.42	0.78			6.50
41	JAL604	22.21	49.74	2.24					2.22			10.00
42	JAL605	21.62	46.97	2.17					4.93			6.00
43	JAL606	21.61	49.82	2.31					2.79			8.00
44	JAL607	23.26	51.39	2.21					3.19			9.50
45	JAL608	17.93	53.49	2.98	2.08	0.23	0.28	0.50	0.39			4.50
46	JAL609	22.23	50.58	2.28					3.52			6.50

Blank Areas = Not Determined

Table 7.2 (Cont.) : Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
47	JAL612	17.35	46.24	2.66					7.35			5.50
48	JAL613	19.04	49.79	2.61					4.31			8.00
49	JAL615	17.47	45.22	2.59					8.67			5.00
50	JAL616A	24.06	54.04	2.25					0.86			3.50
51	JAL617	18.78	49.40	2.63					2.40			2.50
52	JAL619	21.03	48.96	2.33					4.49			7.50
53	JAL620	20.77	48.71	2.35					5.73			6.00
54	JAL621	18.35	54.40	2.96					0.50			1.00
55	JAL623C	23.26	54.43	2.34					0.19			3.50
56	JAL624	16.03	44.58	2.78					6.13			3.00
57	JAL625	16.75	44.70	2.67					8.75			1.00
58	JAL655	15.94	43.68	2.74					9.06			4.00
59	JAL656	17.78	46.02	2.59					7.00			4.50
60	JAL659	17.98	54.41	3.03					0.43			4.50
61	JAL667	23.97	49.42	2.06					3.80			5.00
62	JAL668	23.00	51.55	2.24	2.70	0.19	0.10	0.29	2.52			6.50
63	JAL669B	23.94	51.82	2.16					2.72			5.00
64	JAL670	21.77	50.58	2.32					2.35			6.00
65	JAL671	21.77	46.30	2.13					6.26			2.50
66	JAL672	20.54	50.79	2.47					4.69			6.50
67	JAL673	18.24	46.20	2.53					5.93			1.50
68	JAL674	19.35	45.78	2.37					7.68			2.50
69	JAL712	20.25	53.05	2.62	2.31	0.29	0.35	0.64	0.21			1.00

Blank Areas = Not Determined

Table 7.2 (Cont.) : Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
70	JAL754	18.34	44.96	2.45					6.54			2.50
71	JAL345	17.60								27	1.51	1.00
72	JAL360	20.85										5.50
73	JAL362	19.25								32	1.68	2.00
74	JAL364	15.13								22	1.42	1.00
75	JAL369	18.74								17	0.92	2.50
76	JAL374	22.62								24	1.05	3.00
77	JAL375	17.20								16	0.92	2.00
78	JAL376	21.27								24	1.11	4.00
79	JAL435	17.75										1.00
80	JAL440	15.93										1.50
81	JAL441	18.80										0.50
82	JAL442	19.28										2.00
83	JAL443A	19.20										0.50
84	JAL445	18.90										0.50
85	JAL448	24.35										7.00
86	JAL450A	23.02										7.00
87	JAL451B	21.50										8.00
88	JAL456	16.80										1.00
89	JAL459	15.70										2.50
90	JAL464	18.87										1.50
91	JAL468	23.56										9.50
92	JAL471	21.83										6.00

Blank Areas = Not Determined

Table 7.2 (Cont.) : Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
93	JAL472E	23.31										4.00
94	JAL473	22.88										4.50
95	JAL476B	21.39										7.00
96	JAL477	24.59										6.50
97	JAL478	22.14										9.50
98	JAL492	20.38										4.50
99	JAL497	18.18										2.00
100	JAL500	15.73										1.50
101	JAL501	21.20										5.00
102	JAL502A	21.30										1.00
103	JAL511	15.95										2.00
104	JAL512	20.31										4.00
105	JAL513	20.25										1.00
106	JAL514	17.08										2.00
107	JAL515	18.60										3.00
108	JAL542A	22.83										6.00
109	JAL571	16.80										0.50
110	JAL597	20.14										4.50
111	JAL598	24.68										5.00
112	JAL599	24.04										6.00
113	JAL600	23.37										6.00
114	JAL600	23.37										6.00
115	JAL601	21.43										7.00

Blank Areas = Not Determined

Table 7.2 (Cont.) : Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
116	JAL192	17.30								19	1.10	1.50
117	JAL270	18.07								19	1.05	1.50
118	JAL329	16.70								22	1.32	1.00
119	JAL330	17.50								22	1.26	1.00
120	JAL713	20.34	48.93	2.41	1.51	0.14	0.32	0.46	3.93			3.50
121	JAL714	17.50	44.73	2.56	3.40	0.12	0.09	0.21	7.33			2.00
122	JAL715	16.92	43.73	2.58	2.70	0.11	0.19	0.30	8.27			1.50
123	JAL716	20.00	44.42	2.22	1.18	0.11	0.31	0.42	8.64			2.50
124	JAL717	23.21	43.83	1.89	4.95	0.13	0.29	0.42	7.15			2.00
125	JAL719	15.20	40.20	2.64	0.60	0.07	0.13	0.20	11.77			1.50
126	JAL720	22.17	44.75	2.02	3.00	0.12	0.17	0.29	7.80			1.00
127	JAL171	16.54								15	0.91	2.50
128	JAL259	22.70										2.50
129	JAL271A	19.56								18	0.91	4.00
130	JAL327	18.48								16	0.88	2.00
131	JAL328	17.25					0.17		9.75	23	1.32	2.00
132	JAL358A	17.95								18	0.99	2.00
133	JAL377A	20.34								23	1.14	8.50
134	JAL651	18.70	46.00	2.46					7.43			3.50
135	JAL654	16.33	44.80	2.74					9.43			3.50
136	JAL657	18.69	47.36	2.53					7.00			4.50
137	JAL658	18.59	45.67	2.46					8.11			5.50
138	JAL188	20.50					0.20		3.60	49	2.40	2.50

Blank Areas = Not Determined

Table 7.2 (Cont.) : Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
139	JAL193	16.20								16	0.99	0.50
140	JAL336	18.70								28	1.50	0.50
141	JAL337	21.80								28	1.26	1.00
142	JAL338	17.20								15	0.87	1.00
143	JAL340	20.65								20	0.98	2.00
144	JAL341	20.65								23	1.11	3.00
145	JAL342	20.66								26	1.24	3.00
146	JAL350	16.90								26	1.54	0.50
147	JAL353A	16.30								22	1.35	0.50
148	JAL354	15.10								35	2.28	1.00
149	JAL279	19.49								15	0.74	3.00
150	JAL379	17.50								15	0.86	0.50
151	JAL380	19.33								14	0.72	1.50
152	JAL381	19.17								14	0.71	1.50
153	JAL675A	15.05	41.80	2.78	8.63	0.76	1.31	2.07	6.21			0.50
154	JAL683	19.12	45.76	2.39	4.26	0.28	0.25	0.53	5.14			1.00
155	JAL690	17.40	47.53	2.73	2.25	0.13	0.12	0.25	6.12			0.50
156	JAL691	18.53	48.13	2.60	4.98	0.23	0.20	0.43	4.60			2.00
157	JAL695	17.00	51.83	3.05	2.94	0.11	0.15	0.26	0.46			3.50
158	JAL696	17.33	46.01	2.66	3.27	0.21	0.25	0.46	5.84			3.00
159	JAL698	22.05	54.95	2.49	1.00	0.17	0.21	0.38	0.17			0.50
160	JAL707	18.25	45.90	2.52	0.96	0.12	0.08	0.20	7.04			1.00
161	JAL709	16.61	48.37	2.91	11.03	0.35	0.50	0.85	0.47			1.00

Blank Areas = Not Determined

Table 7.2 (Cont.): Chemical Composition of the Zone 2 Phosphorite (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ / P ₂ O ₅	Thickness (m)
162	JAL725	16.96	50.83	3.00	2.74	0.12	0.18	0.30	1.63			1.00
163	JAL768	15.52	53.95	3.48	1.90	0.26	0.58	0.84	0.35			1.00
164	JAL769	16.60	48.22	2.90	6.12	0.35	0.51	0.86	2.77			1.50
165	JAL770	15.90	46.60	2.93	8.45	0.24	0.39	0.63	2.90			1.00
166	JAL482	17.30										1.00
167	JAL484	16.80										1.50
168	JAL507	19.50										1.00
169	JAL508	17.30										1.00
170	JAL509	21.69										8.00
171	JAL510	15.35										1.00
172	JAL541A	21.71	50.84	2.34	4.13	0.13	0.31	0.44	2.39			12.50
173	JAL592	18.10										4.00
174	JAL594	15.43										2.00
175	JAL596A	15.70										1.00
	Maximum	26.50	55.30	3.48	11.03	0.76	1.31	2.07	13.56	49	2.40	12.50
	Minimum	15.05	37.04	1.83	0.60	0.06	0.08	0.20	0.15	14	0.71	0.50
	Average	19.50	48.13	2.49	3.09	0.17	0.28	0.45	4.76	22	1.18	3.57
	Counts	175	90	90	57	57	60	58	94	37	37	175

Blank Areas = Not Determined

Table 7.3 : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
1	JAL359	9.40	38.53	4.10	0.80	0.32	0.47	0.78	14.52			1.50
2	JAL361	7.45					0.36		0.87			1.50
3	JAL367A	5.52					0.16		18.00			3.50
4	JAL371	12.20	39.98	3.28	3.24	0.17	0.33	0.50	12.42	23	1.86	5.00
5	JAL446	11.93	40.66	3.41	1.18	0.10	0.26	0.36	13.32			5.50
6	JAL449	8.31	40.96	4.93	1.10	0.07	0.18	0.25	11.63			3.50
7	JAL452	8.93	40.47	4.53	4.38	0.22	0.65	0.87	11.08			3.00
8	JAL453B	10.01	41.38	4.13	1.02	0.20	0.05	0.25	12.28			3.00
9	JAL454	11.47	40.53	3.53	0.94	0.03	0.23	0.26	12.74			3.50
10	JAL455	12.92	46.57	3.60	0.94	0.14	0.31	0.45	8.04			3.50
11	JAL465	10.81	38.94	3.60	1.68	0.14	0.27	0.41	13.71			5.00
12	JAL466	10.95	39.02	3.56	0.56	0.10	0.40	0.50	13.67			2.50
13	JAL467	10.43			0.72	0.09	0.28	0.37	14.46			3.00
14	JAL470	10.14	38.93	3.84	0.53	0.09	0.20	0.29	14.35			2.00
15	JAL479A	9.36	38.36	4.10	2.78	0.16	0.18	0.34	14.05			4.50
16	JAL480	10.56	40.98	3.88	0.70	0.06	0.20	0.26	12.53			2.00
17	JAL481	10.93	40.70	3.72	2.65	0.23	0.13	0.35	11.73			4.50
18	JAL490	7.46	37.31	5.00	6.26	0.14	0.20	0.34	13.04			3.50
19	JAL491	12.40	42.35	3.42	0.90	0.67	0.35	1.02	11.8			1.00
20	JAL494	10.75	40.60	3.78	1.10	0.13	0.35	0.48	12.69			1.00
21	JAL495	10.78										4.50
22	JAL496	9.64	38.91	4.04					13.30			4.50
23	JAL498	9.91	39.05	3.94					12.88			2.00

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
24	JAL499	5.99										3.50
25	JAL503	9.24	39.58	4.28	0.58	0.11	0.33	0.44	13.28			3.00
26	JAL505	9.28	39.55	4.26	3.80	0.09	0.18	0.26	12.10			2.00
27	JAL550	10.68	42.28	3.96	0.43	0.48	0.30	0.78	11.84			2.00
28	JAL568	11.78	52.68	4.47	2.73	0.45	0.59	1.03	0.44			4.50
29	JAL570	11.63	39.55	3.40	0.60	0.11	0.15	0.26	14.3			1.00
30	JAL575	4.15	33.6	8.10	10.20	0.16			14			0.50
31	JAL578	11.65	38.05	3.27	6.35	0.11	0.55	0.66	11.8			1.00
32	JAL579	11.80	47.35	4.01	6.45	0.94	1.20	2.14	2.55			1.00
33	JAL581	12.16	40.33	3.32	0.83	0.09	0.25	0.34	12.95			2.00
34	JAL582	11.48	38.66	3.37	1.98	0.05	0.24	0.29	13.4			2.50
35	JAL584	10.98										4.00
36	JAL602	8.33	41.67	5.00	1.63	0.15	0.13	0.28	11.40			1.50
37	JAL603B	5.53	43.08	7.79	0.85	0.06	0.25	0.31	10.42			3.00
38	JAL605	11.40	39.82	3.49					13.47			3.00
39	JAL606	12.08	39.20	3.25					11.41			4.00
40	JAL607	9.82	37.37	3.81					14.08			3.00
41	JAL608	8.96	42.68	4.77	2.24	0.23	0.30	0.53	9.31			4.50
42	JAL609	11.93	39.09	3.28					12.73			3.50
43	JAL612	9.35	39.90	4.27					13.30			1.00
44	JAL615	11.40	41.03	3.60					13.60			1.50
45	JAL616A	12.20	40.35	3.31					13.00			1.00
46	JAL617	8.91	36.03	4.04					11.34			3.50

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
47	JAL619	11.75	42.05	3.58					12.40			2.00
48	JAL620	11.20	41.23	3.68					12.38			2.00
49	JAL621	11.93	46.13	3.87					7.29			5.50
50	JAL623C	8.89	48.28	5.43					6.14			5.00
51	JAL624	10.04	39.43	3.93					10.50			5.00
52	JAL625	8.23	42.68	5.19					9.88			2.00
53	JAL655	10.23	40.90	4.00					10.57			1.50
54	JAL656	5.95	32.50	5.46					8.70			1.00
55	JAL659	8.03	43.99	5.48					9.95			5.50
56	JAL667	8.48	37.98	4.48					13.97			3.00
57	JAL668	8.83	37.33	4.23	1.53	0.16	0.10	0.26	15.41			3.50
58	JAL669B	11.40	39.63	3.48					13.44			3.50
59	JAL670	9.38	39.36	4.20					13.43			4.00
60	JAL671	10.48	39.43	3.76					12.49			4.50
61	JAL672	13.75	40.40	2.94					12.35			1.00
62	JAL673	8.52	41.15	4.83					12.00			1.00
63	JAL674	13.17	41.95	3.19					10.45			1.00
64	JAL712	7.83	48.74	6.22	7.57	0.88	1.71	2.60	0.66			5.00
65	JAL754	10.67	39.90	3.74					12.04			3.50
66	JAL345	12.73								20	1.60	1.50
67	JAL360	13.48										1.00
68	JAL362	3.68										1.00
69	JAL363	6.18										1.00

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
70	JAL364	2.15										1.50
71	JAL365	3.67										1.50
72	JAL369	6.08										4.00
73	JAL374	11.80								24	1.99	1.50
74	JAL375	9.60										3.00
75	JAL376	6.74										2.00
76	JAL435	8.58										1.50
77	JAL439	6.68										1.50
78	JAL440	11.70										1.00
79	JAL441	6.55										4.50
80	JAL442	10.50										2.50
81	JAL444A	9.04										2.00
82	JAL445	8.02										1.50
83	JAL448	11.51										3.50
84	JAL450A	7.72										3.00
85	JAL451B	11.23										2.50
86	JAL456	11.53										3.00
87	JAL457	7.73										6.00
88	JAL459	11.54										4.00
89	JAL464	9.89										2.00
90	JAL468	11.33										3.00
91	JAL471	11.18										2.50
92	JAL472E	11.30										3.50

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
93	JAL473	9.07										3.50
94	JAL476B	12.71										3.50
95	JAL477	10.78										2.00
96	JAL478	13.15										1.50
97	JAL492	13.43										1.50
98	JAL497	8.24										5.50
99	JAL501	12.30										1.50
100	JAL502A	13.95										1.50
101	JAL512	11.48										1.00
102	JAL513	10.74										2.50
103	JAL514	12.08										1.00
104	JAL515	8.63										3.00
105	JAL542A	7.60										4.50
106	JAL571	4.17										1.50
107	JAL597	8.57										3.00
108	JAL598	9.25										2.00
109	JAL599	8.28										2.50
110	JAL600	7.56										3.50
111	JAL601	11.41										4.00
112	JAL192	7.40										2.00
113	JAL270	10.63								16	1.51	7.00
114	JAL329	9.00								23	2.56	2.50
115	JAL330	7.71										5.50

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
116	JAL713	7.20	35.00	4.86	4.17	0.21	0.28	0.49	14.97			3.50
117	JAL714	7.00	34.73	4.96	10.19	0.26	0.83	1.09	12.93			4.50
118	JAL715	9.60	36.86	3.84	5.33	0.11	0.19	0.30	13.20			6.00
119	JAL716	7.40	33.13	4.48	10.20	0.18	0.35	0.53	13.40			3.50
120	JAL717	7.81	33.23	4.25	9.60	0.18	0.25	0.43	13.80			3.00
121	JAL719	8.60	37.90	4.41	6.60	0.05	0.14	0.19	11.10			1.00
122	JAL720	8.70	36.30	4.17	6.80	0.12	0.18	0.30	13.31			4.50
123	JAL171	11.19								14	1.21	1.00
124	JAL271A	9.02										3.50
125	JAL327	13.02								15	1.15	1.50
126	JAL328	10.39					0.17		13.75	13	1.28	2.00
127	JAL358A	8.12										1.50
128	JAL377A	13.38								26	1.94	1.00
129	JAL651	5.87	35.50	6.05					16.47			1.50
130	JAL654	9.73	41.23	4.24					11.41			5.50
131	JAL657	10.71	38.95	3.64					12.23			4.00
132	JAL658	10.78	41.12	3.81					11.82			2.50
133	JAL188	9.88					0.36		16.00	28	2.84	1.00
134	JAL193	6.86										4.50
135	JAL336	9.18										2.50
136	JAL337	7.77										2.50
137	JAL338	11.50										1.00
138	JAL339	7.56										1.50

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
139	JAL340	6.18										2.00
140	JAL341	7.03										2.50
141	JAL342	4.94										1.50
142	JAL350	9.40										1.50
143	JAL353A	5.95										1.50
144	JAL354	7.78										1.00
145	JAL279	8.63										4.50
146	JAL378	4.50										3.00
147	JAL379	5.54										3.50
148	JAL380	6.83										2.50
149	JAL381	8.47										4.50
150	JAL683	10.99	39.83	3.63	0.14	2.40	0.11	2.51	12.16			1.50
151	JAL685	6.00	33.25	5.54	10.72	0.22	0.43	0.65	13.37			2.50
152	JAL690	5.95	33.32	5.60	9.88	0.22	0.36	0.58	13.89			2.50
153	JAL691	6.06	35.00	5.78	6.03	0.21	0.27	0.48	15.30			3.50
154	JAL695	5.20	37.95	7.30	3.07	0.33	0.58	0.91	12.38			1.50
155	JAL696	6.40	32.80	5.13	6.37	0.41	0.69	1.10	14.96			1.50
156	JAL698	5.06	39.02	7.71	5.29	0.28	0.47	0.75	10.39			4.00
157	JAL705	4.70	35.04	7.46	6.56	0.17	0.26	0.43	13.76			5.00
158	JAL707	7.77	37.09	4.77	2.99	0.20	0.32	0.52	13.74			4.50
159	JAL709	7.68	36.69	4.78	4.41	0.16	0.21	0.37	12.79			3.00
160	JAL725	7.45	37.12	4.98	2.60	0.19	0.33	0.52	13.96			5.50
161	JAL726	8.09	47.27	5.84	5.97	0.45	0.74	1.19	3.22			5.00

Blank Area = Not Determined

Table 7.3 (Cont.) : Chemical Composition of the Interval Zone (Hazm-Al-Jalamid Area).

Serial No.	Well No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	U ₃ O ₈ ppm	U ₃ O ₈ /P ₂ O ₅	Thickness (m)
162	JAL768	11.60	53.97	4.65	1.50	0.18	0.27	0.45	0.47			1.50
163	JAL769	9.35	39.18	4.19	2.26	0.13	0.22	0.35	12.06			5.00
164	JAL770	8.71	37.39	4.29	7.91	0.22	0.44	0.66	11.14			4.50
165	JAL460	6.23										4.00
166	JAL461	7.43										2.00
167	JAL462	6.80										1.50
168	JAL482	8.48										2.00
169	JAL483	7.75										1.50
170	JAL484	6.27										3.00
171	JAL489	7.89										2.00
172	JAL509	8.18										1.50
173	JAL510	8.57										2.00
174	JAL541A	9.81	38.78	3.95	1.29	0.09	0.28	0.37	13.98			5.00
175	JAL592	9.33										2.00
176	JAL594	11.15										4.00
177	JAL595	9.85										1.00
178	JAL596A	9.14										3.50
	Maximum	13.95	53.97	8.10	10.72	2.40	1.71	2.60	18.00	28	2.84	7.00
	Minimum	2.15	32.50	2.94	0.14	0.03	0.05	0.19	0.44	13	1.15	0.50
	Average	9.19	39.73	4.41	3.73	0.25	0.35	0.61	11.87	20	1.79	2.80
	Counts	178	86	86	56	56	59	55	91	10	10	178

Blank Area = Not Determined

Table 7.4 : Chemical Composition of the Zone 1 Phosphorite (Thaniyat Turayf Area).

Serial No.	Sample No.	P ₂ O ₅ %	CaO %	CaO / P ₂ O ₅	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Fe ₂ O ₃ + Al ₂ O ₃ %	MgO %	K ₂ O %	Na %	F %	F / P ₂ O ₅	Cl %	S %	MN ppm	V ppm	TOM %	LOI %
1	5	21.25	35.60	1.68	15.15	1.49	2.71	4.20	0.56	0.07	0.104			0.10	0.068	387	616	2.17	11.99
2	10	21.94	39.70	1.81	1.88	2.24	0.36	2.60	0.48	0.02	0.074	0.93	0.04	0.35	0.040	465	1681	1.20	13.74
3	13	23.54	33.00	1.40	16.03	2.80	2.31	5.11	1.28	0.06	0.141	1.86	0.08	0.20	0.068	929	1288	2.36	4.00
4	17	17.67	27.50	1.56	21.46	0.34	2.12	2.46	0.91	0.07	0.148	2.29	0.13	0.70	0.116	387	1064	2.40	4.77
5	18	21.36	30.10	1.41	22.73	0.91	1.04	1.95	1.33	0.04	0.148	0.61	0.03	0.40	0.232	852	1288	1.32	3.65
6	21	27.34	37.80	1.38	4.74	0.64	0.74	1.38	1.34	0.04	0.148	2.86	0.10	0.46	0.168	155	168	1.77	4.35
7	22	27.51	31.90	1.16	3.46	0.54	1.31	1.85	0.50	0.06	0.185	2.89	0.11	0.18	0.100	155	168	1.55	7.59
8	24	22.82	23.20	1.02	21.19	2.11	4.78	6.89	0.65	0.06	0.148			0.20	0.100	1007	504	1.81	3.56
	Maximum	27.51	39.70	1.81	22.73	2.80	4.78	6.89	1.34	0.07	0.185	2.89	0.13	0.70	0.232	1007	1681	2.40	13.74
	Minimum	17.67	23.20	1.02	1.88	0.34	0.36	1.38	0.48	0.02	0.074	0.61	0.03	0.10	0.040	155	168	1.20	3.56
	Average	22.93	32.35	1.43	13.33	1.38	1.92	3.31	0.88	0.05	0.137	1.91	0.08	0.32	0.112	542	847	1.82	6.71

Blank Areas = Not Determined

TOM = Total Organic Matter

LOI = Loss of Ignition

Table 7.5 : Chemical Composition of the Zone 2 Phosphorite from the Drill Hole (P.11), Turayf Area.

Serial No.	Sample No.	P ₂ O ₅ %	CaO %	CaO / P ₂ O ₅ %	Fe ₂ O ₃ %	K ₂ O %	CO ₂ %	CO ₂ / P ₂ O ₅ %	K ₂ O %	Na %	Cl %	S %	V ppm
1	98	18.16	52.88	2.91	0.07	0.25	8.43	0.46	0.25	0.38	7.00	0.27	2185
2	99	14.00	52.74	3.77	0.07	0.26	5.50	0.39	0.26	0.34	10.60	0.33	2409
3	100	16.50	58.67	3.56	0.08	0.36	5.50	0.33	0.36	0.44	9.00	0.60	2801
4	101	18.33	30.36	1.66	0.14	0.08	5.87	0.32	0.08	0.13	8.00	0.53	2801
5	115	19.25	31.78	1.65	0.07	0.12	5.50	0.29	0.12	0.14	5.50	0.40	672
	Maximum	19.25	58.67	3.77	0.14	0.36	8.43	0.46	0.36	0.44	10.60	0.60	2801
	Minimum	14.00	30.36	1.65	0.07	0.08	5.50	0.29	0.08	0.13	5.50	0.27	672
	Average	17.25	45.29	2.71	0.09	0.21	6.16	0.36	0.21	0.28	8.02	0.43	2174

Table 7.6 : Chemical Composition of the Zone 5 Phosphorite from Drill Hole (P.1), Turayf Area.

Serial No.	Sample No.	P ₂ O ₅ %	CaO %	CaO / P ₂ O ₅ %	SiO ₂ %	Fe ₂ O ₃ %	Al ₂ O ₃ %	Fe ₂ O ₃ + Al ₂ O ₃ %	MgO %	K ₂ O %	CO ₂ %	CO ₂ / P ₂ O ₅	MnO %	Na %	Cl %	S %	V ppm	TOM %
1	5	13.74	52.21	3.80	3.16	0.07	0.13	0.20	0.23	0.06	11.00	0.80	< 0.1	0.72	3.10	0.38	168	1.14
2	6	15.11	55.55	3.68	2.55	0.06	0.09	0.15	0.38	0.05	14.00	0.93	< 0.1	0.75	8.15	0.32	56	1.03
3	7	18.32	55.00	3.00	2.89	0.04	0.09	0.13	0.35	0.04	10.50	0.57	< 0.1	0.67	8.00	0.50	112	1.32
4	8	24.71	53.91	2.18	2.91	0.03	0.07	0.10	0.25	0.05	8.50	0.34	< 0.1	0.91	3.63	0.60	56	1.60
5	9	21.02	62.00	2.95	0.89	0.04	0.07	0.11	0.23	0.05	2.75	0.13	< 0.1	0.86	7.30	0.59	112	1.51
	Maximum	24.71	62.00	3.80	3.16	0.07	0.13	0.20	0.38	0.06	14.00	0.93		0.91	8.15	0.60	168	1.60
	Minimum	13.74	52.21	2.18	0.89	0.03	0.07	0.10	0.23	0.04	2.75	0.13		0.67	3.10	0.32	56	1.03
	Average	18.58	55.73	3.12	2.48	0.05	0.09	0.14	0.29	0.05	9.35	0.56		0.78	6.04	0.48	101	1.32

Table 7.7 : Chemical Composition of the Arqah Phosphorite Member (Umm Wu' aal North Area).

Sample No.	P ₂ O ₅ %	CaO %	CaO/P ₂ O ₅	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	Na ₂ O %	K ₂ O %	CO ₂ %	CO ₂ /P ₂ O ₅	S %	Cl %	F %	F/P ₂ O ₅	Sr ppm	U ppm	U/P ₂ O ₅
1	33.2	51.6	1.55	0.55	0.18	0.15	0.33	0.14	< 0.01	0.05	5.3	0.16	0.50	0.700	4.90	0.148	820		
2	22.8	53.1	2.33	0.66	0.13	0.09	0.22	0.12	< 0.01	0.03	17.2	0.75	0.31	0.400	3.40	0.149	550		
3	32.1	51.8	1.61	3.50	0.39	0.26	0.65	0.15	< 0.05	0.08	3.4	0.11	0.76	< 0.2	2.10	0.065	760	35	1.09
4	18.5	55.1	2.98	1.00	0.17	0.11	0.28	0.15	< 0.05	0.05	21.5	1.16	0.42	< 0.2	1.30	0.070	710	50	2.70
5	16.5	53.7	3.25	2.00	0.08	0.08	0.16	0.16	< 0.05	0.06	21.8	1.32	0.36	< 0.2	2.20	0.133	660	40	2.42
6	27.4	53.4	1.95	2.20	0.24	0.20	0.44	0.15	< 0.05	0.05	9.0	0.33	1.10	< 0.2	2.00	0.073	890	75	2.74
7	20.2	55.5	2.75	0.50	0.11	0.11	0.22	0.12	< 0.05	0.06	19.5	0.97	0.38	< 0.2	3.30	0.163	660	70	3.47
8	16.4					0.27	0.27										534	15	0.91
9	16.1					0.30	0.30										590	18	1.12
10	16.5					0.26	0.26										510	11	0.67
11	16.5					0.32	0.32										451	15	0.91
12	16.2					0.37	0.37										490	132	8.15
13	22.6	49.7	2.20	7.17	0.21	0.35	0.56	0.20	0.73	< 0.05	13.0	0.58	1.00	0.530	1.69		810	34	1.50
14	32.6	51.1	1.57	9.35	0.09	0.29	0.38	0.26	0.40	< 0.05	0.9	0.03	1.31	0.002	3.86		1070	32	0.98
Maximum	33.2	55.5	3.25	9.35	0.39	0.37	0.65	0.26	0.730	0.08	21.8	1.32	1.31	0.700	4.90	0.16	1070	132	8.15
Minimum	16.1	49.7	1.55	0.50	0.08	0.08	0.16	0.12	0.400	0.03	0.9	0.03	0.31	0.002	1.30	0.07	451	11	0.67
Average	22.0	52.8	2.24	2.99	0.18	0.23	0.34	0.16	0.565	0.05	12.4	0.60	0.68	0.408	2.75	0.11	679	44	2.22
Counts	14	9	9	9	9	14	14	9	2	7	9.0	9	9	4	9	7	14	12	12

Blank Areas = Not determined

LOI = Loss of Ignition

Table 7.7 (Cont.) : Chemical Composition of the Arqah Phosphorite Member (Umm Wu' aal North Area).

Sample No.	Th ppm	Ti ppm	Pb ppm	Cr ppm	V ppm	AS ppm	Y ppm	Cu ppm	Sc ppm	Cd ppm	Zn ppm	Zn / Cd	Mo ppm	Ni ppm	LOI %
1				105	70	10	120	35	<10	15			10	40	6.80
2				65	40	5	90	25	<10	15			5	45	18.40
3	<10	168		109	69	12	80	18		4	129	32.25	9	23	5.20
4	<10	90		50	40	15	30	13		14	162	11.57	8	9	23.30
5	<10	18		51	43	3	<20	27		5	141	28.20	7	10	24.80
6	<10	102		96	69	14	60	19		23	155	6.74	9	25	11.80
7	<10	24		57	55	5	30	18		19	134	7.05	8	20	21.50
8	3		24				37								
9	7		6				45								
10	2		3				39								
11	3		7				39								
12	4		13				39								
13		180	50	100	70	<5		50	5	30					17.00
14		300	1100	130	100	<5		90	<2	<0.002					1.35
Maximum	7	300	1100	130	100	15	120	90	5	30	162	32.3	10	45	24.80
Minimum	2	18	3	50	40	3	30	13	5	4	129	6.7	5	9	1.35
Average	4	126	172	85	62	9	55	33	5	16	144	17.2	8	25	14.46
Counts	5	7	7	9	9	7	11	9	1	8	5	5	7	7	9

Blank Areas = Not determined

LOI = Loss of Ignition

Table 7.8 : Chemical Composition of the Arqah Phosphorite Member (Al-Amud Area).

Sample No.	P ₂ O ₅ %	CaO %	CaO / P ₂ O ₅	SiO ₂ %	MgO %	Na ₂ O %	K ₂ O %	Al ₂ O ₃ %	Fe ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	CO ₂ %	CO ₂ / P ₂ O ₅	F %	F / P ₂ O ₅	Cl %	S ppm
1	18.20	30.90	1.70	40.0	0.19	< 0.05	0.14	0.22	0.28	0.50	3.50	0.19	1.20	0.066	< 0.02	0.44
2	18.90	55.10	2.92	0.7	0.28	< 0.05	0.06	0.14	0.16	0.30	21.00	1.11	1.30	0.069	< 0.02	0.50
3	18.90	53.90	2.85	2.1	0.29	< 0.05	0.07	0.33	0.27	0.60	20.00	1.06	1.10	0.058	< 0.02	0.53
4	24.50	51.30	2.09	5.8	0.67	< 0.05	0.05	0.32	0.32	0.64	11.30	0.46	1.40	0.057	< 0.02	0.54
Maximum	24.50	55.10	2.92	40.0	0.67		0.14	0.33	0.32	0.64	21.00	1.11	1.40	0.069		0.54
Minimum	18.20	30.90	1.70	0.7	0.19		0.05	0.14	0.16	0.30	3.50	0.19	1.10	0.057		0.44
Average	20.13	47.80	2.39	12.2	0.36		0.08	0.25	0.26	0.51	13.95	0.71	1.25	0.063		0.50

Table 7.8 (Cont.) : Chemical Composition of the Arqah Phosphorite Member (Al-Amud Area).

Sample No.	U ppm	U / P ₂ O ₅	Th ppm	Cr ppm	V ppm	As ppm	Ti ppm	Y ppm	Sr ppm	Cu ppm	Zn ppm	Cd ppm	Zn / Cd	Mo ppm	Ni ppm	LOI %
1	55	3.02	< 10	122	114	44	42	190	870	22	129	9	14	7	22	6.00
2	50	2.65	< 10	90	64	7	33	80	920	30	203	32	6	8	17	23.10
3	50	2.65	< 10	105	53	6	33	40	1010	25	173	20	9	8	15	22.10
4	70	2.86	< 10	136	179	43	123	200	960	45	192	14	14	7	25	14.20
Maximum	70	3.02		136	179	44	123	200	1010	45	203	32	14	8	25	23.10
Minimum	50	2.65		90	53	6	33	40	870	22	129	9	6	7	15	6.00
Average	56	2.79		113	103	25	58	128	940	31	174	19	11	8	20	16.35

LOI = Loss of Ignition

Table 7.9 : Chemical Composition of Thaniyat Phosphorite Member (Southwestern Area).

Sample No.	P ₂ O ₅ %	CaO %	CaO / P ₂ O ₅	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	MgO %	CO ₂ %	CO ₂ / P ₂ O ₅	F %	F / P ₂ O ₅	Cl %	Pb %	Ti ppm	Cr ppm	V ppm	As ppm	Cd ppm	Cu ppm	Zn ppm	Mo ppm	Ni ppm	LOI %
1	22.20	28.60	1.29	37.80	0.80	1.40	2.20	0.28	1.90	0.086			0.11	0.0	102	60	120	200	10	20	100	10	10	2.6
2	27.30	39.90	1.46		1.00	0.90	1.90				3.0	0.11												
3	31.60			12.10	0.94	1.50	2.44	0.28																
4	30.90			14.10	0.94	1.60	2.54	0.31																
Maximum	31.60	39.90	1.46	37.80	1.00	1.60	2.54	0.31	1.90	0.086	3	0.11	0.11		102	60	120	200	10	20	100	10	10	2.6
Minimum	22.20	28.60	1.29	12.10	0.80	0.90	1.90	0.28	1.90	0.086	3	0.11	0.11		102	60	120	200	10	20	100	10	10	2.6
Average	28.00	34.25	1.37	21.33	0.92	1.35	2.27	0.29	1.90	0.086	3	0.11	0.11		102	60	120	200	10	20	100	10	10	2.6

Blank Areas = Not Detected

Table 7.10 : Chemical Composition of the Thaniyat Phosphorite Member (Hazm Al-Jalamid Area).

Sample No.	P ₂ O ₅ %	CaO %	CaO / P ₂ O ₅	SiO ₂ %	MgO %	Al ₂ O ₃ %	Fe ₂ O ₃ %	Al ₂ O ₃ + Fe ₂ O ₃ %	CO ₂ %	CO ₂ / P ₂ O ₅	MnO ₂ %	K ₂ O %	Na %	S %	C %	Cl %
1	18.60	51.30	2.76	4.71	1.46	0.16	0.52	0.68	21.50	1.16	< 0.01	< 0.05	0.10	0.32	0.04	0.020
2	34.80	51.80	1.49	8.20	0.28	0.03	0.25	0.28	0.98	0.03	< 0.01	< 0.05	0.16	0.33	0.05	0.006
3	23.90	51.40	2.15	4.17	0.39	0.11	0.17	0.28	16.30	0.68	< 0.01	< 0.05	0.13	0.20	0.09	0.020
4	36.20	53.30	1.47	7.10	0.20	0.02	0.18	0.20	0.78	0.02	< 0.01	< 0.05	0.19	0.31	0.03	0.008
5	17.40	42.70	2.45	0.53	10.60	0.16	0.10	0.26	26.00	1.49	< 0.01	< 0.05	0.10	0.20	0.05	0.020
6	39.10	56.40	1.44	1.24	1.66	0.02	0.21	0.23	1.12	0.03	< 0.01	< 0.05	0.15	0.20	0.02	0.005
7	18.30	53.70	2.93	2.32	0.32	0.22	0.19	0.41	22.60	1.23	< 0.01	< 0.05	0.17	0.20	0.04	0.130
8	35.60	54.80	1.54	5.20	0.23	0.13	0.31	0.44	0.90	0.03	< 0.01	< 0.05	0.22	0.36	0.02	0.009
Maximum	39.10	56.40	2.93	8.20	10.60	0.22	0.52	0.68	26.00	1.49			0.22	0.36	0.09	0.130
Minimum	17.40	42.70	1.44	0.53	0.20	0.02	0.10	0.20	0.78	0.02			0.10	0.20	0.02	0.005
Average	27.99	51.93	2.03	4.18	1.89	0.11	0.24	0.35	11.27	0.58			0.15	0.26	0.04	0.027

Blank Areas = Not determined

AIR = Acid Insoluble Residue

LOI = Loss of Ignition

Table 7.10 (Cont.) : Chemical Composition of the Thaniyat Phosphorite Member (Hazm Al-Jalamid Area).

Sample No.	F %	F / P ₂ O ₅	As %	Pb %	U ppm	U / P ₂ O ₅	Cr ppm	V pp m	Sr ppm	Ti ppm	Cu ppm	Sc pp m	Cd ppm	Hg ppb	LOI (1000) %	LOI (550) %	AIR %
1	1.28	0.07	< 0.005	< 0.005	20	1.08	40	30	240	60	60	2	8	< 50	22.50	1.40	3.50
2	3.96	0.11	< 0.005	0.0100	25	0.72	110	60	360	180	70	<2	< 2	< 50	1.31	0.39	7.44
3	1.73	0.07	< 0.005	< 0.005	26	1.09	60	30	310	128	<10	2	8	< 50	17.20	1.20	3.65
4	4.28	0.12	< 0.005	0.0060	24	0.66	100	60	390	120	20	<2	< 2	< 50	0.96	0.24	6.53
5	1.20	0.07	< 0.005	< 0.005	16	0.92	70	30	260	60	<10	2	4	< 50	27.60	3.30	0.34
6	4.32	0.11	< 0.005	< 0.005	26	0.66	120	70	440	120	20	<2	< 2	< 50	1.26	0.45	1.19
7	1.22	0.07	< 0.005	0.0120	16	0.87	50	30	230	120	10	<2	5	< 50	24.30	2.00	1.85
8	3.74	0.11	< 0.005	< 0.005	29	0.81	100	70	380	240	40	<2	< 2	< 50	1.46	0.44	3.90
Maximum	4.32	0.12		0.0120	29	1.09	120	70	440	240	70	2	8		27.60	3.30	7.44
Minimum	1.20	0.07		0.0060	16	0.66	40	30	230	60	10	2	4		0.96	0.24	0.34
Average	2.72	0.09		0.0093	23	0.85	81	48	326	128	37	2	6		12.07	1.18	3.55

Blank Areas = Not determined

AIR = Acid Insoluble Residue

LOI = Loss of Ignition

Table 7.11 : Microprobe analysis for a Phosphorite thin section (P1-8) from Drill Hole (P1), Turayf Area.

1- Spot Analysis (Grains)																		
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	Ca (Ele.) %	Ca (Ato.) %
	63.95	80.51	0.55	0.48	0.01	0.01					8.50	5.53	0.64	0.41	0.40	0.23	26.80	13.74
	52.21	71.13	1.06	1.00	0.23	0.20	0.25	0.20			14.41	10.14	0.77	0.52			31.57	17.17
	50.25	69.54	1.08	1.04	0.68	0.62					13.79	9.86	1.36	0.94	0.36	0.23	33.16	18.32
	48.53	67.96	1.42	1.39	0.53	0.49	0.19	0.16			14.70	10.63	0.74	0.52	0.29	0.18	34.04	19.03
	51.82	70.91	0.88	0.84	0.20	0.18					14.36	10.15	1.07	0.73	0.23	0.14	31.95	17.45
	39.65	60.24	0.54	0.57	0.15	0.15	0.04	0.04	0.27	0.23	14.37	11.28	1.24	0.94	0.17	0.12	43.56	26.42
	52.27	71.27	0.80	0.76	0.26	0.23	0.12	0.09			14.04	9.89	1.07	0.73	0.08	0.05	31.76	17.29
	46.86	66.72	0.74	0.73	0.38	0.35	0.22	0.18			14.98	11.01	1.07	0.76	0.19	0.12	35.97	20.44
	49.38	68.88	0.68	0.66	0.21	0.19	0.17	0.14			15.24	10.98	0.84	0.58	0.10	0.06	33.79	18.82
	55.88	74.24	0.71	0.66	0.25	0.22	0.07	0.06			12.19	8.37	0.62	0.41	0.44	0.26	29.99	15.90
Maximum	63.95	80.51	1.42	1.39	0.68	0.62	0.25	0.20	0.27	0.23	15.24	11.28	1.36	0.94	0.44	0.26	43.56	26.42
Minimum	39.65	60.24	0.54	0.48	0.01	0.01	0.04	0.04	0.27	0.23	8.50	5.53	0.62	0.41	0.08	0.05	26.80	13.74
Average	51.08	70.14	0.85	0.81	0.29	0.26	0.15	0.12	0.27	0.23	13.66	9.78	0.94	0.65	0.25	0.15	33.26	18.46
No. of Spots	10.00	10.00	10.00	10.00	10.00	10.00	7.00	7.00	1.00	1.00	10.00	10.00	10.00	10.00	9.00	9.00	10.00	10.00
2- Spot Analysis (Matrix)																		
	54.68	74.57	0.30	0.29	0.20	0.18	0.10	0.08	0.07	0.05	3.12	2.20	0.19	0.13	0.06	0.04	41.28	22.47
3- General Scan (Grains + Matrix)																		
	52.65	71.77	1.01	0.96	0.22	0.20	0.12	0.10			11.58	8.15	0.84	0.57	0.20	0.12	33.51	18.23
	54.83	73.78	0.61	0.58	0.13	0.12	0.15	0.12			9.98	6.94	0.60	0.40	0.12	0.08	33.74	18.13
Average	53.74	72.78	0.81	0.77	0.18	0.16	0.14	0.11			10.78	7.55	0.72	0.49	0.16	0.10	33.63	18.18
No. of Scans	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00			2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Blank Areas = Not Detected
(Ele.) = Element
(Ato.) = Atomic

Table 7.12 : Microprobe analysis for a Phosphorite thin section (P11-98) from Drill Hole (P11), Turayf Area.

1- Spot Analysis (Grains)																
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Ca (Ele.) %	Ca (Ato.) %
	53.33	72.04	0.91	0.86	0.29	0.26	0.03	0.03			13.77	9.61	1.12	0.75	30.64	16.53
	49.97	69.28	1.04	1.00	0.27	0.24	0.05	0.04	0.34	0.27	13.93	9.98	1.07	0.74	33.33	18.45
	52.45	71.29	1.11	1.05	0.35	0.31	0.14	0.11			13.83	9.71	1.03	0.70	31.29	16.98
	53.85	72.48	0.89	0.84	0.31	0.27	0.10	0.08			13.40	9.32	0.90	0.61	30.60	16.44
	49.57	68.82	0.90	0.87	0.33	0.30	0.03	0.03	0.94	0.74	14.67	10.52	0.92	0.64	32.63	18.08
Maximum	53.85	72.48	1.11	1.05	0.35	0.31	0.14	0.11	0.94	0.74	14.67	10.52	1.12	0.75	33.33	18.45
Minimum	49.57	68.82	0.89	0.84	0.27	0.24	0.03	0.03	0.34	0.27	13.40	9.32	0.90	0.61	30.60	16.44
Average	51.83	70.78	0.97	0.92	0.31	0.28	0.07	0.06	0.64	0.51	13.92	9.83	1.01	0.69	31.70	17.30
No. of Spots	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	2.00	2.00	5.00	5.00	5.00	5.00	5.00	5.00
2- General Scan (Grains + Matrix)																
	53.87	72.24	0.93	0.87	0.16	0.14			3.52	2.69	11.31	7.83	1.04	0.70	29.50	15.79
	55.08	73.82	0.87	0.82	0.41	0.36	0.07	0.05	0.18	0.14	9.59	6.64	0.63	0.42	33.00	17.65
Average	54.48	73.03	0.90	0.85	0.29	0.25	0.07	0.05	1.85	1.42	10.45	7.24	0.84	0.56	31.25	16.72
No. of Scan	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Blank Areas = Not Detected

(Ele.) = Element

(Ato.) = Atomic

Table 7.13 : Microprobe analysis for a Phosphorite thin section (S-3) from West Bardawil Anticline.

1- Spot Analysis (Grains)																
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Ca (Ele.) %	Ca (Ato.) %	Fe (Ele.) %	Fe (Ato.) %
	53.80	72.58	0.50	0.47	0.25	0.22	0.01	0.01	14.03	9.77	0.65	0.44	31.04	16.72		
	54.27	72.84	0.65	0.61	0.33	0.29	0.15	0.12	13.93	9.66	0.58	0.39	30.25	16.21		
	54.85	73.47	0.55	0.51	0.13	0.12			13.35	9.24	0.67	0.45	30.57	16.35	0.09	0.03
	53.31	72.25	0.54	0.51	0.10	0.09	0.10	0.08	13.85	9.70	0.82	0.55	31.61	17.10	0.06	0.02
	54.62	73.35	0.30	0.28	0.04	0.04	0.08	0.07	13.85	9.61	0.62	0.41	30.79	16.51	0.09	0.03
	51.98	71.22	0.37	0.35	0.07	0.07	0.11	0.09	14.57	10.31	0.51	0.35	32.83	17.95		
	55.75	74.12	0.77	0.71	0.38	0.33			12.65	8.69	0.83	0.55	29.92	15.87	0.12	0.05
Maximum	55.75	74.12	0.77	0.71	0.38	0.33	0.15	0.12	14.57	10.31	0.83	0.55	32.83	17.95	0.12	0.05
Minimum	51.98	71.22	0.30	0.28	0.04	0.04	0.01	0.01	12.65	8.69	0.51	0.35	29.92	15.87	0.06	0.02
Average	54.08	72.83	0.53	0.49	0.19	0.17	0.09	0.07	13.75	9.57	0.67	0.45	31.00	16.67	0.09	0.03
No. of Spots	7.00	7.00	7.00	7.00	7.00	7.00	5.00	5.00	7.00	7.00	7.00	7.00	7.00	7.00	4.00	4.00

Blank Areas = Not Detected

(Ele.) = Element

(Ato.) = Atomic

Table 7.14 : Microprobe analysis for a Phosphorite thin section (W-1) from 60 Km East Turayf Area.

1- Spot Analysis (Grains)																		
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	Ca (Ele.) %	Ca (Ato.) %	Fe (Ele.) %	Fe (Ato.) %
	48.08	67.08	0.54	0.53	0.11	0.10	5.47	4.35	14.64	10.55	1.16	0.81			30.40	16.93	0.02	0.01
	53.59	71.31	0.89	0.83	0.14	0.13	6.90	5.23	13.18	9.06	0.88	0.58			24.98	13.27		
	52.42	70.68	0.83	0.77	0.11	0.10	4.96	3.81	13.74	9.57	1.06	0.72			27.17	14.62	0.11	0.04
	53.82	71.89	0.76	0.71	0.23	0.20	4.07	3.09	13.60	9.38	0.83	0.55			26.88	14.33	0.02	0.01
	52.25	70.48	0.80	0.75	0.15	0.14	5.50	4.23	13.59	9.47	0.94	0.63			26.98	14.53	0.12	0.05
	50.03	68.83	0.57	0.55	0.13	0.12	4.77	3.74	14.03	9.97	1.15	0.79			29.67	16.29	0.02	0.01
	51.41	70.06	0.55	0.52	0.07	0.06	4.01	3.11	14.45	10.17	0.53	0.36	0.31	0.19	29.05	15.80		
	50.48	69.26	0.72	0.69	0.18	0.16	4.21	3.29	13.79	9.77	0.93	0.64	0.15	0.09	29.65	16.24	0.14	0.06
	50.50	69.24	0.64	0.61	0.13	0.11	4.40	3.43	14.69	10.40	0.51	0.35	0.24	0.15	29.28	16.02	0.04	0.01
	50.97	69.56	0.93	0.89	0.22	0.20	4.17	3.24	13.80	9.73	1.00	0.68	0.25	0.16	28.93	15.76		
	54.95	72.52	0.98	0.90	0.23	0.20	5.48	4.12	12.91	8.80	1.45	0.95			24.49	12.90	0.02	0.01
	52.90	71.09	0.64	0.60	0.20	0.18	5.03	3.85	13.38	9.29	0.95	0.64			27.16	14.57	0.03	0.01
	55.18	73.14	0.59	0.55	0.16	0.14	2.81	2.12	14.20	9.72	0.65	0.43			26.67	14.11		
Maximum	55.18	73.14	0.98	0.90	0.23	0.20	6.90	5.23	14.69	10.55	1.45	0.95	0.31	0.19	30.40	16.93	0.14	0.06
Minimum	48.08	67.08	0.54	0.52	0.07	0.06	2.81	2.12	12.91	8.80	0.51	0.35	0.15	0.09	24.49	12.90	0.02	0.01
Average	52.04	70.40	0.73	0.68	0.16	0.14	4.75	3.66	13.85	9.68	0.93	0.63	0.24	0.15	27.79	15.03	0.06	0.02
No.of Spots	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	4.00	4.00	13.00	13.00	9.00	9.00
2- Spot Analysis (Marix)																		
	53.80	67.76					41.77	29.96	2.62	1.71	0.07	0.05			3.13	1.57		
	56.62	70.15	0.60	0.52	0.08	0.07	38.18	26.94	2.47	1.58			0.26	0.14	2.99	1.48		
Average	55.21	68.96	0.60	0.52	0.08	0.07	39.98	28.45	2.55	1.65	0.07	0.05	0.26	0.14	3.06	1.53		
No.of Spots	2.00	2.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00	2.00	2.00		

Blank Areas = Not Detected

(Ele.) = Element

(Ato.) = Atomic

Table 7.15 : Microprobe analysis for a Phosphorite thin section (P1-6) from Drill Hole (P1), Turayf Area.

1- Spot Analysis (Grains)																				
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	Ca (Ele.) %	Ca (Ato.) %	Fe (Ele.) %	Fe (Ato.) %
	53.18	71.95	1.13	1.06	0.27	0.24	0.06	0.05			13.45	9.40	0.98	0.66	0.20	0.12	30.80	16.63	0.16	0.06
	56.61	74.62	1.02	0.93	0.38	0.33	0.11	0.08			12.36	8.41	1.05	0.69	0.21	0.13	28.41	14.95	0.10	0.04
	51.85	70.98	0.66	0.63	0.13	0.12	0.07	0.05			14.35	10.15	0.68	0.46	0.22	0.14	32.26	17.63		
	48.29	68.19	0.32	0.32							14.79	10.79	0.94	0.66	0.32	0.20	35.85	20.21		
	53.21	72.15	0.28	0.27	0.23	0.21			0.21	0.16	14.03	9.83	0.39	0.27	0.13	0.08	31.62	17.11		
	54.12	72.91	0.51	0.48	0.19	0.17	0.10	0.08			13.31	9.26	0.83	0.56	0.23	0.14	31.08	16.71	0.07	0.03
	55.03	73.68	0.68	0.64	0.40	0.35	0.20	0.16			12.29	8.50	0.99	0.66	0.12	0.07	28.62	15.30		
	53.63	72.66	0.25	0.24			0.16	0.13			13.26	9.28	0.56	0.38	0.13	0.08	32.16	17.39	0.11	0.04
	49.57	69.07	0.83	0.80	0.42	0.38	0.10	0.08			13.82	9.94	0.89	0.62	0.14	0.09	34.37	19.12		
Maximum	56.61	74.62	1.13	1.06	0.42	0.38	0.20	0.16	0.21	0.16	14.79	10.79	1.05	0.69	0.32	0.20	35.85	20.21	0.16	0.06
Minimum	48.29	68.19	0.25	0.24	0.13	0.12	0.06	0.05	0.21	0.16	12.29	8.41	0.39	0.27	0.12	0.07	28.41	14.95	0.07	0.03
Average	52.83	71.80	0.63	0.60	0.29	0.26	0.11	0.09	0.21	0.16	13.52	9.51	0.81	0.55	0.19	0.12	31.69	17.23	0.11	0.04
No. of Spots	9.00	9.00	9.00	9.00	7.00	7.00	7.00	7.00	1.00	1.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	4.00	4.00
2- General Scan (Grains + Matrix)																				
	56.40	75.02	0.55	0.51	0.24	0.21	0.04	0.03	0.03	0.02	9.00	6.18	0.56	0.37	0.24	0.14	33.11	17.58		
	56.95	75.82	0.57	0.53	0.09	0.08			0.10	0.08	6.59	4.53	0.35	0.24	0.33	0.20	34.78	18.48	0.35	0.13
Average	56.68	75.42	0.56	0.52	0.17	0.15	0.04	0.03	0.07	0.05	7.80	5.36	0.46	0.31	0.29	0.17	33.95	18.03	0.35	0.13
No. of Scan	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00

Blank Areas = Not Detected

(Ele.) = Element

(Ato.) = Atomic

Table 7.16 : Microprobe analysis for a Phosphorite thin section (S-5) from West Bardawil Anticline.

1- Spot Analysis (Grains)																		
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	K (Ele.) %	K (Ato.) %	Ca (Ele.) %	Ca (Ato.) %
	50.21	69.58	1.04	1.01	0.25	0.23	0.08	0.06	14.36	10.28	0.77	0.53	0.22	0.14	0.61	0.35	32.96	18.23
	45.99	65.96	0.68	0.68	0.29	0.27	0.10	0.09	16.04	11.88	0.69	0.50	0.27	0.17	0.63	0.37	35.83	20.51
	50.40	69.67	1.04	1.00	0.29	0.27	0.07	0.06	14.65	10.46	0.93	0.64	0.15	0.10	0.63	0.35	32.34	17.85
	49.22	68.63	1.08	1.05	0.31	0.28	0.04	0.03	15.48	11.15	0.90	0.63	0.26	0.17	0.63	0.36	32.74	18.22
	42.82	62.90	1.14	1.17	0.28	0.27	0.14	0.12	16.64	12.63	1.09	0.80	0.28	0.19	0.80	0.48	37.35	21.90
Maximum	50.40	69.67	1.14	1.17	0.31	0.28	0.14	0.12	16.64	12.63	1.09	0.80	0.28	0.19	0.80	0.48	37.35	21.90
Minimum	42.82	62.90	0.68	0.68	0.25	0.23	0.04	0.03	14.36	10.28	0.69	0.50	0.15	0.10	0.61	0.35	32.34	17.85
Average	47.73	67.35	1.00	0.98	0.28	0.26	0.09	0.07	15.43	11.28	0.88	0.62	0.24	0.15	0.66	0.38	34.24	19.34
No. of Spots	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
2- Spot Analysis (Bore)																		
	51.64	70.78	0.85	0.81	0.24	0.21	0.11	0.09	13.51	9.56	0.80	0.55	0.23	0.14	0.43	0.24	32.21	17.62
	49.30	68.86	0.78	0.76	0.25	0.23	0.09	0.08	14.20	10.24	0.78	0.54	0.19	0.12	0.38	0.21	34.12	19.03
	45.02	65.17	1.00	1.00	0.14	0.13			14.65	10.95	0.79	0.57	0.33	0.22	0.47	0.28	37.82	21.85
	54.88	73.46	0.98	0.92	0.39	0.34	0.21	0.16	11.08	7.66	0.43	0.29	0.28	0.17	0.60	0.33	31.04	16.58
Maximum	54.88	73.46	1.00	1.00	0.39	0.34	0.21	0.16	14.65	10.95	0.80	0.57	0.33	0.22	0.60	0.33	37.82	21.85
Minimum	45.02	65.17	0.78	0.76	0.14	0.13	0.09	0.08	11.08	7.66	0.43	0.29	0.19	0.12	0.38	0.21	31.04	16.58
Average	50.21	69.57	0.90	0.87	0.26	0.23	0.14	0.11	13.36	9.60	0.70	0.49	0.26	0.16	0.47	0.27	33.80	18.77
No. of Spots	4.00	4.00	4.00	4.00	4.00	4.00	3.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00

Blank Areas = Not Detected
(Ele.) = Element
(Ato.) = Atomic

Table 7.16 (Cont.) : Microprobe analysis for a Phosphorite thin section (S-5) from West Bardavil Anticline.

3- General Scan (Grains + Matrix)																		
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	K (Ele.) %	K (Ato.) %	Ca (Ele.) %	Ca (Ato.) %
	53.77	72.77	0.86	0.81					11.40	7.97	0.64	0.43	0.08	0.05	0.54	0.30	32.71	17.67
	53.01	72.28	0.74	0.70	0.23	0.20	0.12	0.09	10.18	7.17	0.55	0.37	0.28	0.17	0.38	0.21	34.48	18.77
	52.22	71.37	1.00	0.95	0.21	0.19	0.07	0.06	12.50	8.83	0.66	0.45	0.23	0.14	0.70	0.39	32.64	17.81
Maximum	53.77	72.77	1.00	0.95	0.23	0.20	0.12	0.09	12.50	8.83	0.66	0.45	0.28	0.17	0.70	0.39	34.48	18.77
Minimum	52.22	71.37	0.74	0.70	0.21	0.19	0.07	0.06	10.18	7.17	0.55	0.37	0.08	0.05	0.38	0.21	32.64	17.67
Average	53.00	72.14	0.87	0.82	0.22	0.20	0.10	0.08	11.36	7.99	0.62	0.42	0.20	0.12	0.54	0.30	33.28	18.08
No. of Scans	3.00	3.00	3.00	3.00	2.00	2.00	2.00	2.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

Blank Areas = Not Detected
(Ele.) = Element
(Ato.) = Atomic

Table 7.17 : Microprobe analysis for a Phosphorite thin section (S-33) from East of Khor Umm Wu'aal.

1-Spot Analysis (Grains)																						
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	K (Ele.) %	K (Ato.) %	Ca (Ele.) %	Ca (Ato.) %	Fe (Ele.) %	Fe (Ato.) %
	49.69	69.54	0.74	0.72	0.28	0.26	0.11	0.09			13.69	9.90	0.81	0.56					31.84	17.79	2.84	1.14
	50.47	70.64	0.57	0.56	0.13	0.12	0.24	0.20			12.97	9.38	0.83	0.58					28.99	16.20	5.79	2.32
	51.79	71.06	0.73	0.70	0.25	0.23	0.07	0.06			13.67	9.69	1.00	0.68					31.10	17.04	1.38	0.54
	53.15	72.10	0.58	0.55	0.11	0.10	0.04	0.04			13.66	9.57	0.71	0.48					31.58	17.10	0.16	0.06
	51.49	70.68	0.60	0.57	0.35	0.31	0.05	0.04			14.18	10.06	0.85	0.59					32.17	17.63	0.31	0.12
	47.67	67.79	0.74	0.73	0.28	0.26	0.09	0.08			13.86	10.18	0.80	0.57					34.24	19.44	2.33	0.95
	50.61	69.98	0.56	0.54	0.29	0.26					14.85	10.61	0.52	0.36					32.88	18.15	0.31	0.12
	51.36	70.66	0.45	0.43	0.23	0.21	0.10	0.08			14.07	10.00	0.65	0.45					32.96	18.10	0.17	0.70
	52.72	72.10	0.44	0.41	0.25	0.22	0.09	0.08			12.82	9.06	0.59	0.40					30.90	16.87	2.20	0.86
Maximum	53.15	72.10	0.74	0.73	0.35	0.31	0.24	0.20			14.85	10.61	1.00	0.68					34.24	19.44	5.79	2.32
Minimum	47.67	67.79	0.44	0.41	0.11	0.10	0.04	0.04			12.82	9.06	0.52	0.36					28.99	16.20	0.16	0.06
Average	50.99	70.51	0.60	0.58	0.24	0.22	0.10	0.08			13.75	9.83	0.75	0.52					31.85	17.59	1.72	0.76
No. of Spots	9.00	9.00	9.00	9.00	9.00	9.00	8.00	8.00			9.00	9.00	9.00	9.00					9.00	9.00	9.00	9.00

Blank Areas = Not Detected

(Ele.) = Element

(Ato.) = Atomic

Table 7.17 (Cont.) : Microprobe analysis for a Phosphorite thin section (S-33) from East of Khor Umm Wu'aal.

2- Spot Analysis (Bore)															
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Fe (Ele.) %
	50.29	69.24	3.67	3.52	0.54	0.49	0.11	0.09	0.07	0.06	8.96	6.37	1.00	0.69	0.07
	33.03	52.91	1.98	2.21	0.14	0.15	0.20	0.19	0.03	0.03	15.41	12.75	1.59	1.27	0.18
	48.11	67.96	0.55	0.54	0.22	0.20	0.12	0.10			14.48	10.56	0.73	0.52	0.23
Maximum	50.29	69.24	3.67	3.52	0.54	0.49	0.20	0.19	0.07	0.06	15.41	12.75	1.59	1.27	0.18
Minimum	33.03	52.91	0.55	0.54	0.14	0.15	0.11	0.09	0.03	0.03	8.96	6.37	0.73	0.52	0.07
Average	43.81	63.37	2.07	2.09	0.30	0.28	0.14	0.13	0.05	0.05	12.95	9.89	1.11	0.83	0.12
No. of Spots	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.00	2.00	3.00	3.00	3.00	3.00	3.00
3- General Scan (Grains + Matrix)															
	50.49	70.53	0.65	0.63	0.21	0.19	0.10	0.09	0.12	0.10	8.82	6.37	0.50	0.35	0.17
	51.68	71.46	0.50	0.49	0.16	0.14	0.06	0.05	0.02	0.02	9.62	6.87	0.42	0.29	0.08
	49.75	69.65	0.41	0.40	0.36	0.33	0.04	0.03	0.36	0.29	10.80	7.81	0.60	0.42	0.02
	50.87	70.73	0.33	0.32	0.17	0.15	0.05	0.04	0.11	0.08	10.44	7.50	0.56	0.39	0.06
Maximum	51.68	71.46	0.65	0.63	0.36	0.33	0.10	0.09	0.36	0.29	10.80	7.81	0.60	0.42	0.17
Minimum	49.75	69.65	0.33	0.32	0.16	0.14	0.04	0.03	0.02	0.02	8.82	6.37	0.42	0.29	0.02
Average	50.70	70.59	0.47	0.46	0.23	0.20	0.06	0.05	0.15	0.12	9.92	7.14	0.52	0.36	0.08
No. of Spots	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00

Blank Areas = Not Detected
(Ele.) = Element
(Ato.) = Atomic

Table 7.18 : Microprobe analysis for a Phosphorite thin section (S-35) from East of Khor Umm Wu'aal.

1- Spot Analysis (Grains)																							
Statistics	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	K (Ele.) %	K (Ato.) %	Ca (Ele.) %	Ca (Ato.) %	Fe (Ele.) %	Fe (Ato.) %	
	50.20	69.69	0.49	0.48	0.16	0.15	0.09	0.07			14.64	10.50	0.58	0.40	0.16	0.10	0.44	0.25	32.86	18.21	0.37	0.15	
	51.34	70.54	0.70	0.67	0.16	0.14	0.04	0.03			14.62	10.38	0.61	0.42	0.10	0.06	0.49	0.27	31.88	17.49	0.12	0.05	
	50.63	69.98	0.59	0.57	0.13	0.12	0.09	0.07			15.11	10.79	0.55	0.38	0.11	0.07	0.37	0.21	32.51	17.94	0.13	0.05	
	49.39	68.92	0.67	0.65	0.23	0.21	0.08	0.07			15.21	10.96	0.68	0.47	0.15	0.10	0.45	0.26	33.21	18.50	0.18	0.07	
	53.84	72.65	0.60	0.57	0.15	0.13	0.10	0.08			13.83	9.64	0.70	0.47	0.15	0.09	0.57	0.32	30.32	16.33	0.18	0.07	
	52.82	71.89	0.44	0.41	0.13	0.11	0.09	0.07			14.01	9.85	0.54	0.37	0.04	0.02	0.38	0.21	31.73	17.24	0.11	0.04	
	53.57	72.31	0.92	0.87	0.22	0.19	0.11	0.09			13.47	9.39	0.89	0.60	0.30	0.18	0.54	0.30	30.02	16.17	0.18	0.07	
	54.62	73.16	0.61	0.57	0.31	0.27	0.13	0.11			13.82	9.56	0.76	0.51	0.06	0.04	0.46	0.25	29.53	15.79	0.06	0.02	
	Maximum	54.62	73.16	0.92	0.87	0.31	0.27	0.13			0.11	15.21	10.96	0.89	0.60	0.30	0.18	0.57	0.32	33.21	18.50	0.37	0.15
Minimum	49.39	68.92	0.44	0.41	0.13	0.11	0.04	0.03	13.47	9.39	0.54	0.37	0.04	0.02	0.37	0.21	29.53	15.79	0.06	0.02			
Average	52.05	71.14	0.63	0.60	0.19	0.17	0.09	0.07	14.34	10.13	0.66	0.45	0.13	0.08	0.46	0.26	31.51	17.21	0.17	0.07			
No. of spots	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	
2- Spot Analysis (Bone)																							
	62.60	80.16	0.48	0.42	0.16	0.13	0.07	0.05	0.18	0.13	2.81	1.86	0.16	0.10	0.07	0.04	0.44	0.23	32.89	16.81	0.15	0.05	
	56.20	75.45	0.72	0.68	0.19	0.17	0.05	0.04	0.21	0.16	3.99	2.76	0.27	0.18	0.18	0.11	0.43	0.24	37.67	20.18	0.10	0.04	
	51.28	70.51	0.81	0.77	0.07	0.06	0.02	0.02			14.59	10.37	0.72	0.49	0.06	0.04	0.31	0.17	32.33	17.75	0.06	0.02	
	51.08	70.37	0.70	0.67	0.30	0.27	0.05	0.04			14.00	9.96	0.64	0.44	0.20	0.12	0.37	0.21	32.71	17.99	0.11	0.05	
	Maximum	62.60	80.16	0.81	0.77	0.30	0.27	0.07	0.05	0.21	0.16	14.59	10.37	0.72	0.49	0.20	0.12	0.44	0.24	37.67	20.18	0.15	0.05
Minimum	51.08	70.37	0.48	0.42	0.07	0.06	0.02	0.02	0.18	0.13	2.81	1.86	0.16	0.10	0.06	0.04	0.31	0.17	32.33	16.81	0.06	0.02	
Average	55.29	74.12	0.68	0.64	0.18	0.16	0.05	0.04	0.20	0.15	8.85	6.24	0.45	0.30	0.13	0.08	0.39	0.21	33.90	18.18	0.11	0.04	
No. of spots	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	2.00	2.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00

Blank Areas = Not Detected
(Ele.) = Element
(Ato.) = Atomic

Table 7.19 : Average Microprobe analysis of eight Phosphorite thin sections from Northwestern Saudi Arabia.

1- Spot Analysis (Grains)																						
Sample Name	O (Ele.) %	O (Ato.) %	Na (Ele.) %	Na (Ato.) %	Mg (Ele.) %	Mg (Ato.) %	Al (Ele.) %	Al (Ato.) %	Si (Ele.) %	Si (Ato.) %	P (Ele.) %	P (Ato.) %	S (Ele.) %	S (Ato.) %	Cl (Ele.) %	Cl (Ato.) %	K (Ele.) %	K (Ato.) %	Ca (Ele.) %	Ca (Ato.) %	Fe (Ele.) %	Fe (Ato.) %
P1-8	51.08	70.14	0.85	0.81	0.29	0.26	0.15	0.12	0.27	0.23	13.66	9.78	0.94	0.65	0.25	0.15			33.26	18.46		
P11-98	51.83	70.78	0.97	0.92	0.31	0.28	0.07	0.06	0.64	0.51	13.92	9.83	1.01	0.69					31.70	17.30		
S-3	54.08	72.83	0.53	0.49	0.19	0.17	0.09	0.07			13.75	9.57	0.67	0.45					31.00	16.67	0.09	0.03
P1-6	52.83	71.80	0.63	0.60	0.29	0.26	0.11	0.09	0.21	0.16	13.52	9.51	0.81	0.55	0.19	0.12			31.69	17.23	0.11	0.04
W-1	52.04	70.40	0.73	0.68	0.16	0.14			4.75	3.66	13.85	9.68	0.93	0.63	0.24	0.15			27.79	15.03	0.06	0.02
S-5	47.73	67.35	1.00	0.98	0.28	0.26	0.09	0.07			15.43	11.28	0.88	0.62	0.24	0.15	0.66	0.38	34.24	19.34		
S-33	50.99	70.51	0.60	0.58	0.24	0.22	0.10	0.08	0.15	0.12	13.75	9.83	0.75	0.52					31.85	17.59	1.72	0.76
S-35	52.05	71.14	0.63	0.60	0.19	0.17	0.09	0.07			14.34	10.13	0.66	0.45	0.13	0.08	0.46	0.26	31.51	17.21	0.17	0.07
verag	51.58	70.62	0.74	0.71	0.24	0.22	0.10	0.08	1.20	0.94	14.03	9.95	0.83	0.57	0.21	0.13	0.56	0.32	31.63	17.35	0.43	0.18
2- General Scan (Grains + Matrix)																						
P-1-8	53.74	72.78	0.81	0.77	0.18	0.16	0.14	0.11			10.78	7.55	0.72	0.49	0.16	0.10			33.63	18.18		
W-2	54.48	73.03	0.90	0.85	0.29	0.25	0.07	0.05	1.85	1.42	10.45	7.24	0.84	0.56								
P1-6	56.68	75.42	0.56	0.52	0.17	0.15	0.04	0.03	0.07	0.05	7.80	5.36	0.46	0.31	0.29	0.17			33.95	18.03	0.35	0.13
S-5	53.00	72.14	0.87	0.82	0.22	0.20	0.10	0.08			11.36	7.99	0.62	0.42	0.20	0.12	0.54	0.30	33.28	18.08		
S-33	50.70	70.59	0.47	0.46	0.23	0.20	0.06	0.05	0.15	0.12	9.92	7.14	0.52	0.36	0.15	0.10	0.10	0.05	37.49	20.84	0.21	0.08
verag	53.72	72.79	0.72	0.68	0.21	0.19	0.08	0.06	0.69	0.53	10.06	7.05	0.63	0.43	0.20	0.12	0.32	0.18	34.58	18.78	0.28	0.11

Blank Areas = Not detected

(Ele.) = Element

(Ato.) = Atomic

**Table 7.20 : PIXE analysis for a Phosphorite thin section (S-33)
from East Khor Umm wu'aal.**

Elements	Relative Concentration from PIXE	Absolute Conc. (ppm) normalized to Ca = 38 % by wt.	Error (%) (stats. + systematic)	Remarks (decision on presence)
Ca	17320	38E + 04	5	Y
V	17	373	7	Y
Cr	8	176	8	Y
Fe	203	4454	5	Y
Ni	3	66	9	Y
Cu	0.7	15	15	Y
Zn	4	88	8	Y
As	3	66	9	Y
Sr	14	307	8	Y
Y	3	66	14	Y
Hg	0.5	11	68	?
U	2	44	24	Y

PIXE = Proton Induced X-ray Emission.

**Table 7.21 : PIXE analysis for a Phosphorite thin section (P1-6)
from Drill Hole (P1), Turayf Area.**

Elements	Relative Concentration from PIXE	Absolute Conc. (ppm) normalized to Ca = 38 % by wt.	Error (%) (stats. + systematic)	Remarks (decision on presence)
Ca	19642	35E + 04	5	Y
V	8	143	9	Y
Cr	3	53	12	Y
Fe	87	1550	5	Y
Ni	1	18	16	Y
Cu	0.7	12	13	Y
Zn	4	71	7	Y
As	4	71	8	Y
Sr	12	214	8	Y
Y	0.6	11	28	?

PIXE = Proton Induced X-ray Emission

Table 7.22 : Natural Radioactivity analysis for selected Phosphorite samples from Northwestern Saudi Arabia.

Locality	Sample No.	U ppm	Th ppm	K wt. %	P ₂ O ₅ %	U/Th	U/K	U/P ₂ O ₅	Th/K	Th/P ₂ O ₅	K/P ₂ O ₅	K Error (±)	Th Error (±)	K Error (%)	U Error (±)	Th Error (%)
P1	5	42	9	0.744	13.74	4.55	56.25	3.04	12.35	0.67	0.05	0.009	0.166	0.232	1.18	0.40
P1	6	29	6	0.477	15.11	4.64	61.07	1.93	13.17	0.42	0.03	0.009	0.151	0.251	1.91	0.52
P1	7	47	10	0.649	18.32	4.64	72.11	2.55	15.55	0.55	0.04	0.026	0.359	0.762	4.04	0.77
P1	8	37	8	0.756	24.71	4.78	48.36	1.48	10.11	0.31	0.03	0.008	0.142	0.196	1.03	0.39
P1	9	39	8	0.744	21.02	4.79	51.89	1.84	10.84	0.38	0.04	0.008	0.147	0.199	1.05	0.38
P1	18	126	24	2.158		5.31	58.50		11.01			0.075	0.983	2.088	3.48	0.78
P1	33	29	6	0.607	22.32	5.12	48.16	1.31	9.41	0.26	0.03	0.009	0.145	0.232	1.49	0.50
P1	44	30	5	0.726	13.70	5.69	41.06	2.18	7.22	0.38	0.05	0.020	0.245	0.534	2.81	0.82
P11	57	38	9	0.844		4.35	44.83		10.30			0.014	0.206	0.354	1.62	0.54
P11	98	34	6	0.543	18.16	5.33	62.75	1.88	11.76	0.35	0.03	0.014	0.213	0.395	2.61	0.62
P11	99	32	7	0.523	14.00	4.93	61.26	2.29	12.43	0.46	0.04	0.014	0.206	0.392	2.69	0.64
P11	100	38	10	0.593	16.50	3.83	64.81	2.33	16.91	0.61	0.04	0.022	0.299	0.646	3.78	0.78
P11	101	45	7	0.481	18.33	6.26	94.18	2.47	15.05	0.39	0.03	0.027	0.379	0.835	5.68	0.84
P11	105	36	8	0.550	11.46	4.72	65.11	3.12	13.81	0.66	0.05	0.029	0.347	0.836	5.29	0.97
P11	115	37	9	0.777	19.25	4.34	47.58	1.92	10.95	0.44	0.04	0.018	0.243	0.471	2.27	0.66
T. T. No.10	10	103	23	2.272		4.48	45.36		10.12			0.034	0.529	0.878	1.50	0.51
T. P. T.	3	69	17	1.245		4.13	55.24		13.39			0.009	0.201	0.240	0.75	0.29
T. P. T.	4	77	19	1.532		4.03	50.43		12.52			0.010	0.216	0.253	0.66	0.28
T. P. T.	7	17	10	0.703		1.77	24.04		13.58			0.012	0.134	0.311	1.73	0.80
T. P. T.	8	127	28	2.418		4.56	52.63		11.54			0.016	0.350	0.396	0.66	0.27
E. K. U. T.	33	29	7	0.602		4.51	48.72		10.79			0.008	0.137	0.213	1.37	0.47
E. K. U. B.	35	45	13	0.989		3.38	45.03		13.33			0.008	0.156	0.214	0.85	0.35

Blank Areas = Not Detected

Table 7.22 (Cont.): Natural Radioactivity analysis for selected Phosphorite samples from Northwestern Saudi Arabia.

Locality	Sample No.	U ppm	Th ppm	K wt. %	P ₂ O ₅ %	U/Th	U/K	U/P ₂ O ₅	Th/K	Th/P ₂ O ₅	K/P ₂ O ₅	K Error (±)	U Error (±)	Th Error (±)	K Error (%)	U Error (%)	Th Error (%)
T. T. Se. I		30	11	0.672		2.78	44.10		15.88			0.009	0.143	0.240	1.33	0.48	2.25
P. 65 Km. to T.	2	21	4	0.260		4.94	79.20		16.04			0.010	0.143	0.284	3.70	0.69	6.82
60 Km. E. T.		35	7	0.318		5.26	109.71		20.86			0.014	0.228	0.437	4.32	0.65	6.58
W. B. A.	3	29	6	0.501	12.90	4.57	57.87	2.25	12.68	0.49	0.04	0.008	0.139	0.222	1.63	0.48	3.49
W. B. A.	5	52	11	0.900	11.70	4.94	57.72	4.44	11.69	0.90	0.08	0.009	0.180	0.230	0.98	0.35	2.18
T. T. S.	6	14	5	1.014		2.58	13.62		5.28			0.008	0.089	0.178	0.83	0.64	3.32
T. T. S.	8	32	8	0.697		3.85	46.07		11.97			0.008	0.140	0.214	1.19	0.44	2.56
T. T. S.	11	53	12	0.991		4.59	53.52		11.66			0.009	0.175	0.220	0.87	0.33	1.90
T. T. S.	13	30	8	0.632		3.63	47.18		13.01			0.008	0.137	0.216	1.30	0.46	2.63
W. W. Se. cut II, B. L. Ph. B.	9	9	3	0.181		2.99	51.10		17.06			0.006	0.076	0.169	3.34	0.82	5.48
W. W. Se. cut II, T. L. Ph. B.	10	35	10	0.675		3.61	51.73		14.35			0.007	0.134	0.190	1.06	0.38	1.96
W. W. Se. cut II, U. Ph. B.	12	15	4	0.307		4.20	49.69		11.84			0.006	0.091	0.166	2.02	0.60	4.58
J. W. W.Th. T Se. T. Tr. Z.	8	20	5	0.448		3.82	44.38		11.63			0.008	0.116	0.211	1.78	0.58	4.04
J. W. W.Th. T Se. M. Ph. B.	9*	18	4	0.276		4.31	64.65		15.02			0.007	0.105	0.190	2.43	0.59	4.58
J. W. W.Th. T Se. M Ph. B. Ba	9	27	6	0.339		4.23	79.15		18.72			0.007	0.130	0.208	2.08	0.48	3.28
J. W. W.Th. T. Se. Ph. ho.	10	50	12	1.087		4.36	46.26		10.62			0.008	0.161	0.200	0.75	0.32	1.73
J. W W.Th. T. Se. Ph. ho. T.	11	45	10	0.820		4.51	54.74		12.12			0.008	0.158	0.208	0.98	0.35	2.09
Maximum		127	28	2.42	24.71	6.26	109.71	4.44	20.86	0.90	0.08	0.08	0.98	2.09	5.68	0.97	11.54
Minimum		9	3	0.18	11.46	1.77	13.62	1.31	5.28	0.26	0.03	0.01	0.08	0.17	0.66	0.27	1.32
Average		42	10	0.80	16.75	4.34	55.13	2.34	12.73	0.49	0.04	0.01	0.21	0.38	2.03	0.54	4.32
Counts		39	39	39	15	39	39	15	39	15	15	39	39	39	39	39	39

Blank Areas = Not Detected

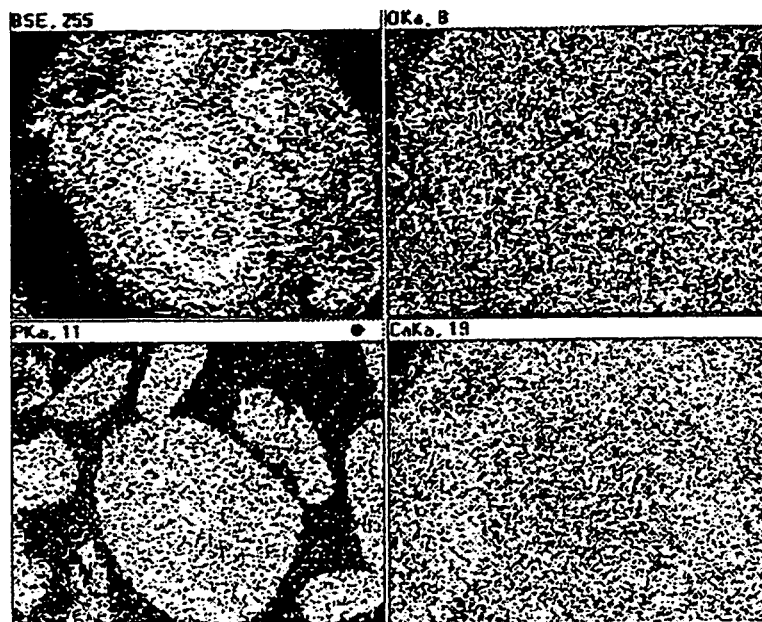


Fig. 7.1 : Electron beam scan photographs of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit showing distribution of O, P, and Ca. The relative concentration of each element is proportional to the density of white dots within the field of each photograph.

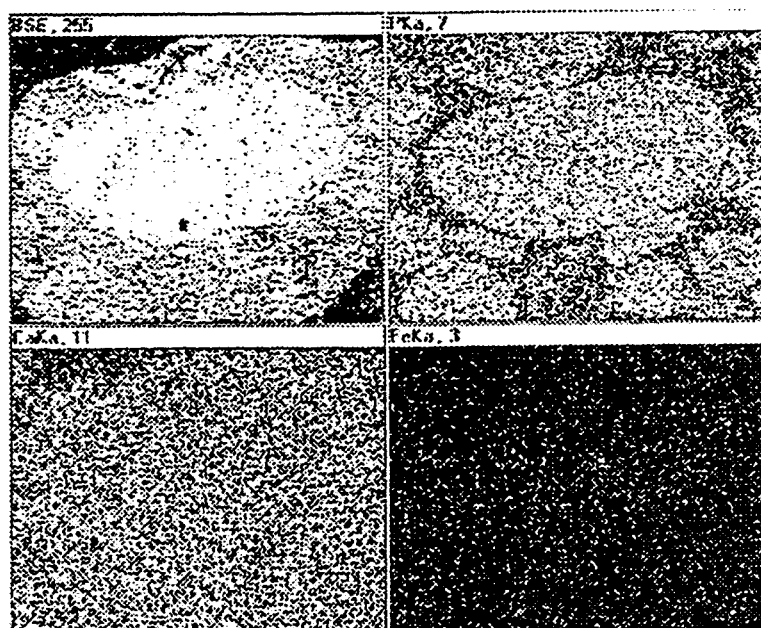


Fig. 7.2 : Electron beam scan photographs of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit showing distribution of P, Ca and Fe. The relative concentration of each element is proportional to the density of white dots within the field of each photograph.

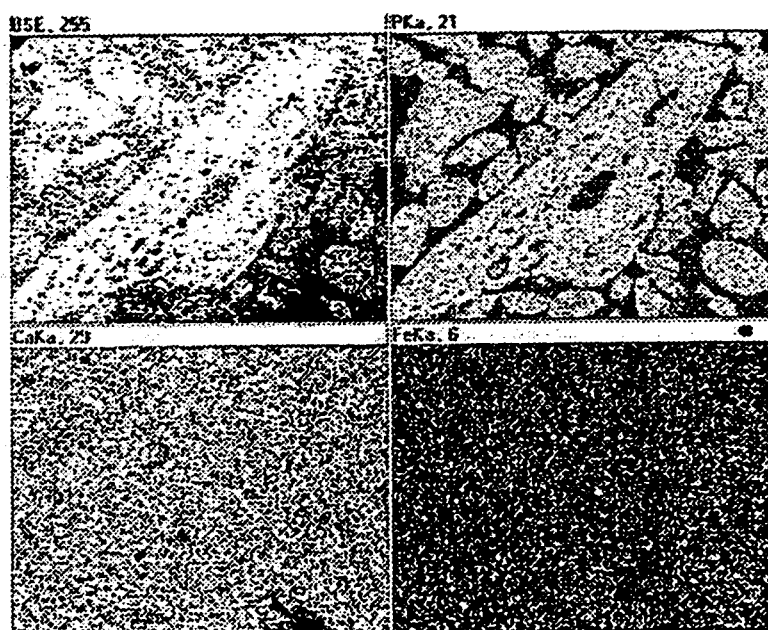


Fig. 7.3 : Electron beam scan photographs of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit showing distribution of P, Ca and Fe. The relative concentration of each element is proportional to the density of white dots within the field of each photograph.

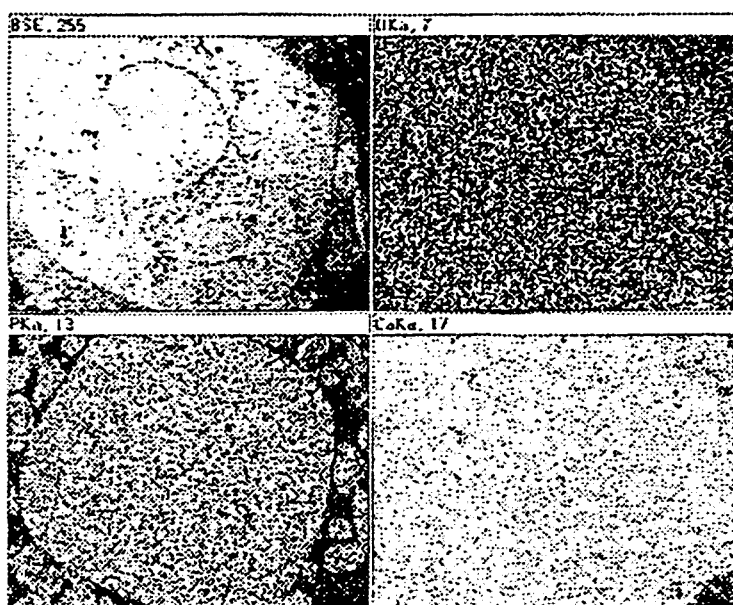


Fig. 7.4 : Electron beam scan photographs of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit showing distribution of O, P, and Ca. The relative concentration of each element is proportional to the density of white dots within the field of each photograph.

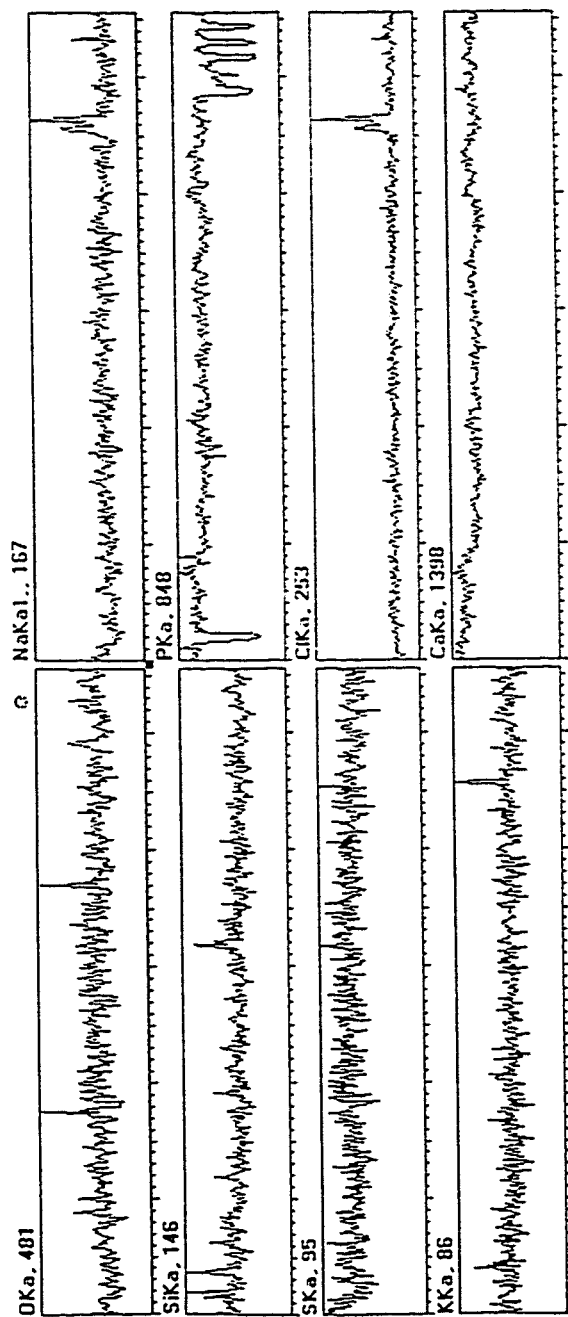


Fig. 7.5 : Electron line scan profiles of part of phosphorite sample from Drill Hole (P1), Turayf area, showing distribution of O, Na, Si, P, S, Cl, K and Ca.

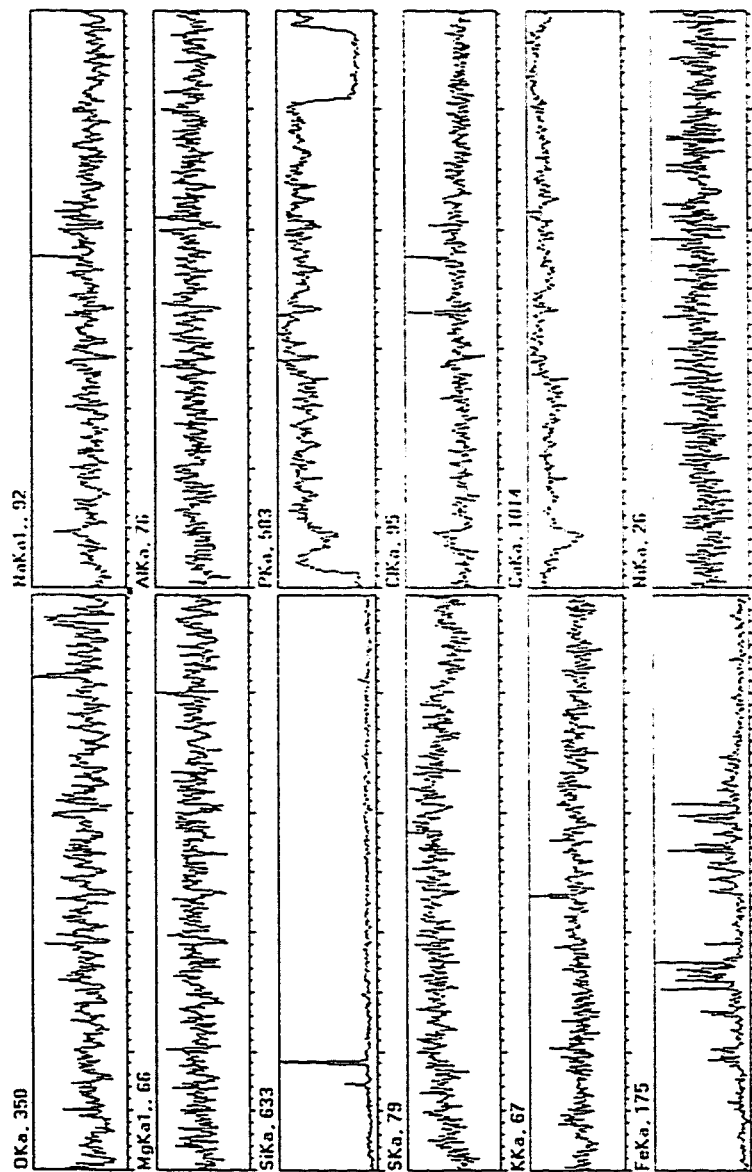


Fig. 7.6 : Electron line scan profiles of part of phosphorite sample from East Khawr Umm Wu' aal
Phosphorite deposit showing distribution of O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe and Ni.

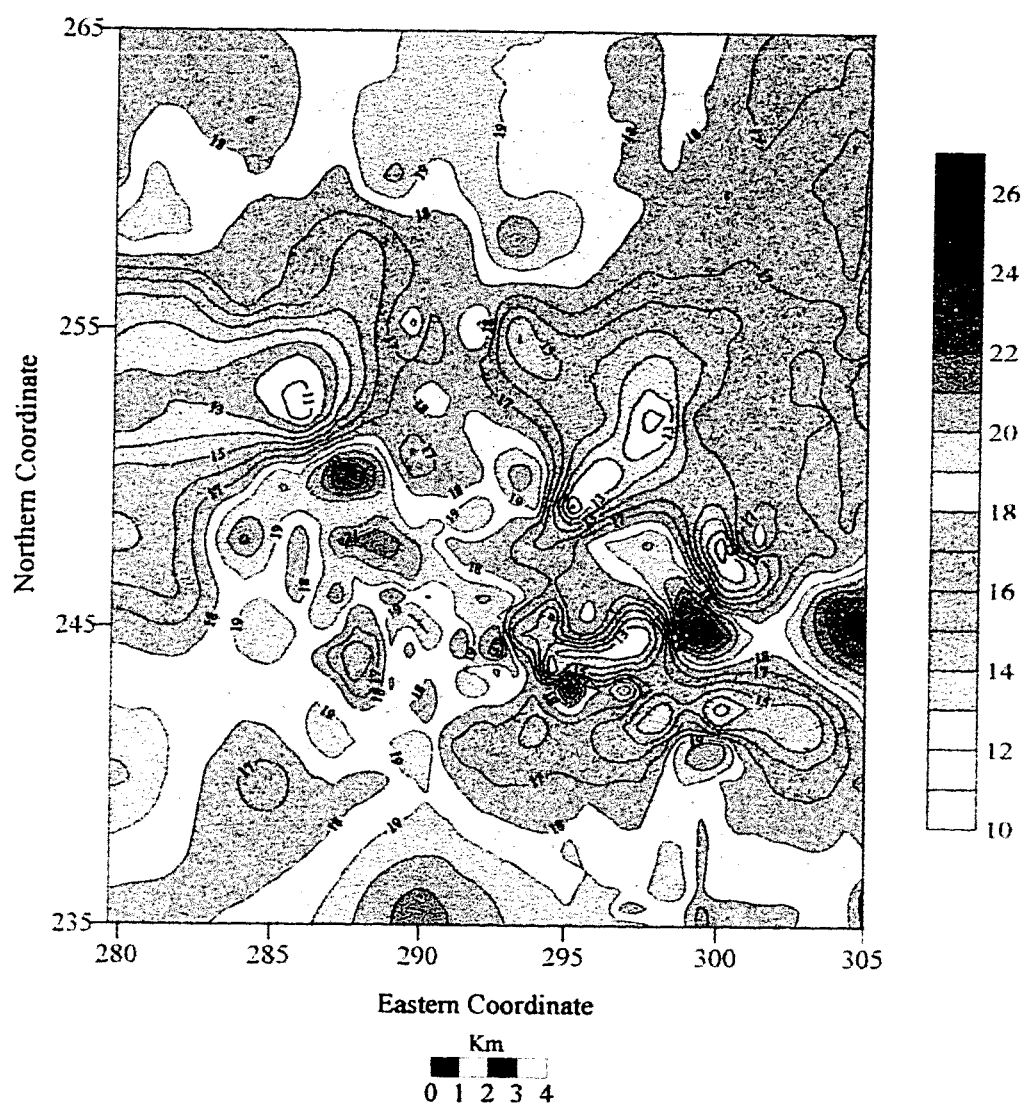


Fig. 7.7 : Iso-tenor Map for the Zone 1 Phosphorite in the Hazm Al-Jalamid area based on P_2O_5 %.

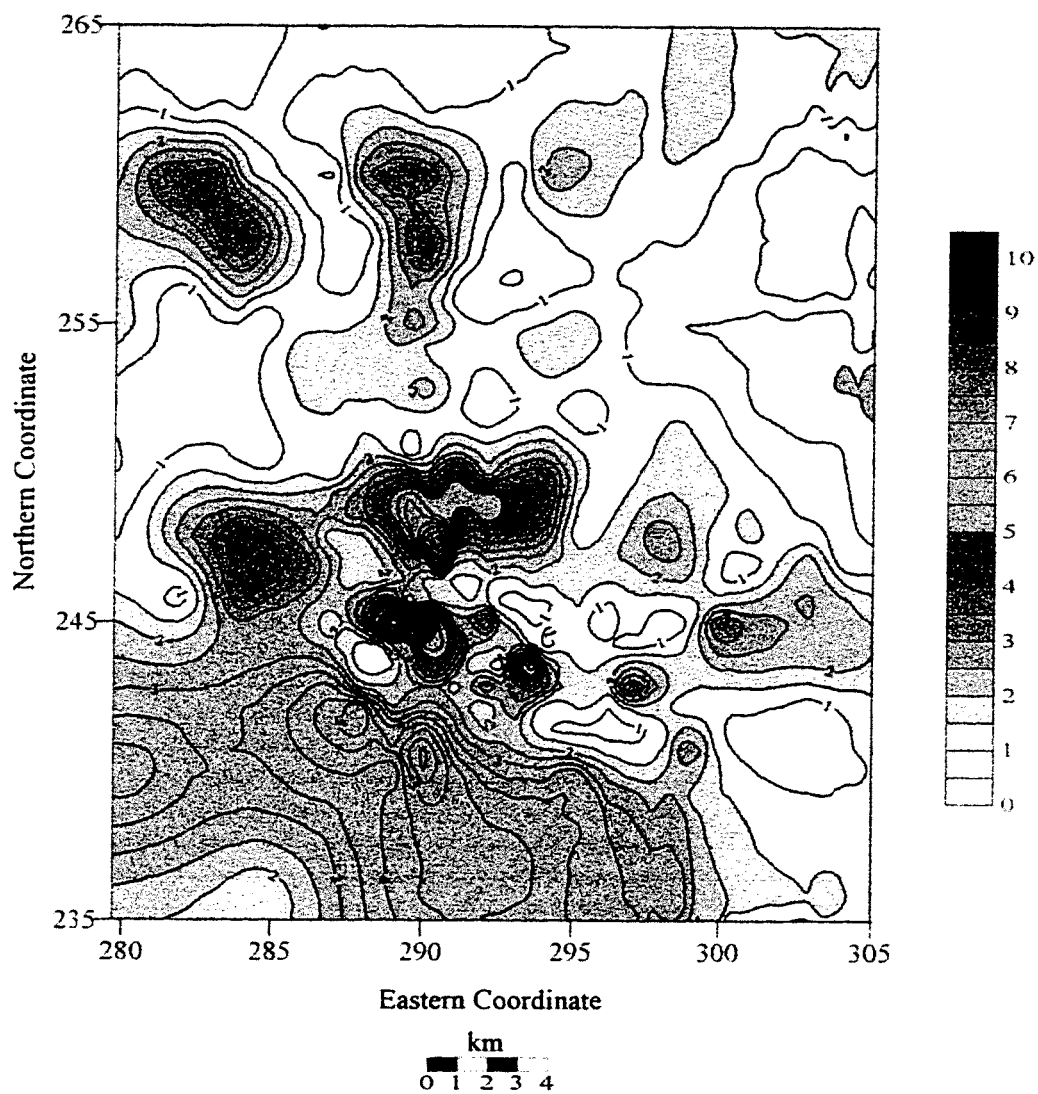


Fig. 7.8 : Isopach Map for the Zone 1 Phosphorite in the Hazm Al-Jalamid area based on bed thickness.

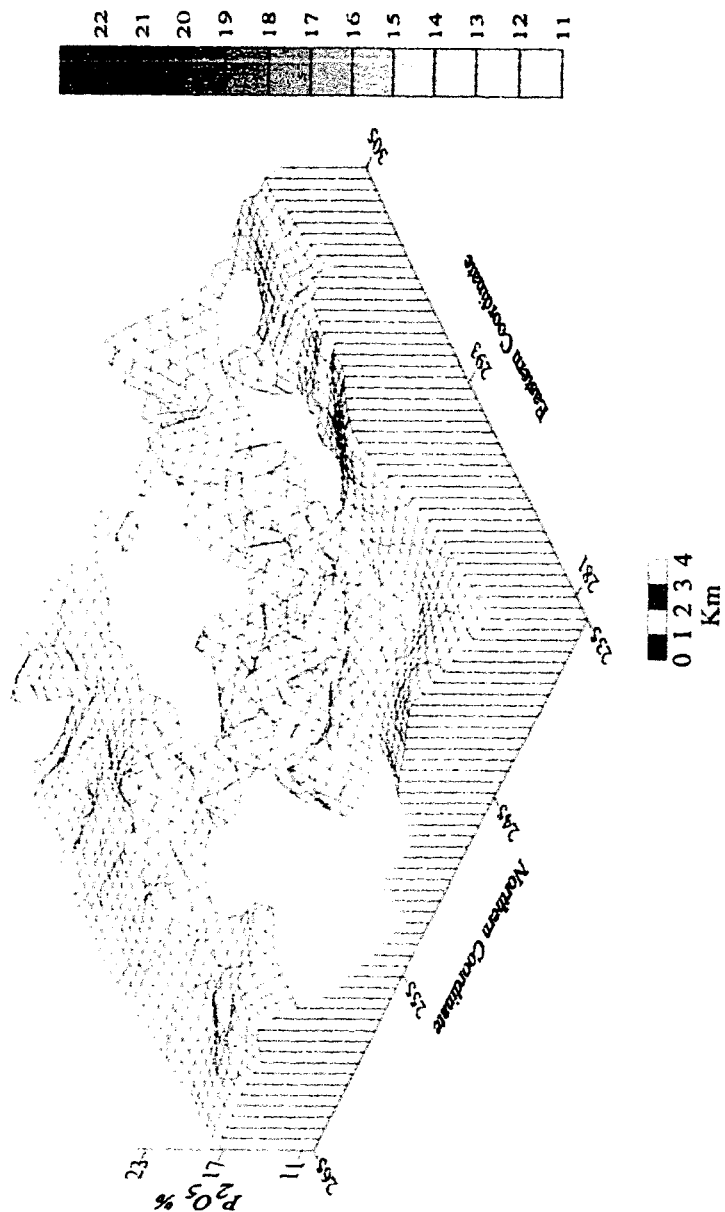


Fig. 7.9 : Three-Dimensional View for the P_2O_5 content in the
Zone 1 Phosphorite of the Hazm Al-Jalamid area.

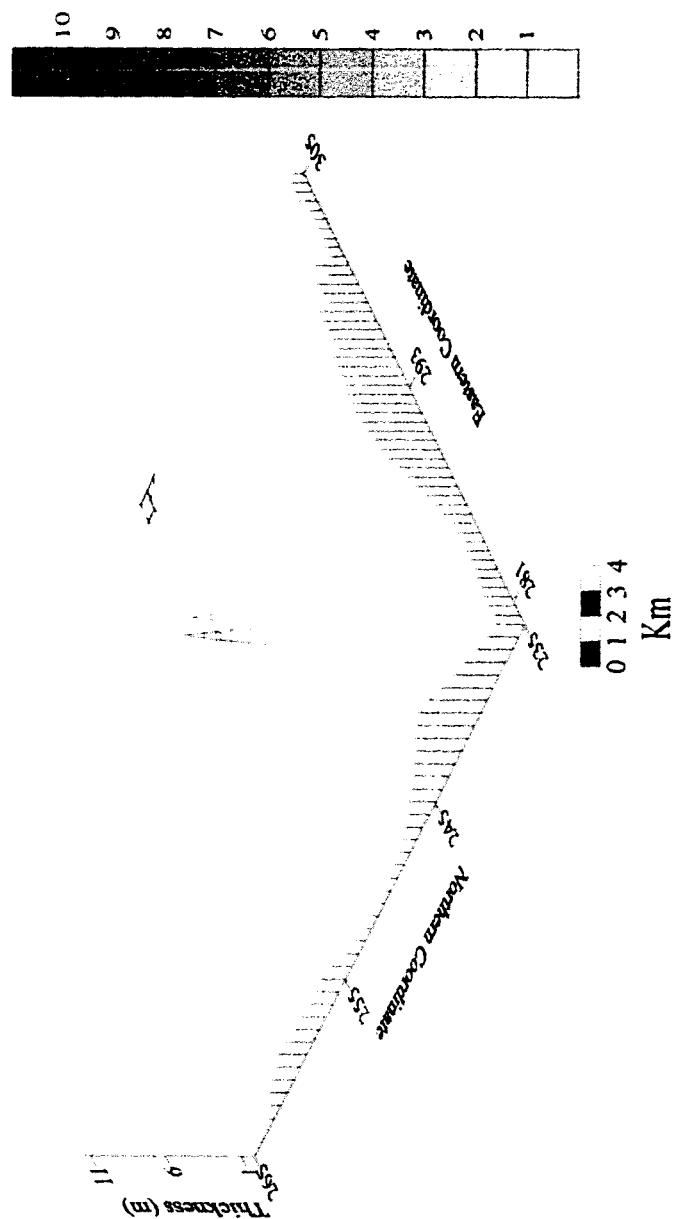


Fig. 7.10 : Three-Dimensional View for the Thickness of the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

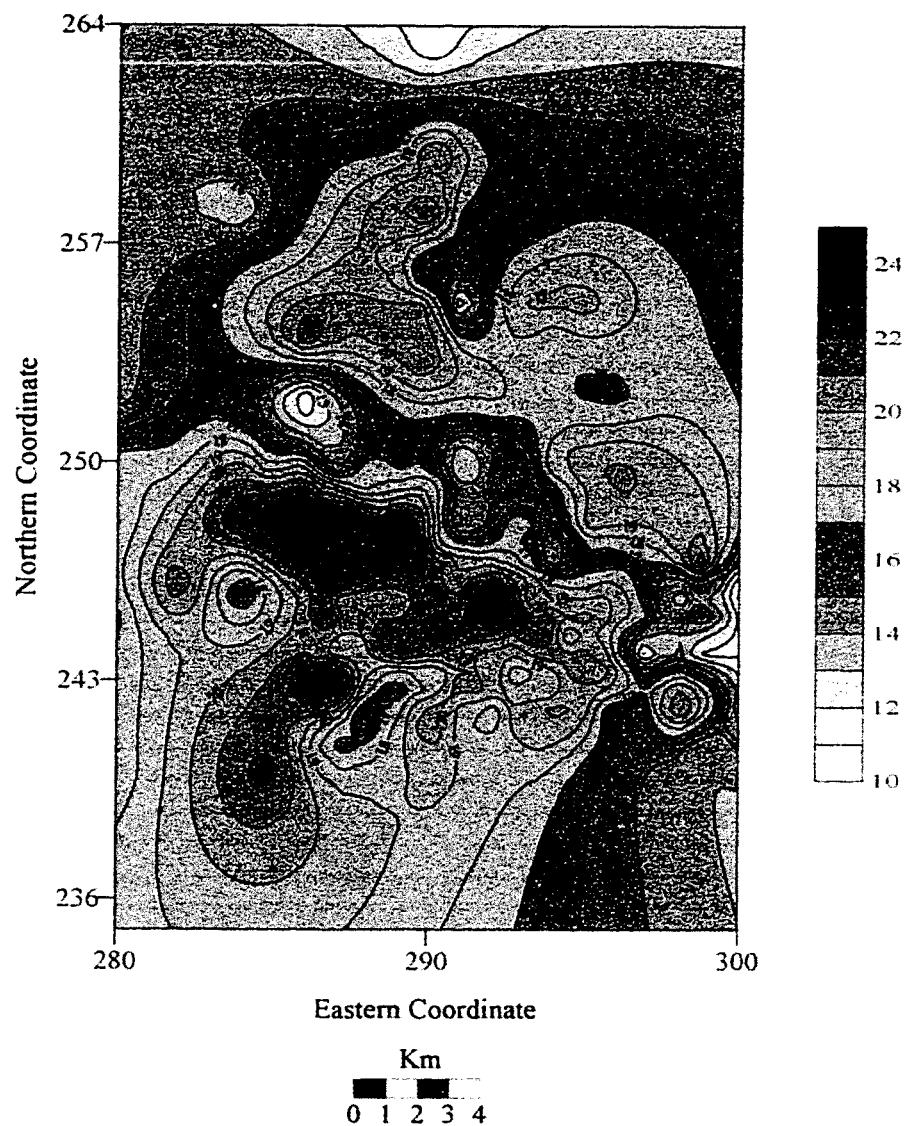


Fig. 7.11 : Iso-tenor Map for the Zone 2 Phosphorite in the Hazm Al-Jalamid area based on P_2O_5 %.

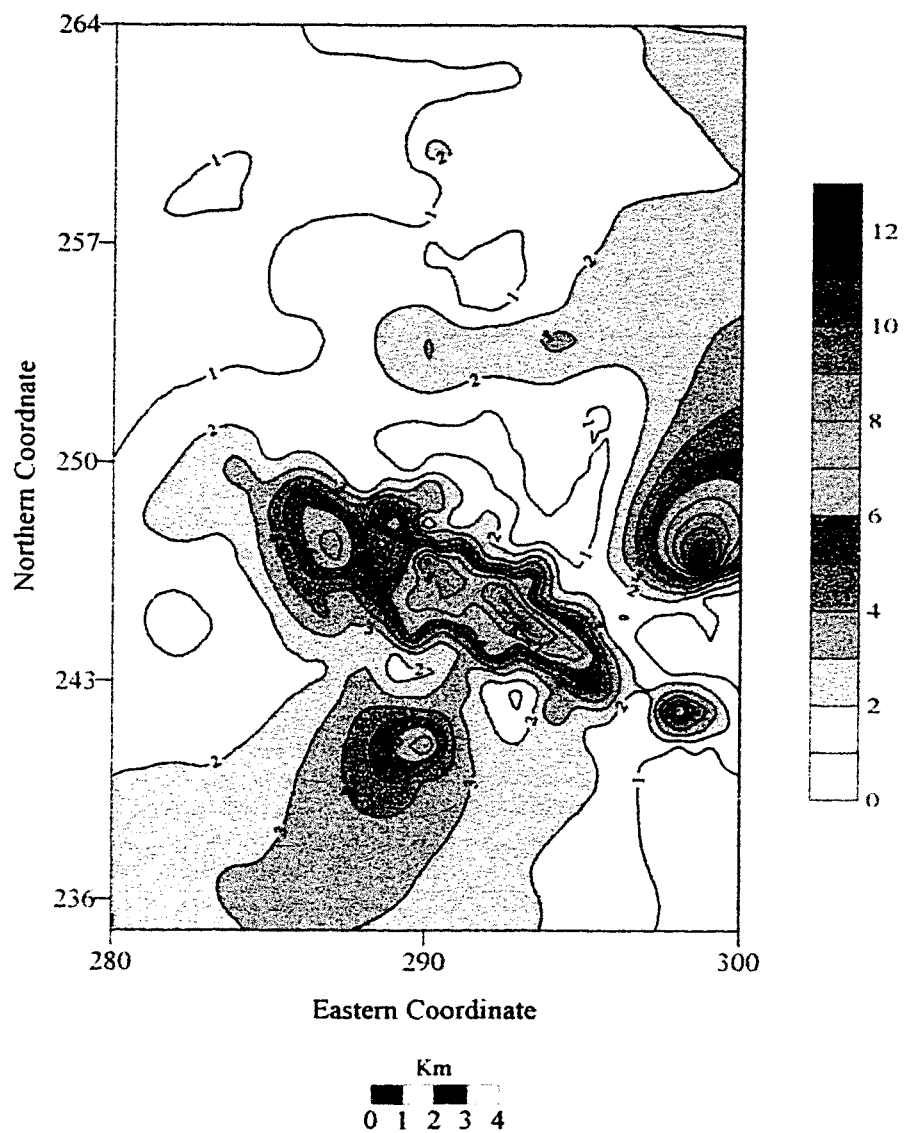


Fig. 7.12 : Isopach Map for the Zone 2 Phosphorite in the Hazm Al-Jalamid area based on bed thickness.

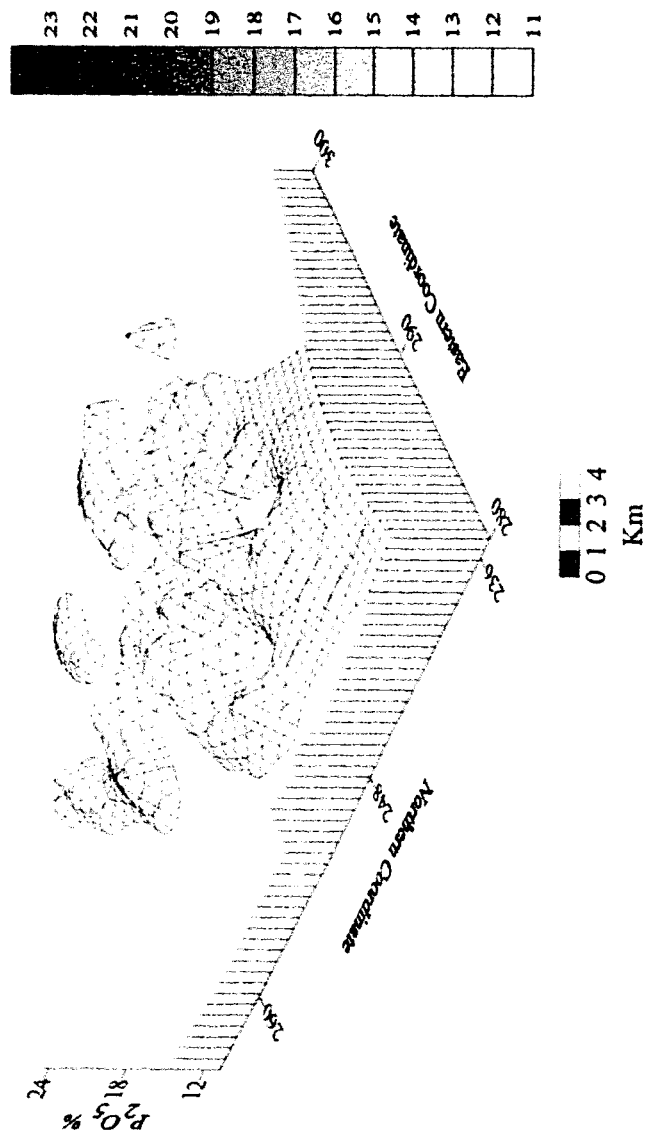


Fig. 7.13 : Three-Dimensional View for the P_2O_5 content in the
Zone 2 Phosphorite of the Hazm Al-Jalamid area.

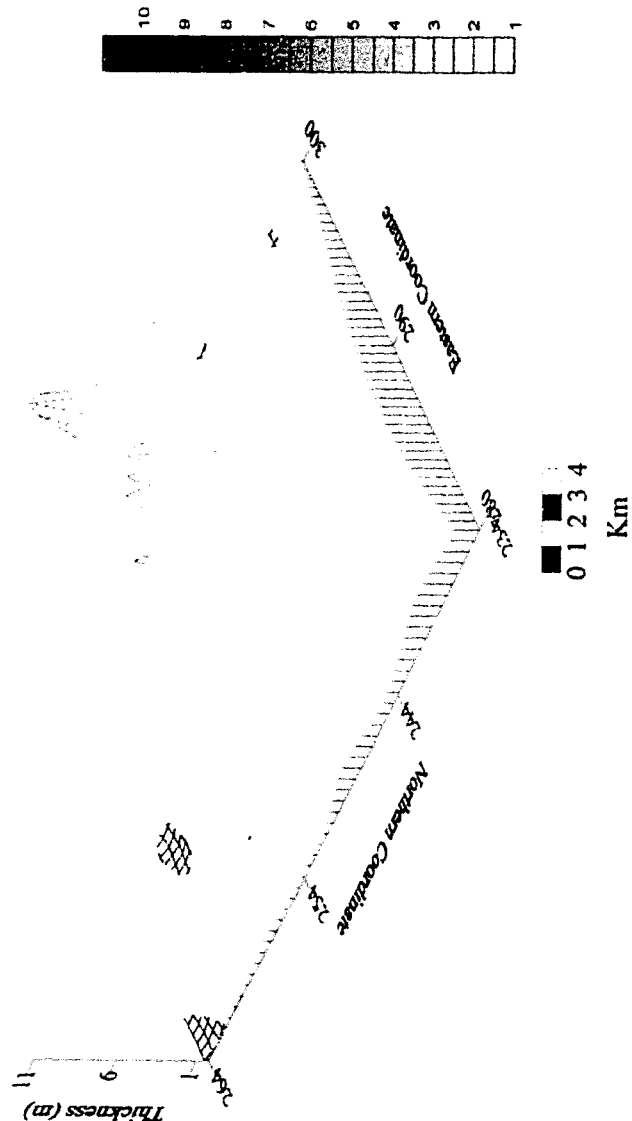


Fig. 7.14 : Three-Dimensional View for the Thickness of the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

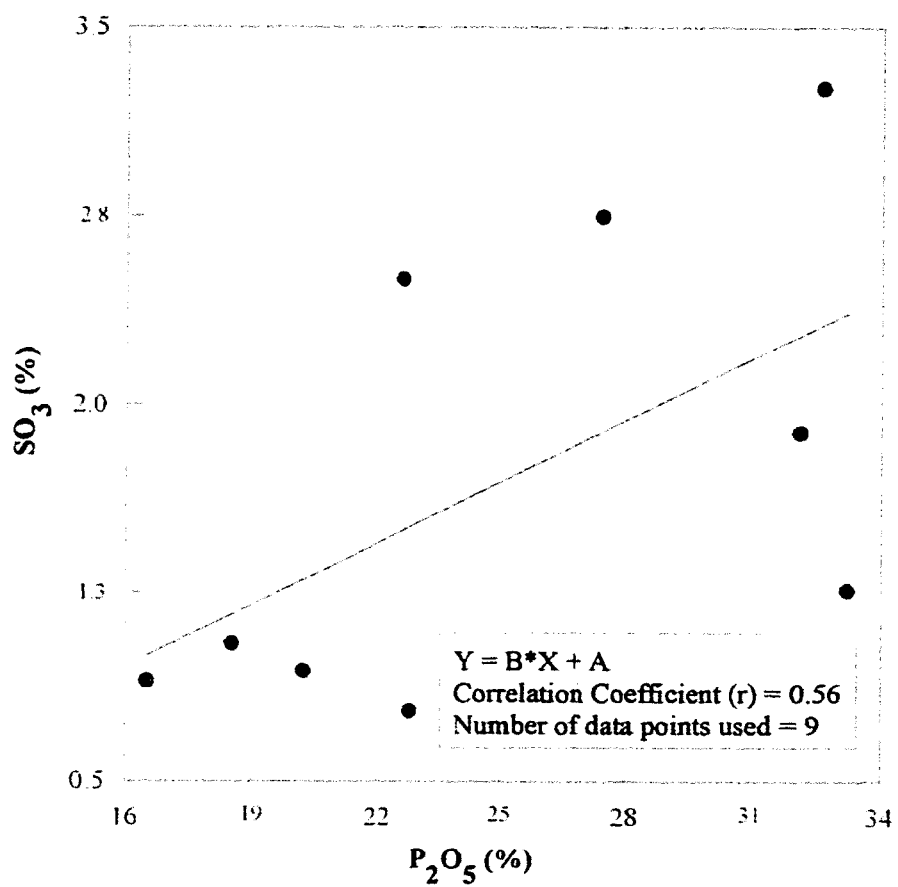


Fig. 7.15 : Relationship between P₂O₅ % & SO₃ % in the Arqah Phosphorite Member of the Umm Wu'sal North area.

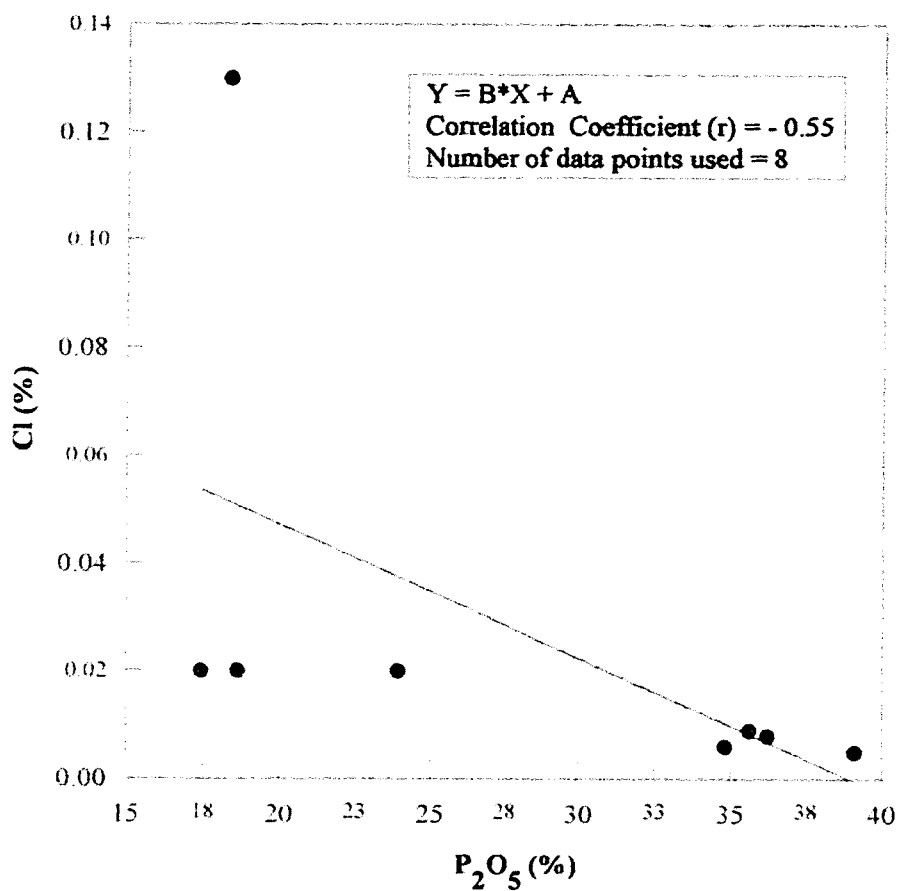


Fig. 7.16 : Relationship between P₂O₅ % & Cl % in the Thaniyat Phosphorite Member of the Hazm Al-Jalamid area.

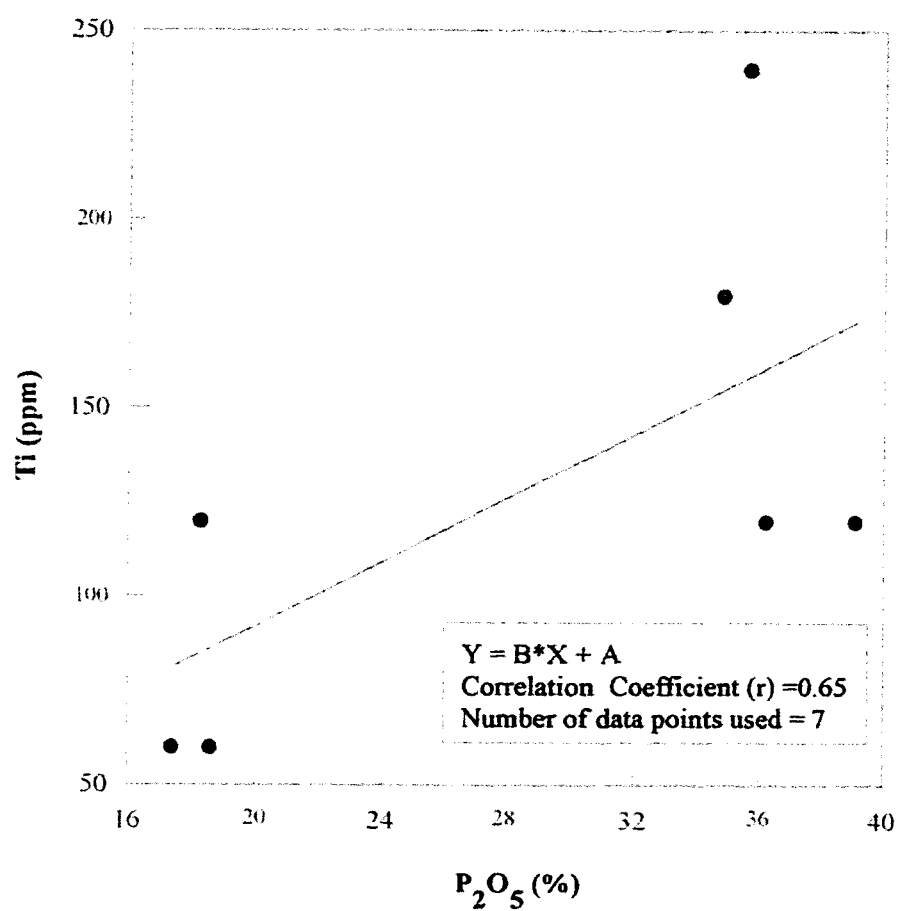


Fig. 7.17 : Relationship between P₂O₅ % and Ti ppm in the Thaniyat Phosphorite Member of the Hazm Al-Jalamid area.

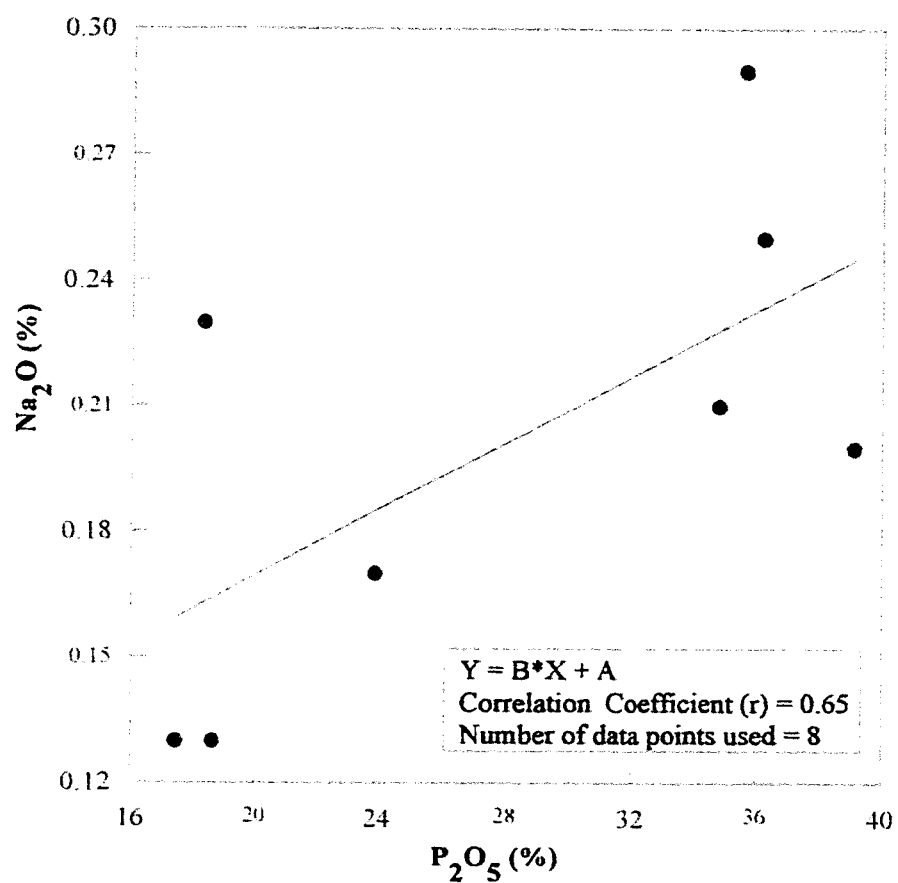


Fig. 7.18 : Relationship between P_2O_5 % & Na_2O % in the Thanlyat Phosphorite Member of the Hazm Al-Jalamid area.

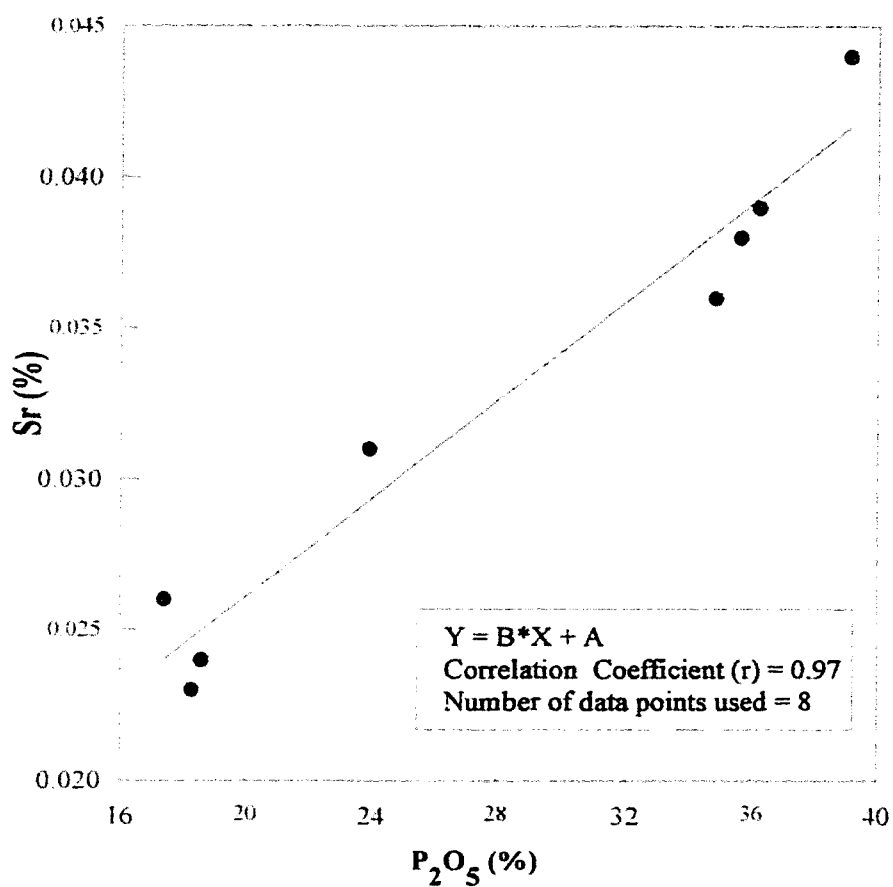


Fig. 7.19 : Relationship between P₂O₅ % & Sr % in the Thaniyat Phosphorite Member of the Hazm Al-Jalamid area.

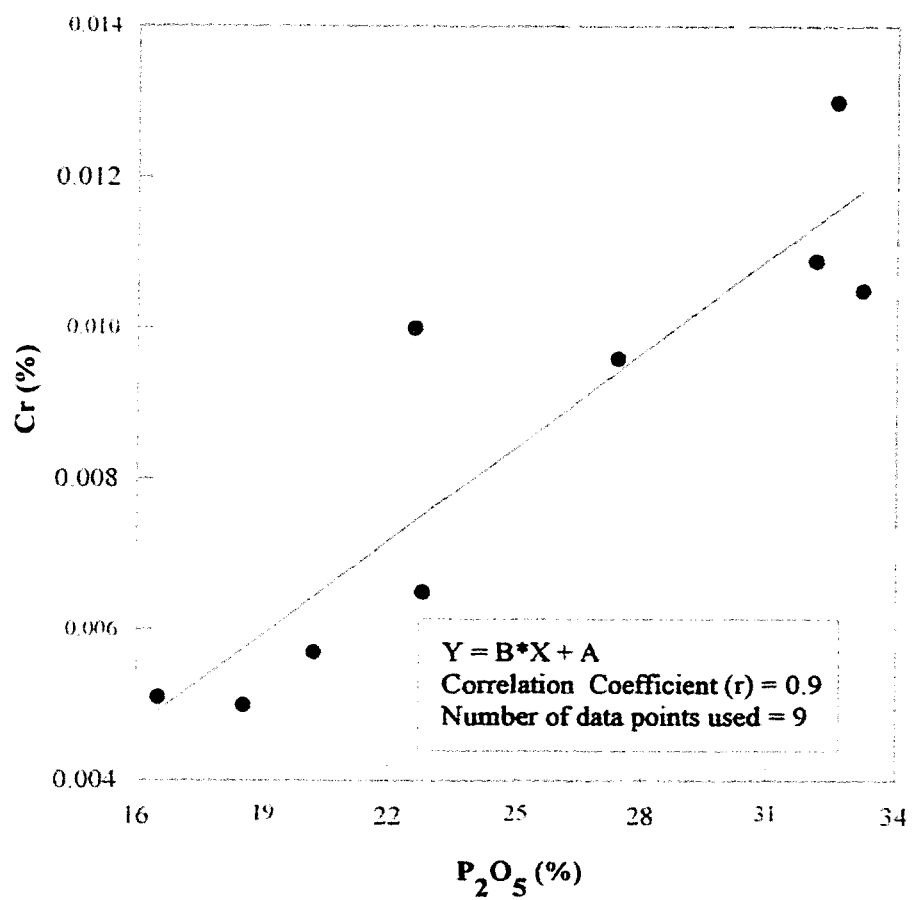


Fig. 7.20 : Relationship between P_2O_5 % and Cr % in the Arqah Phosphorite Member of the Umm Wu'aal North area.

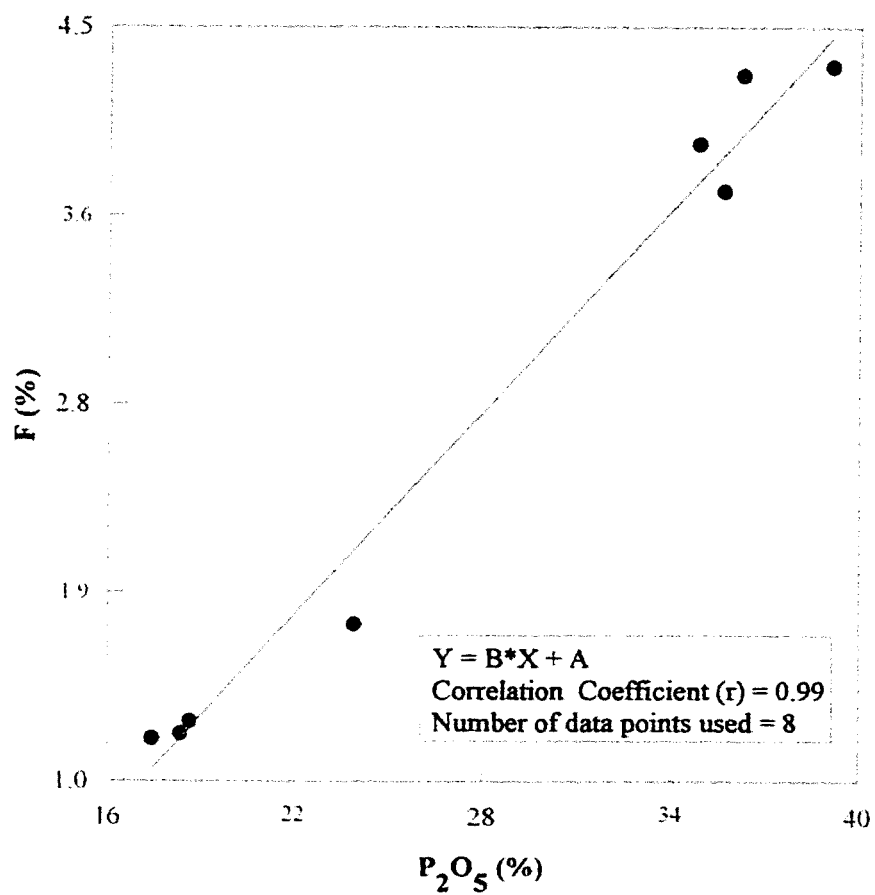


Fig. 7.21 : Relationship between P_2O_5 % & F % in the Thanlyat Phosphorite Member of the Hazm Al-Jalamid area.

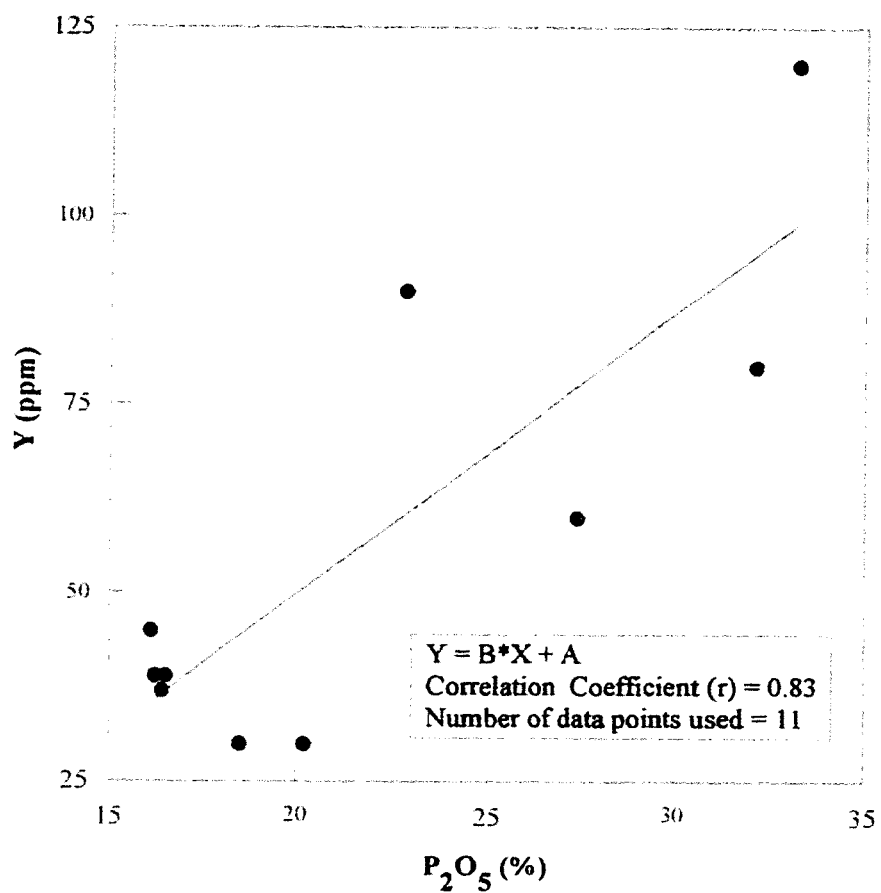


Fig. 7.22 : Relationship between P_2O_5 % & Y ppm in the Arqah Phosphorite Member of the Umm Wu'aal North area.

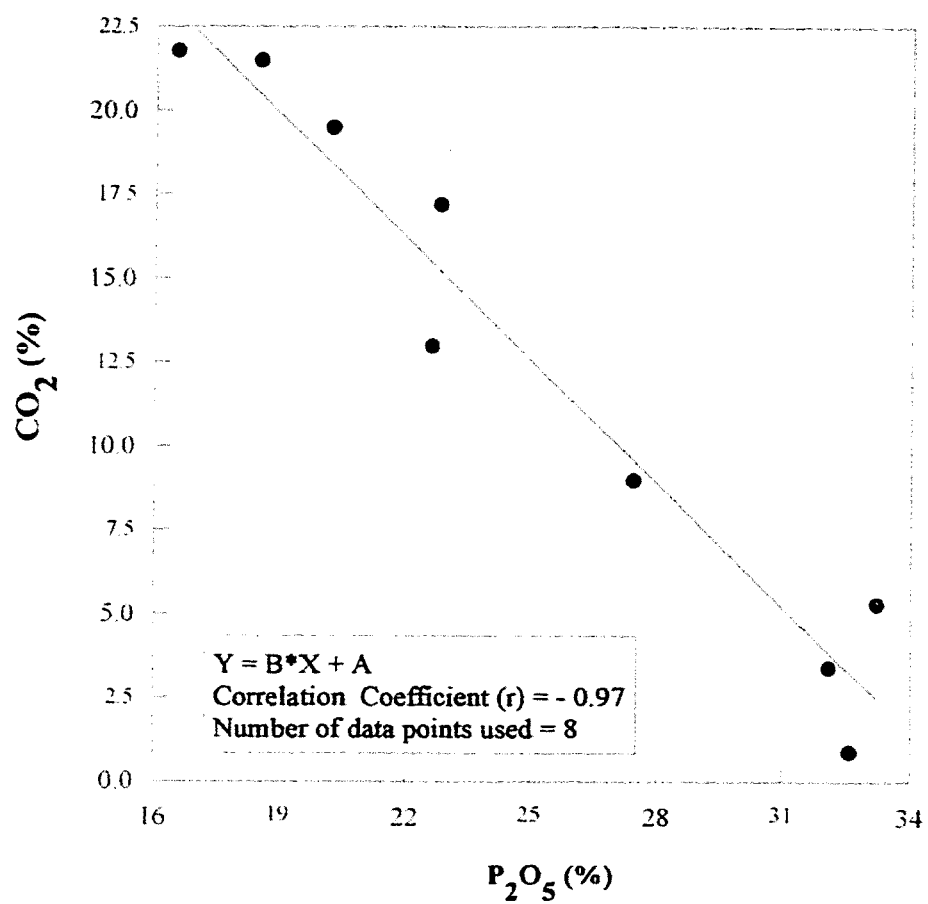


Fig. 7.23 : Relationship between P₂O₅ % & CO₂ % in the Arqah Phosphorite Member of the Umm Wu'aal North area.

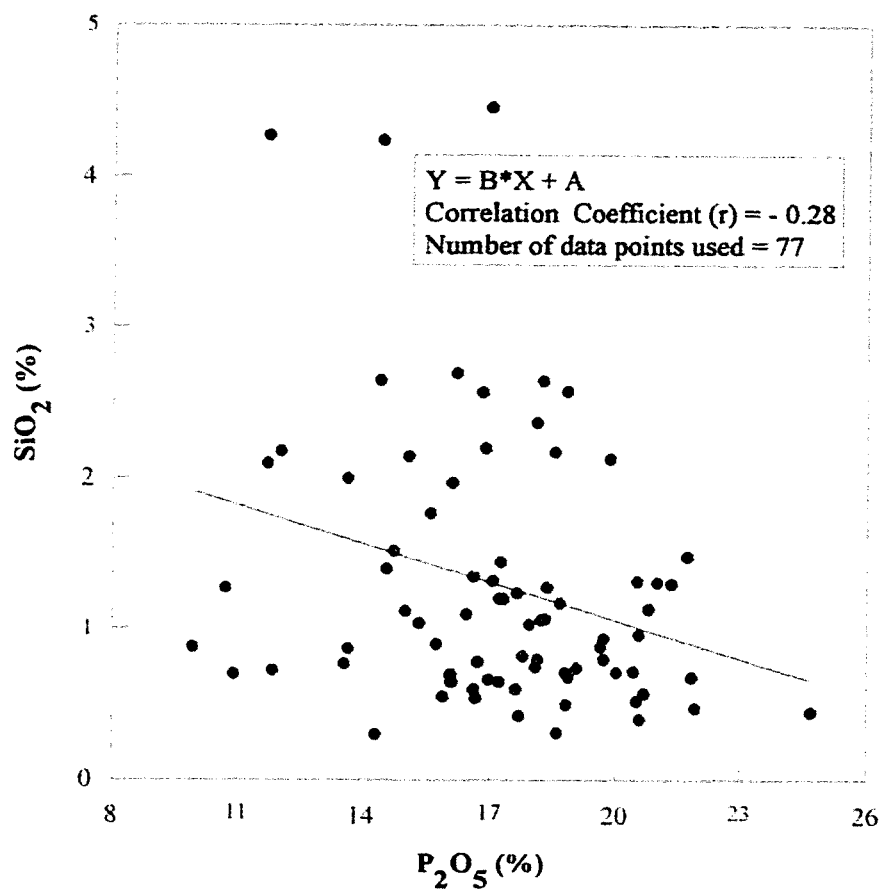


Fig. 7.24 : Relationship between P₂O₅ % & SiO₂ % in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

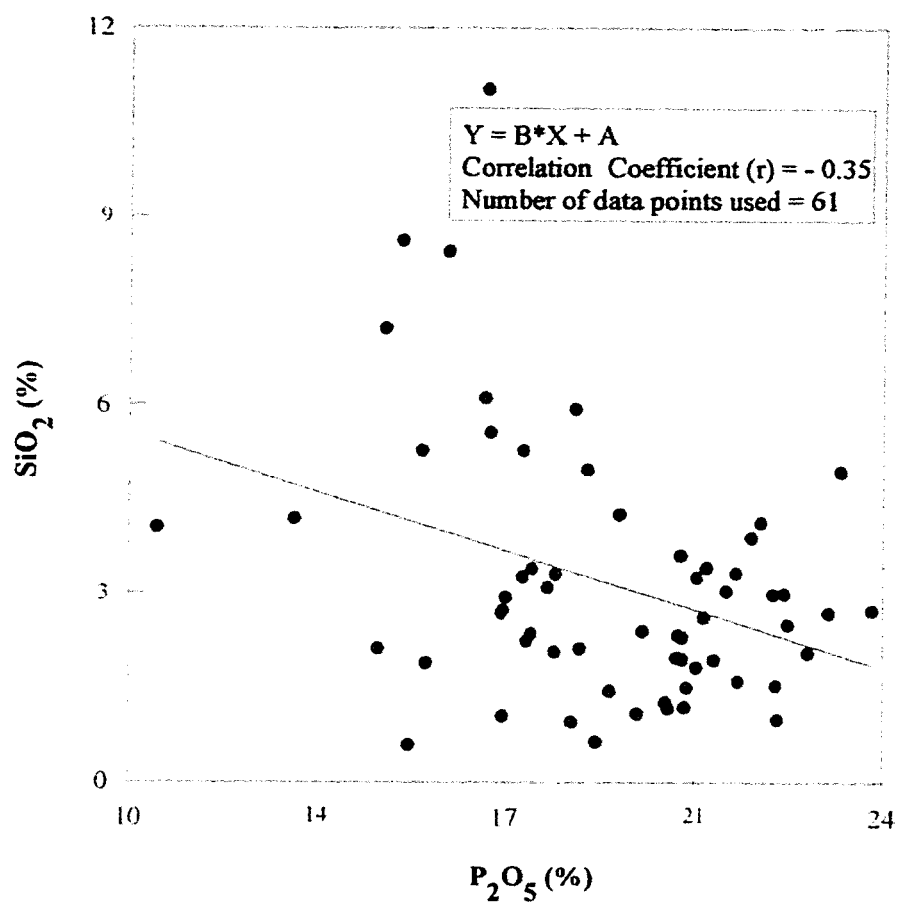


Fig. 7.25 : Relationship between P₂O₅ % & SiO₂ % in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

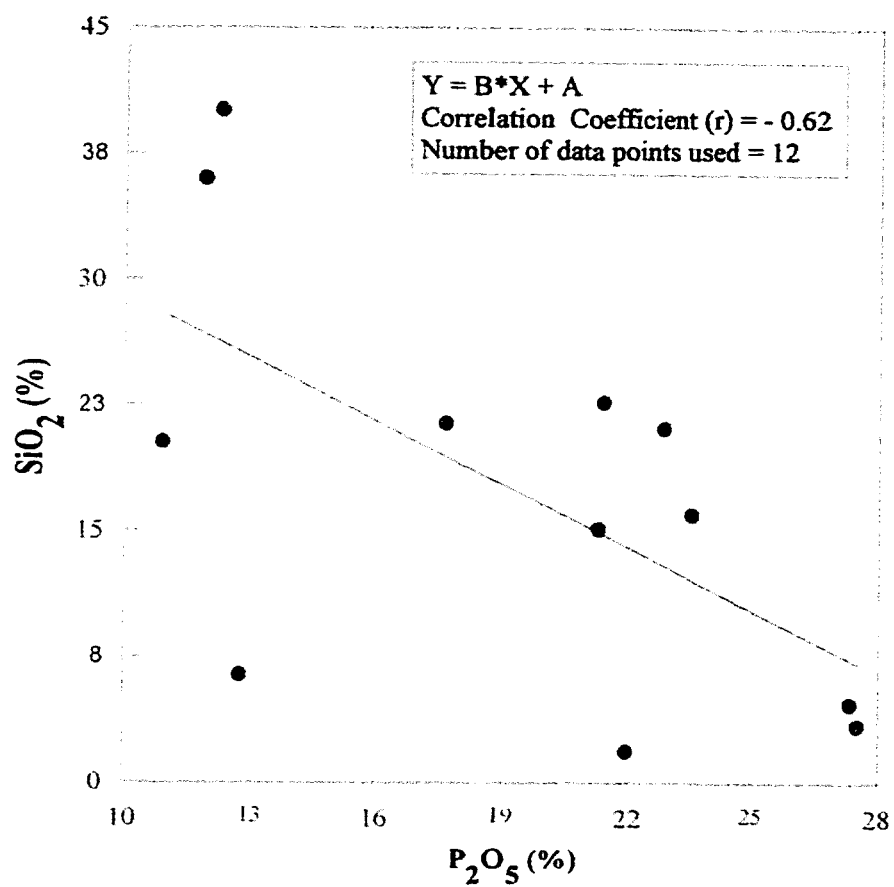


Fig. 7.26 : Relationship between P₂O₅ % & SiO₂ % in the Zone 1 Phosphorite of the Thaniyat Turayf area.

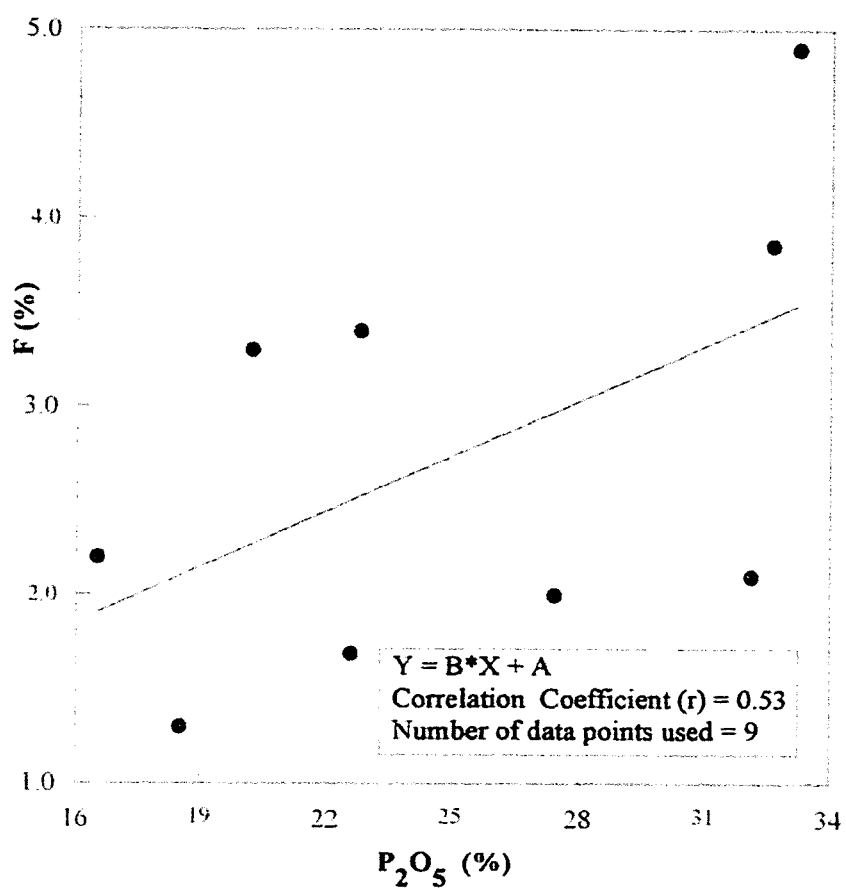


Fig. 7.27 : Relationship between P_2O_5 % and F % in the Arqah Phosphorite Member of the Umm Wu'aal North area.

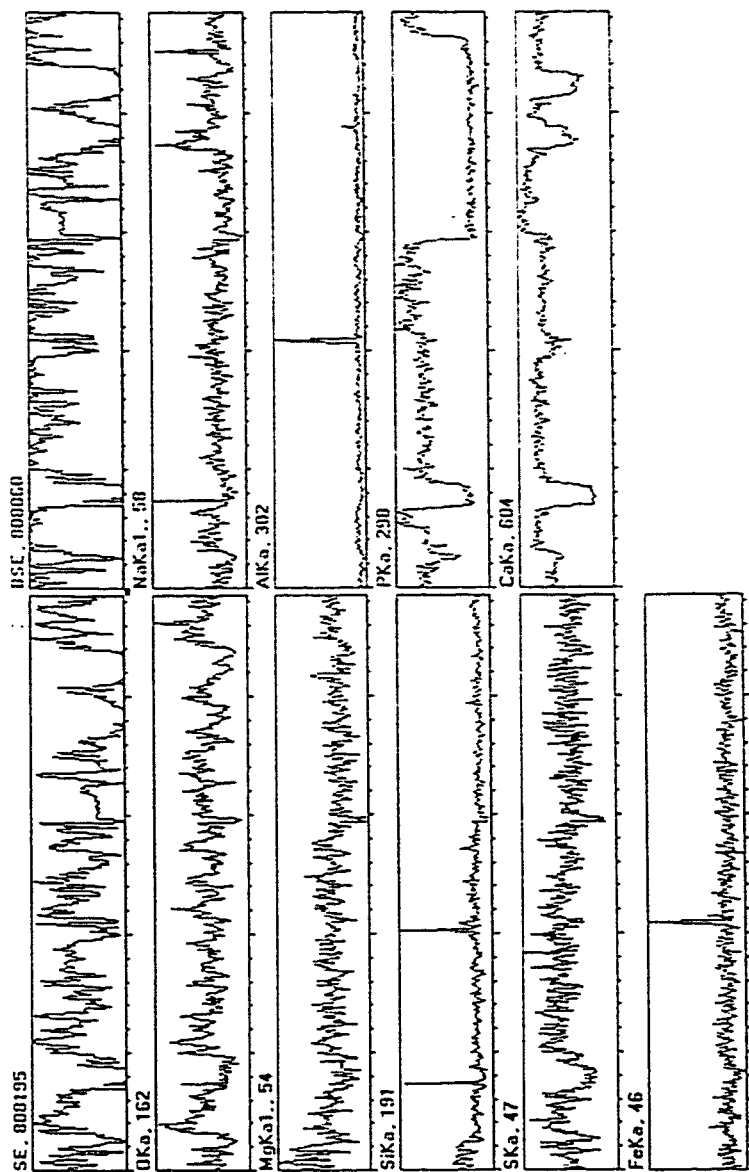


Fig. 7.28 : Electron line scan profiles of part of phosphorite sample from East Khawr Umm Wu'ad
Phosphorite deposit showing distribution of O, Na, Mg, Al, Si, P, S, Ca, and Fe.

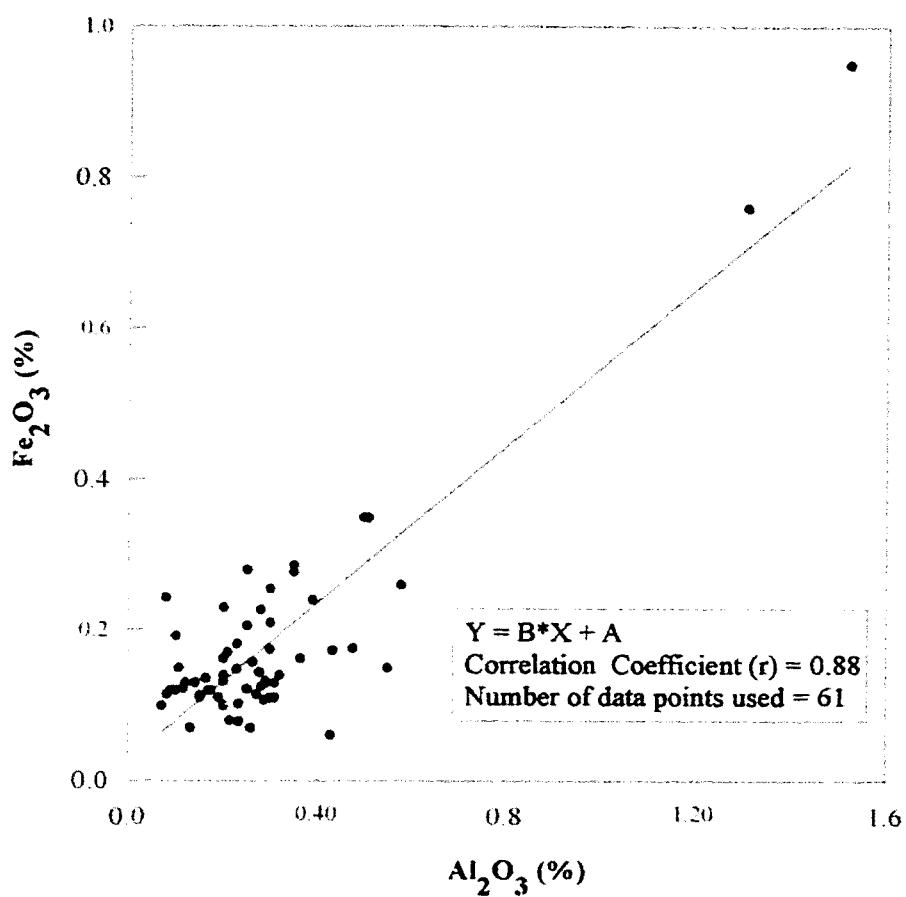


Fig. 7.29 : Relationship between Al_2O_3 % & Fe_2O_3 % in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

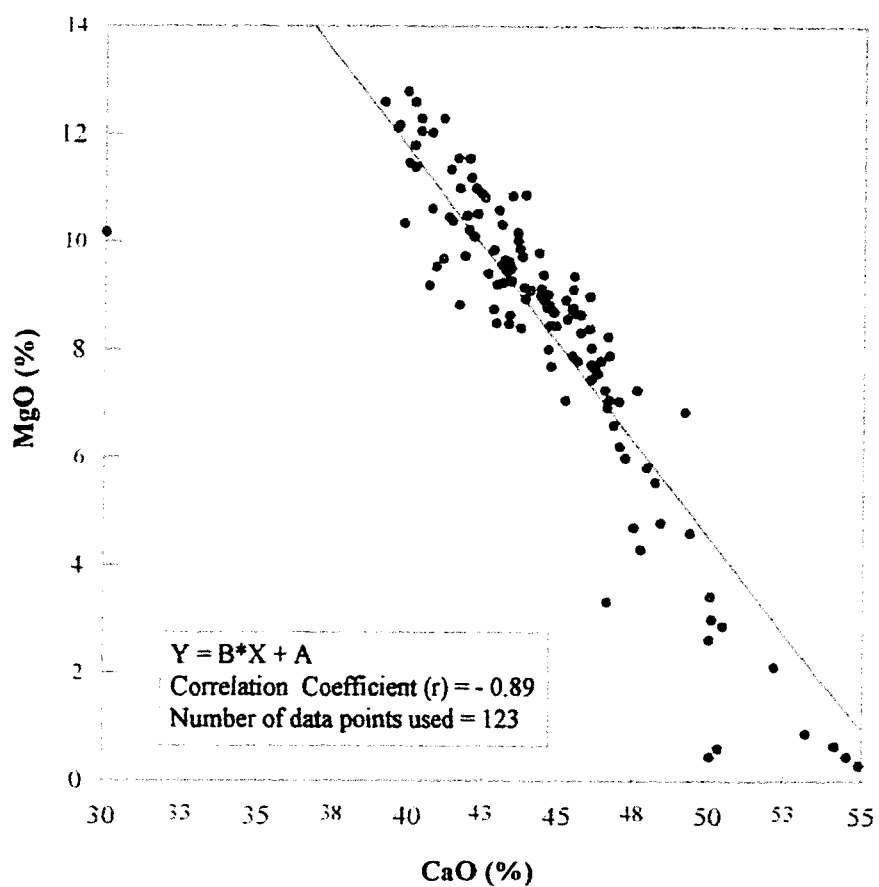


Fig. 7.30 : Relationship between CaO % & MgO % in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

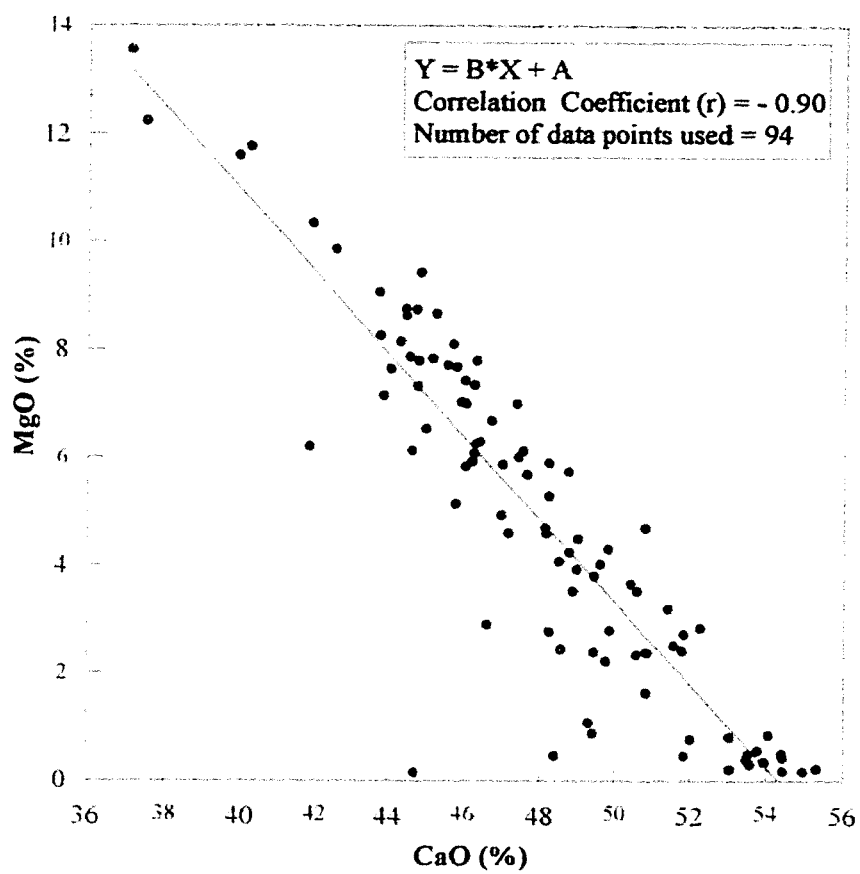


Fig. 7.31 : Relationship between CaO % & MgO % in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

Element	Element %	Atomic %
O	48.01	72.84
Na	0.48	0.51
Mg	0.16*	0.16*
Al	1.09	0.98
Si	2.06	1.78
P	2.81	2.21
S	0.38	0.29
Cl	0.40	0.27
K	0.54	0.34
Ca	8.18	4.95
V	1.54	0.73
Cr	0.56	0.26
Fe	33.80	14.69
Total	100	100

* = < 2 Sigma

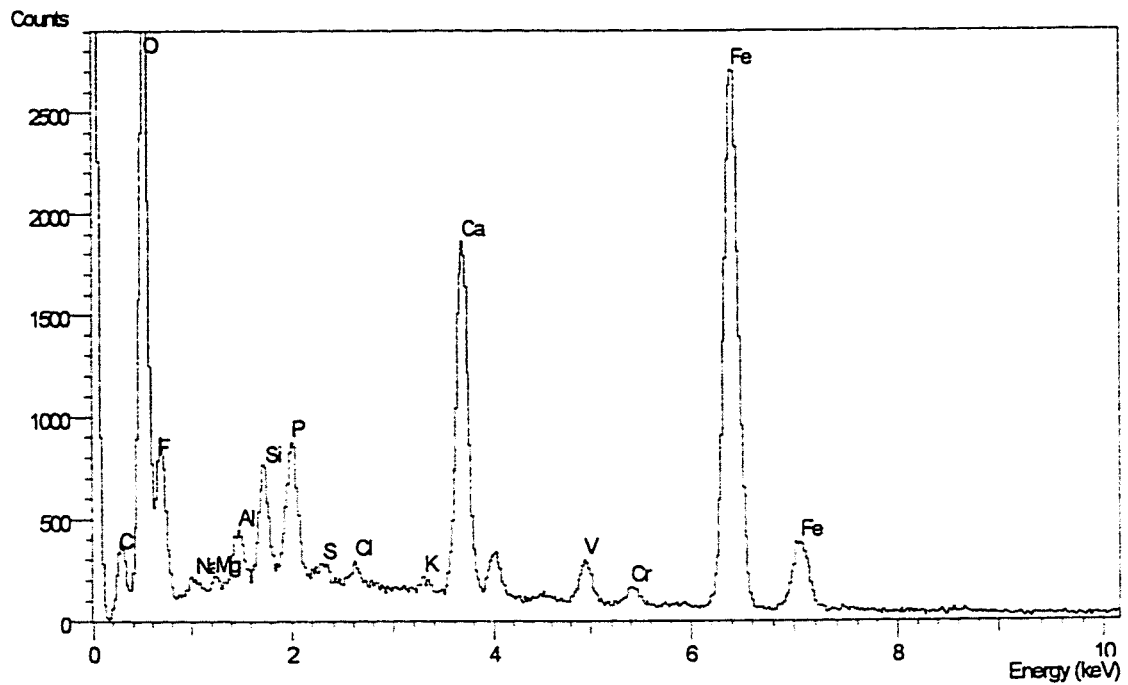


Fig. 7.32 : Spot analysis of part of phosphorite sample from East Khawr Umm Wu'aal Phosphorite deposit.

Element	Element %	Atomic %
O	47.11	71.25
F	0.26*	0.33*
Na	0.34*	0.36*
Mg	0.31*	0.30*
Al	0.40	0.36
Si	0.60	0.51
P	5.64	4.41
S	0.29	0.22
Cl	0.26	0.18
Ca	15.33	9.25
V	1.03	0.49
Cr	0.40	0.19
Fe	28.03	12.15
Total	100	100

* = < 2 Sigma

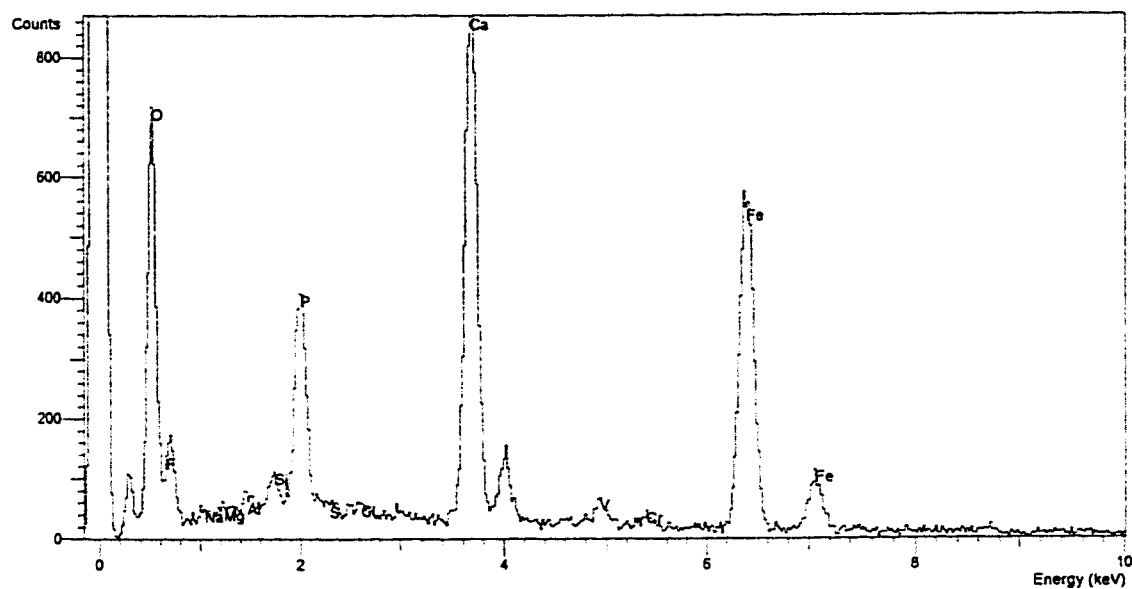


Fig. 7.33 : Spot analysis of part of phosphorite sample from Drill Hole (P1), Turayf area.

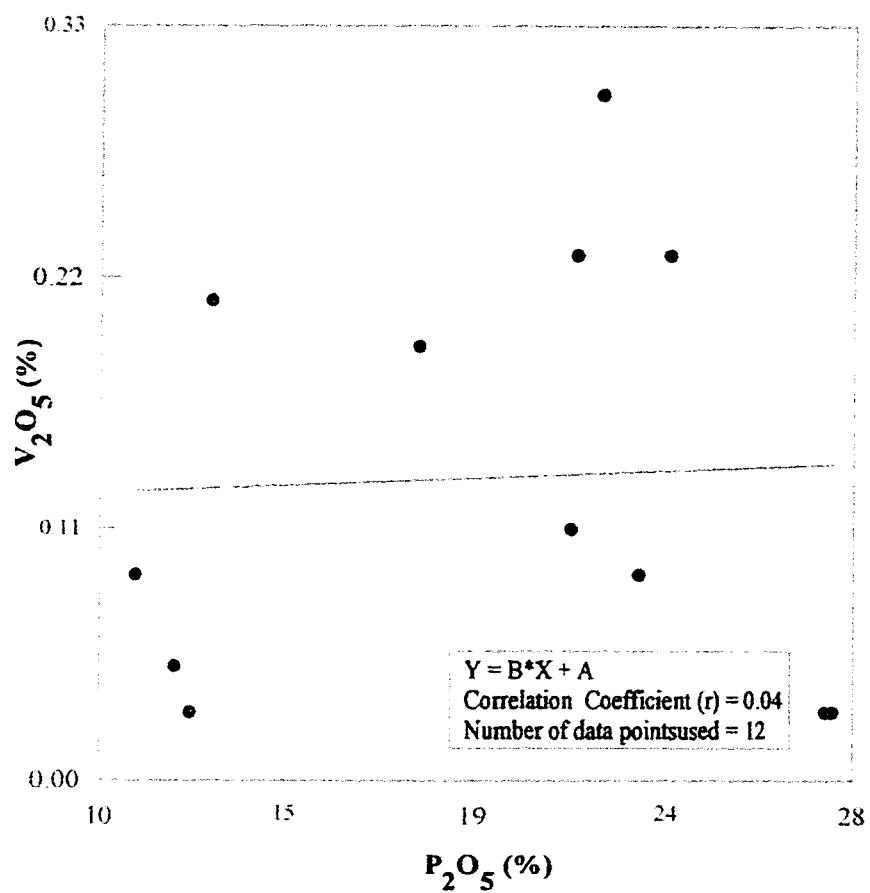


Fig. 7.34 : Relationship between P_2O_5 % & V_2O_5 % in the Zone 1 Phosphorite of the Thanlyat Turayf area.

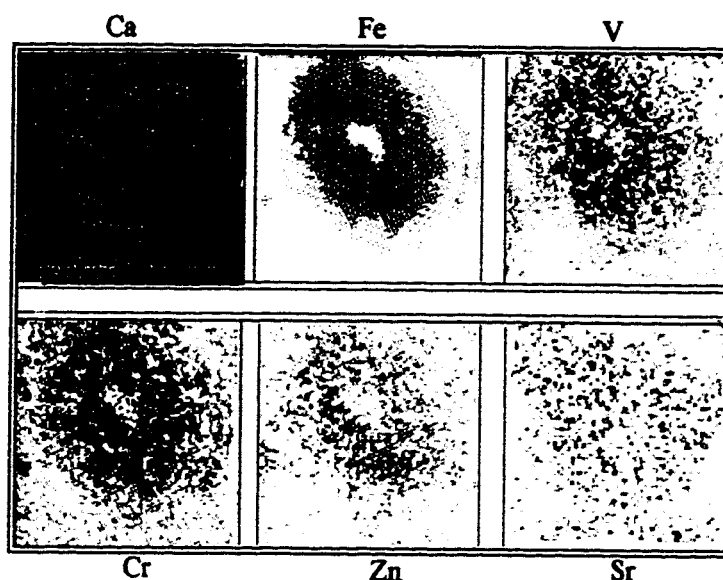


Fig. 7.35 : PIXE photographs of part of phosphorite sample from East Khawr Umm Wu'aal phosphorite deposit showing distribution of Ca, Fe, V, Cr, Zn and Sr. The relative concentration of each element is proportional to the density of blue dots within the field of each photograph.

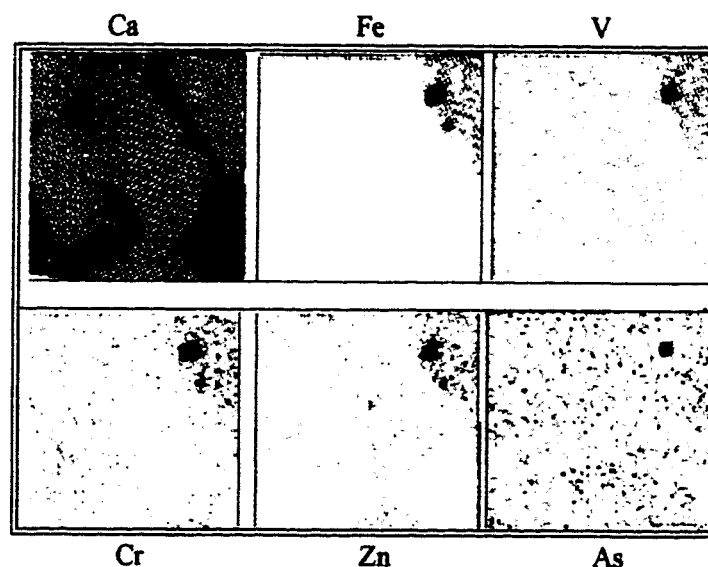


Fig. 7.36 : PIXE photographs of part of phosphorite sample from East Khawr Umm Wu'aal phosphorite deposit showing distribution of Ca, Fe, V, Cr, Zn and Sr. The relative concentration of each element is proportional to the density of blue dots within the field of each photograph.

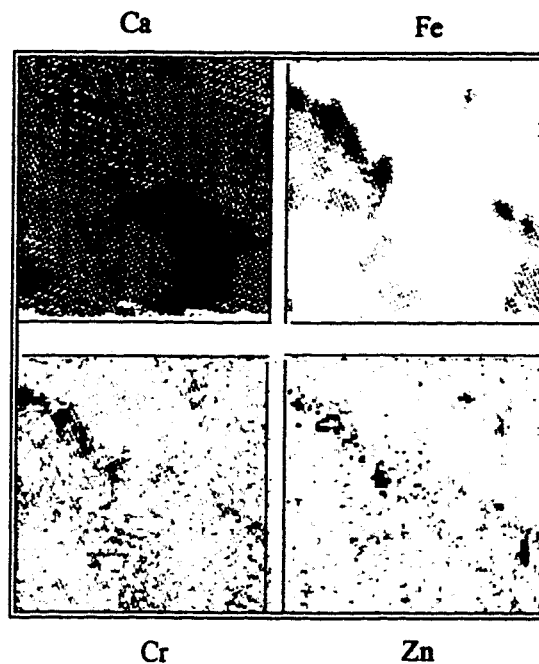


Fig. 7.37 : PIXE photographs of part of phosphorite sample from East Khawr Umm Wu'aal phosphorite deposit showing distribution of Ca, Fe, V, Cr and Zn. The relative concentration of each element is proportional to to the density of blue dots within the field of each photograph.

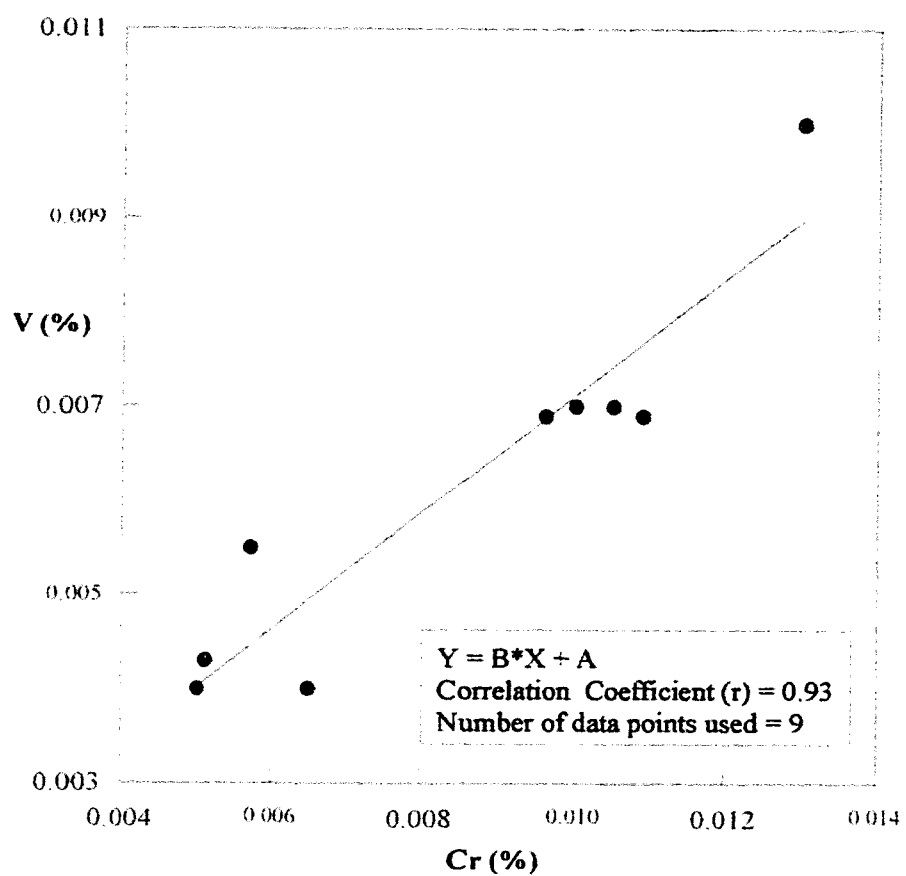


Fig. 7.38 : Relationship between Cr % & V % in the Arqah Phosphorite Member of the Umm Wu'aal North area.

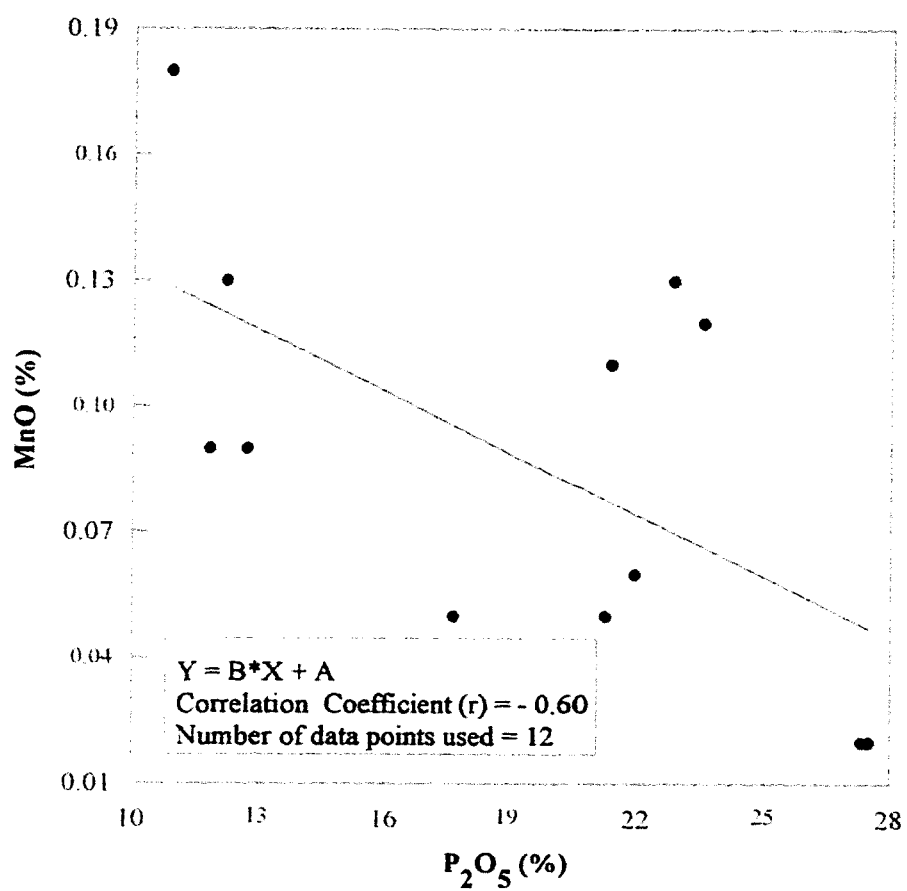


Fig. 7.39 : Relationship between P_2O_5 % & MnO % in the Zone 1 Phosphorite of the Thaniyat Turayf area.

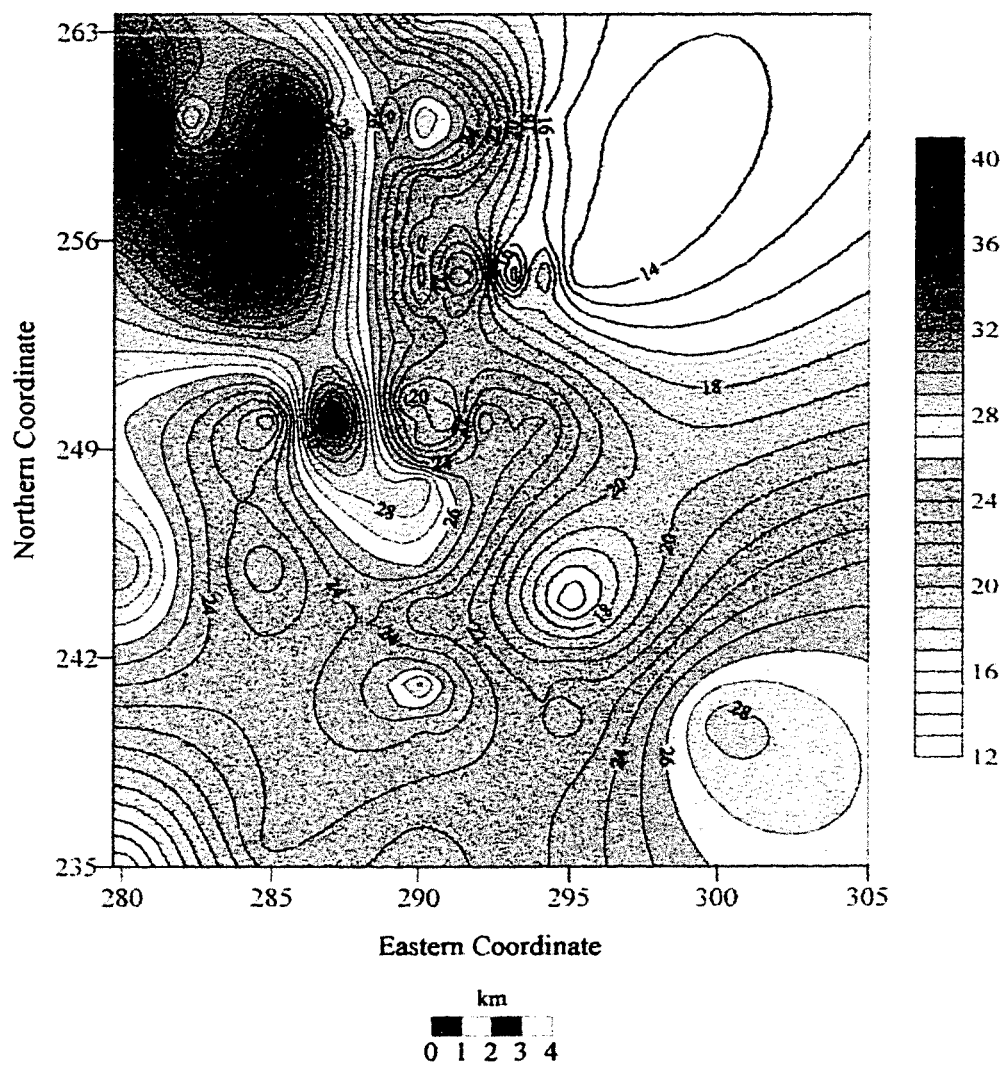


Fig. 7.40 : Iso-tenor Map for the Zone 1 Phosphorite in the Hazm Al-Jalamid area based on U_3O_8 ppm.

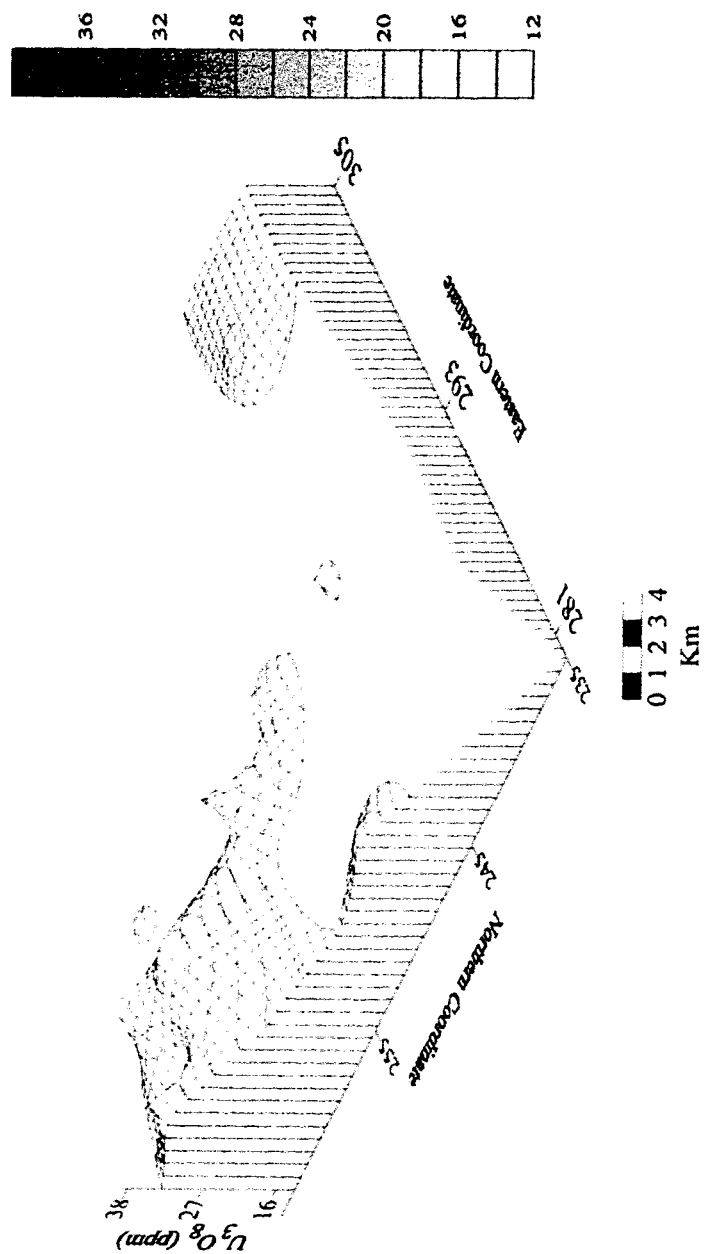


**Fig. 7.41 : Three-Dimensional View for U_3O_8 content in the
Zone 1 Phosphorite of the Hazm Al-Jalamid area.**

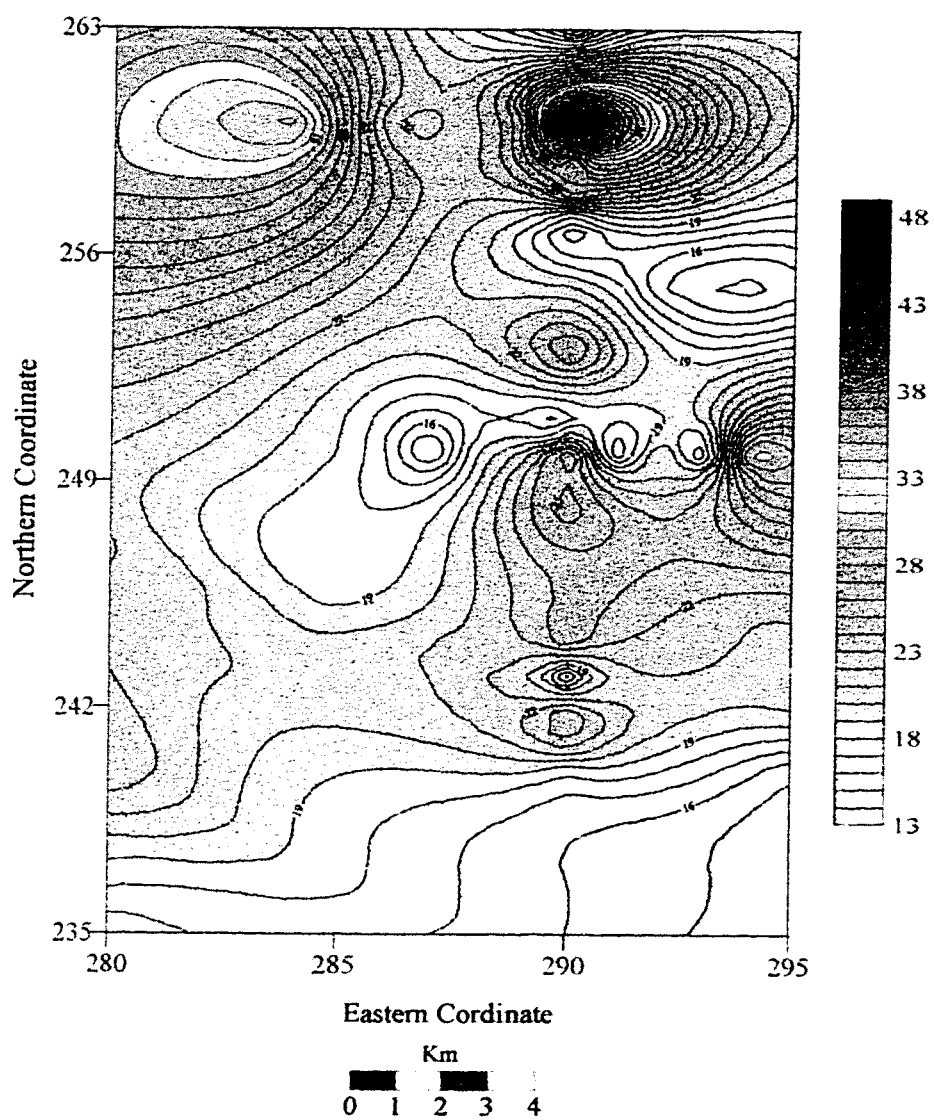


Fig. 7.42 : Iso-tenor Map for the Zone 2 Phosphorite in the Hazm Al-Jalamid area based on U_3O_8 ppm.

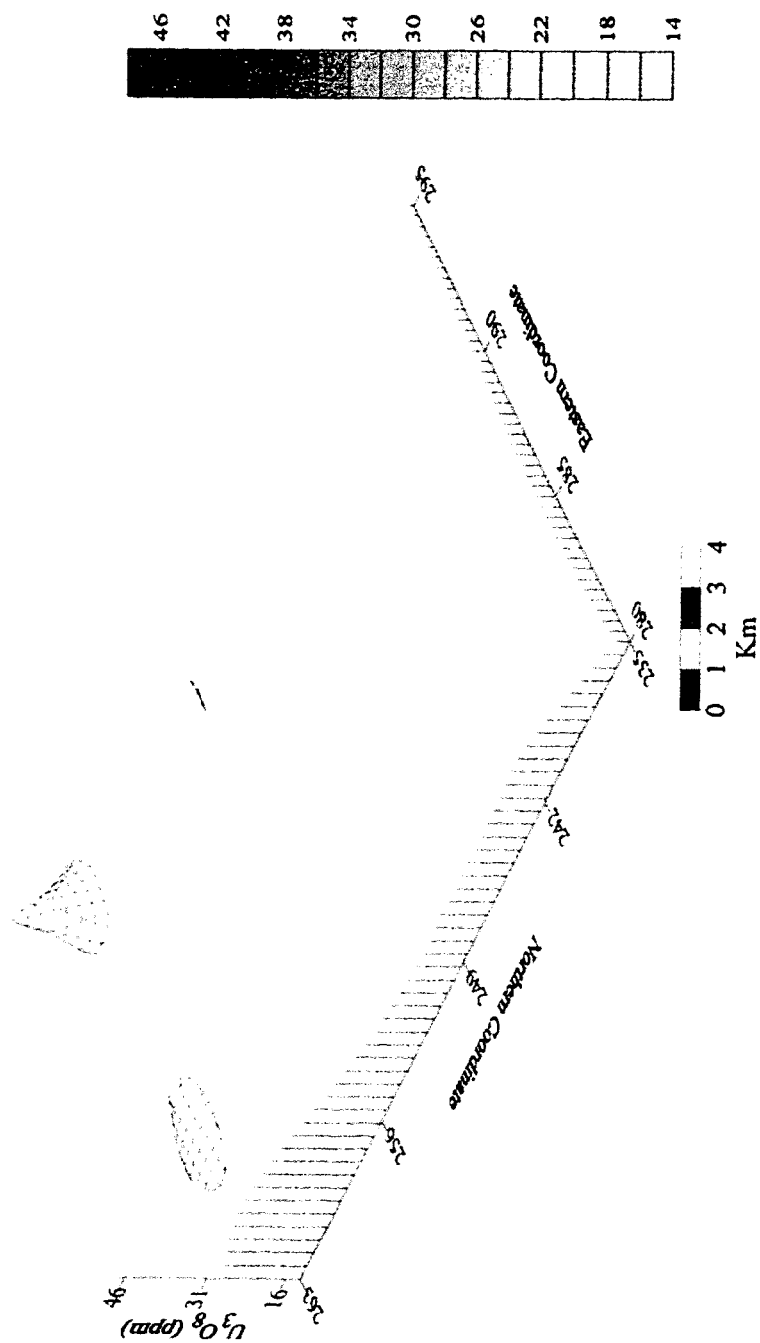


**Fig. 7.43 : Three-Dimensional View for U_3O_8 content in the
Zone 2 Phosphorite of the Hazm Al-Jalamid area.**

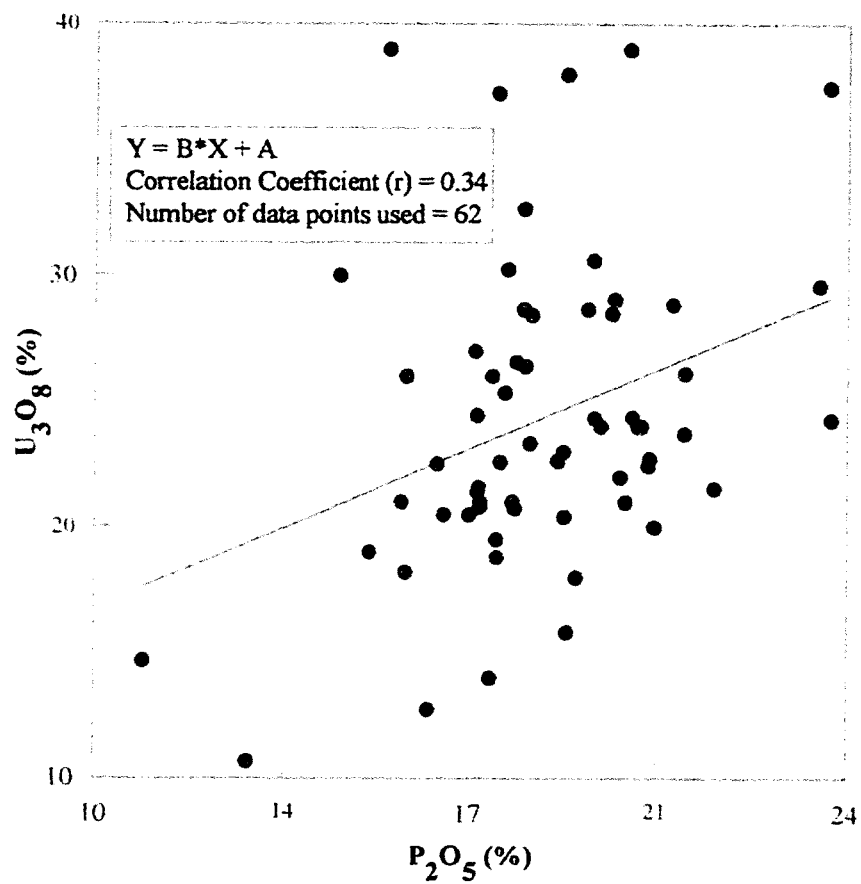


Fig. 7.44 : Relationship between P₂O₅ % & U₃O₈ ppm in the Zone 1 Phosphorite of the Hazm Al-Jalamid area.

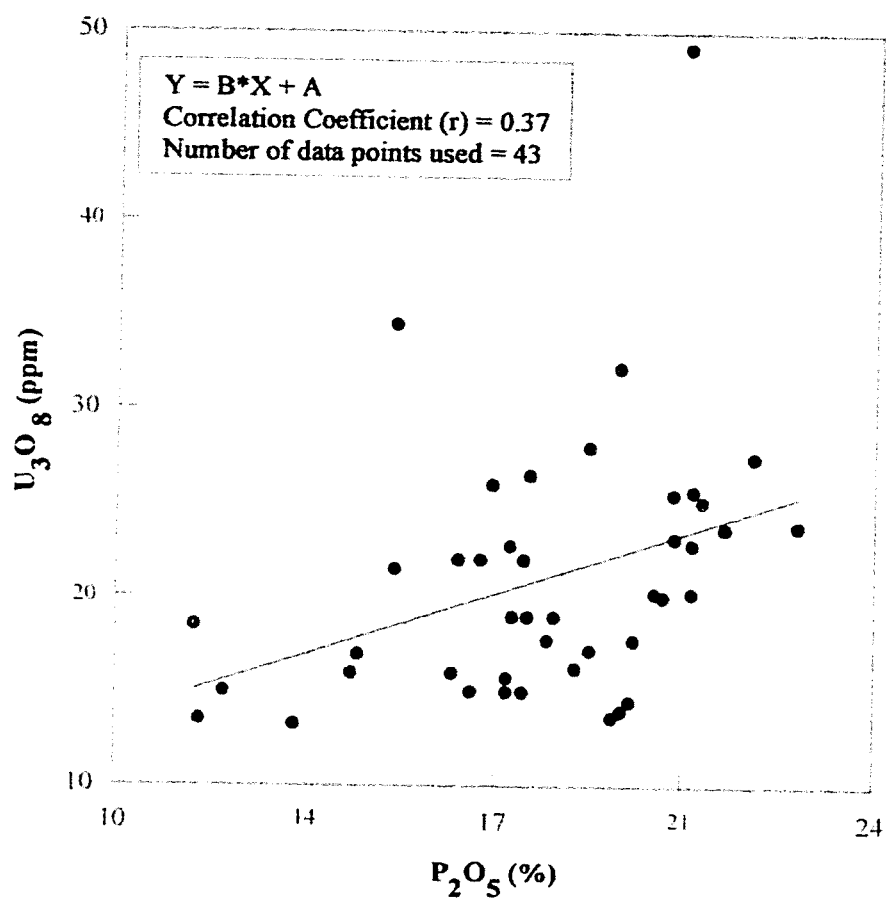


Fig. 7.45 : Relationship between P_2O_5 % & U_3O_8 ppm in the Zone 2 Phosphorite of the Hazm Al-Jalamid area.

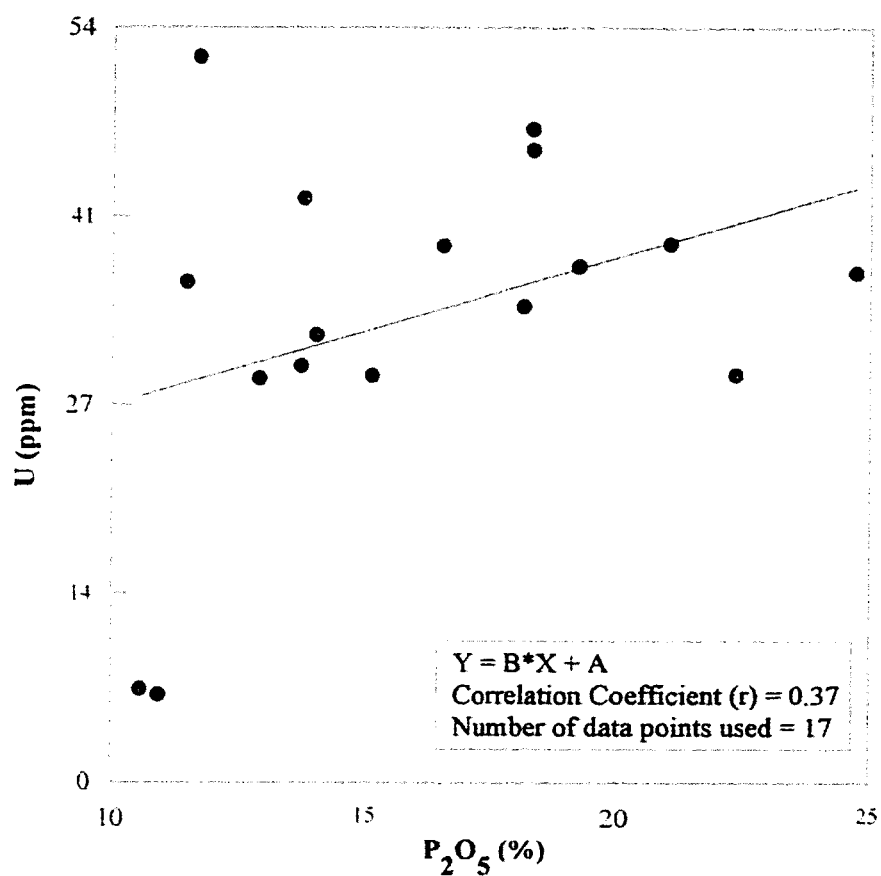


Fig. 7.46 : Relationship between P_2O_5 % & U ppm in the Saudi Arabian Phosphorite samples tested for natural radioactivity.

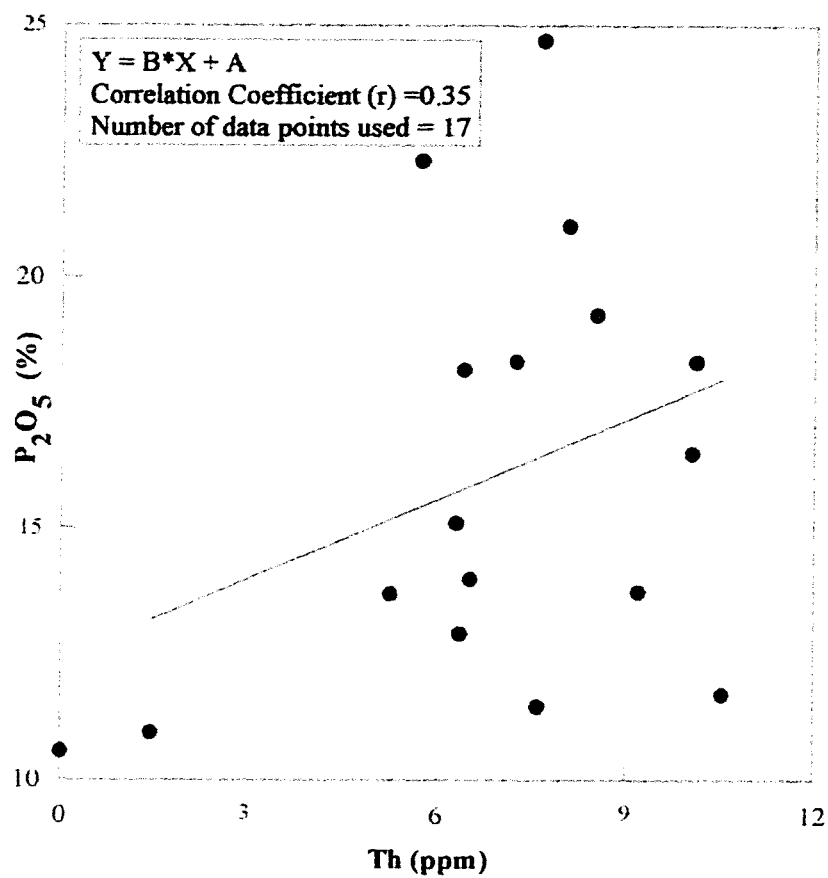


Fig. 7.47 : Relationship between P₂O₅ % & Th ppm in the Saudi Arabian Phosphorite samples tested for natural radioactivity.

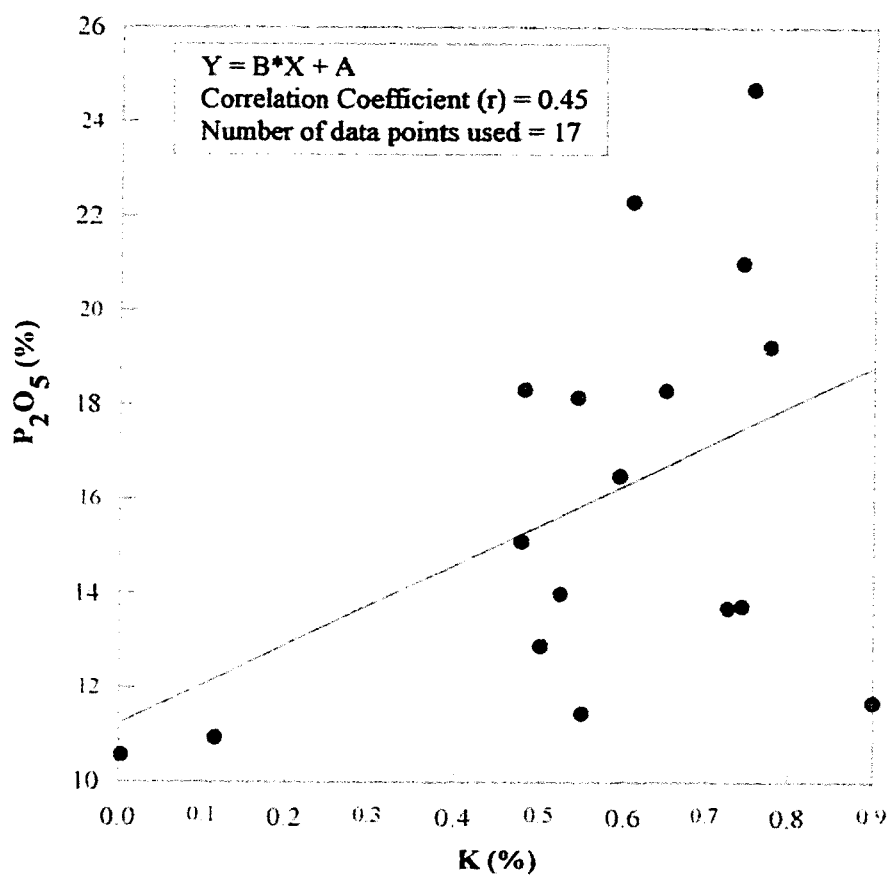


Fig. 7.48 : Relationship between P₂O₅% & Radioactive K % in the Saudi Arabian Phosphorite samples tested for natural radioactivity.

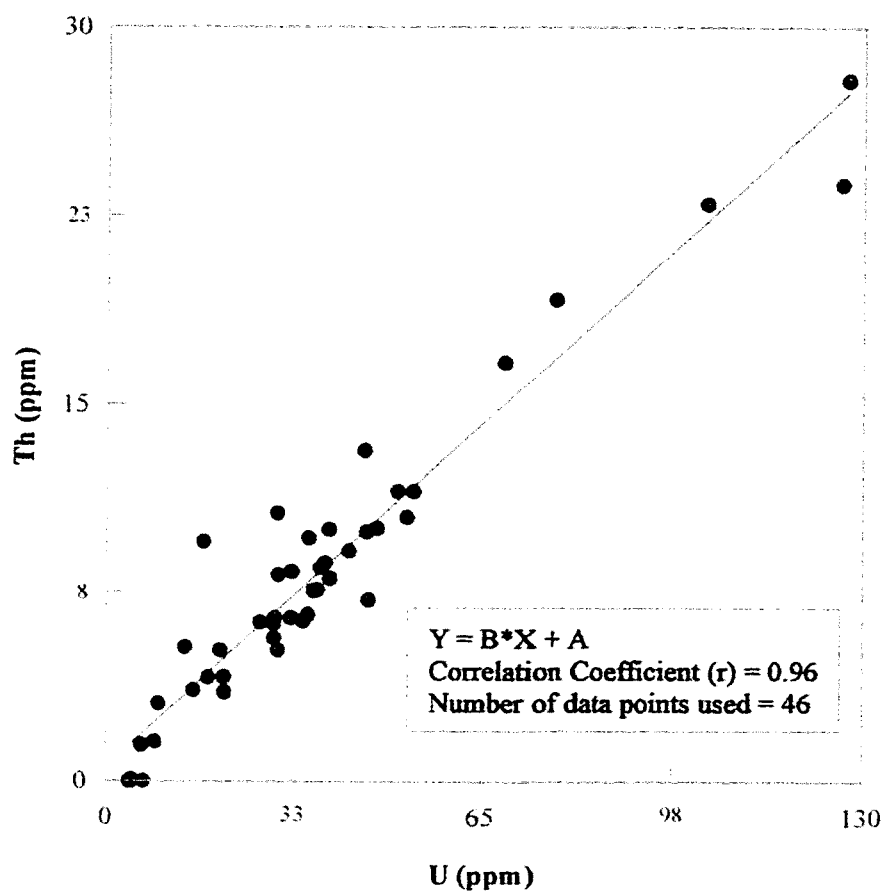


Fig. 7.49 : Relationship between U ppm & Th ppm in the Saudi Arabian Phosphorite samples tested for natural radioactivity.

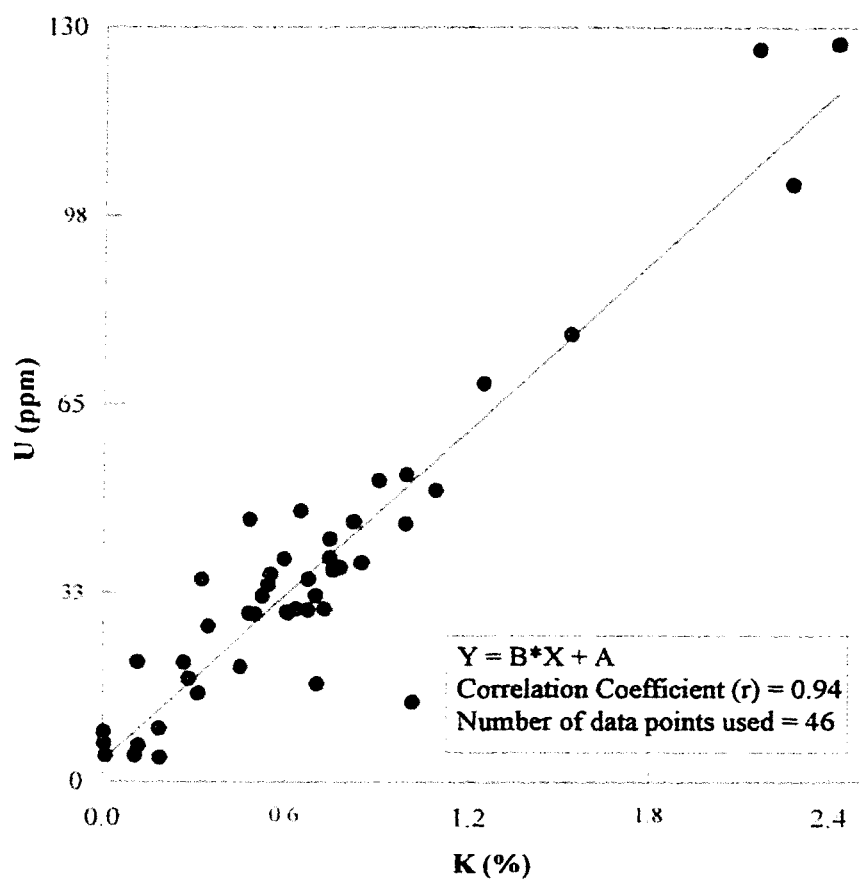


Fig. 7.50 : Relationship between U ppm & Radioactive K % in the Saudi Arabian Phosphorite samples tested for natural radioactivity.

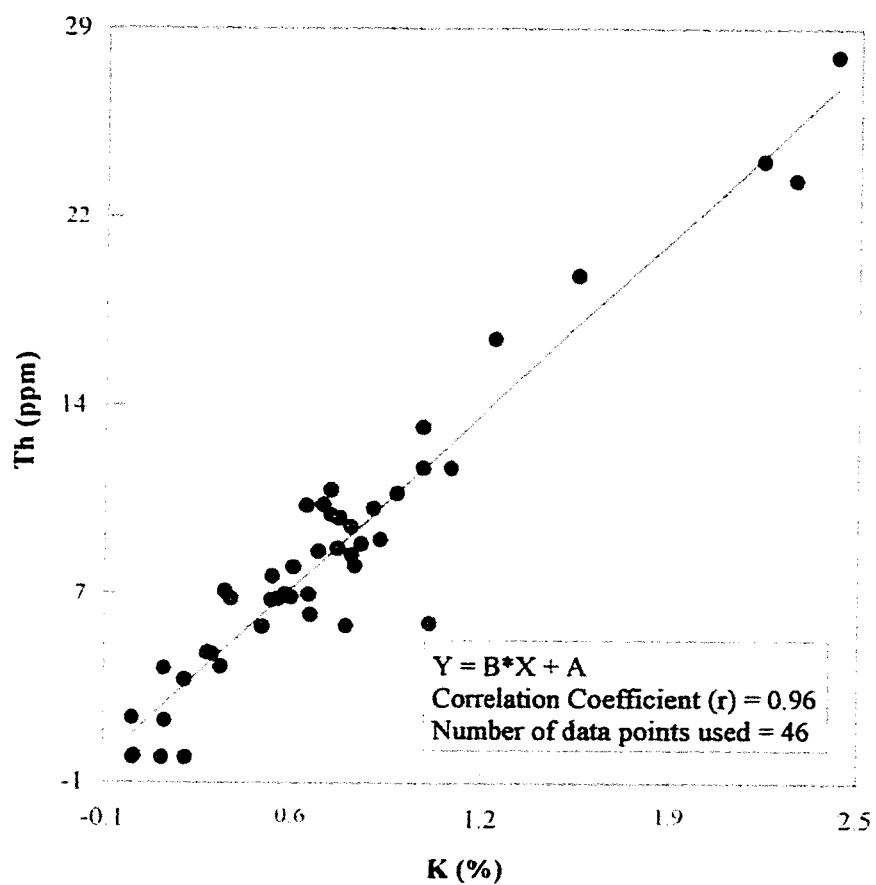


Fig. 7.51 : Relationship between Radioactive K % & Th ppm in the Saudi Arabian Phosphorite samples tested for natural radioactivity.

CHAPTER EIGHT

ORIGIN OF THE STUDIED

PHOSPHORITE DEPOSITS

Sedimentary phosphorites are known to occur on almost every continent, except the Antarctica (fig. 8.1), and range in age from the Early Proterozoic to the Holocene. Paleogeographic reconstructions (cf. Sheldon, 1964a; Cook and McElhinny, 1979) clearly show that these deposits tend to occur at low paleolatitudes with a preference for a subequatorial (10° - 20°) location rather than an equatorial (0° - 10°) site (fig. 8.2), although a number of Jurassic and possibly some Cambrian deposits formed at intermediate latitudes (30° - 50°).

Recent sedimentary phosphorites are depositing along many of the continental margins of the world as nodules, irregular masses, pellets, oolites, sands and rarely as fine-grained mud. Individual deposits may range in area from a few to hundreds of square kilometers, and hence, reserves can vary from a few million tons of ore, to several billions of tons. Both the “dilutents” (non-phosphoritic matrix and thin interbeds) and the associated sediments are also highly variable, including mudstones, cherts, limestones, dolomites, sands and sandstones.

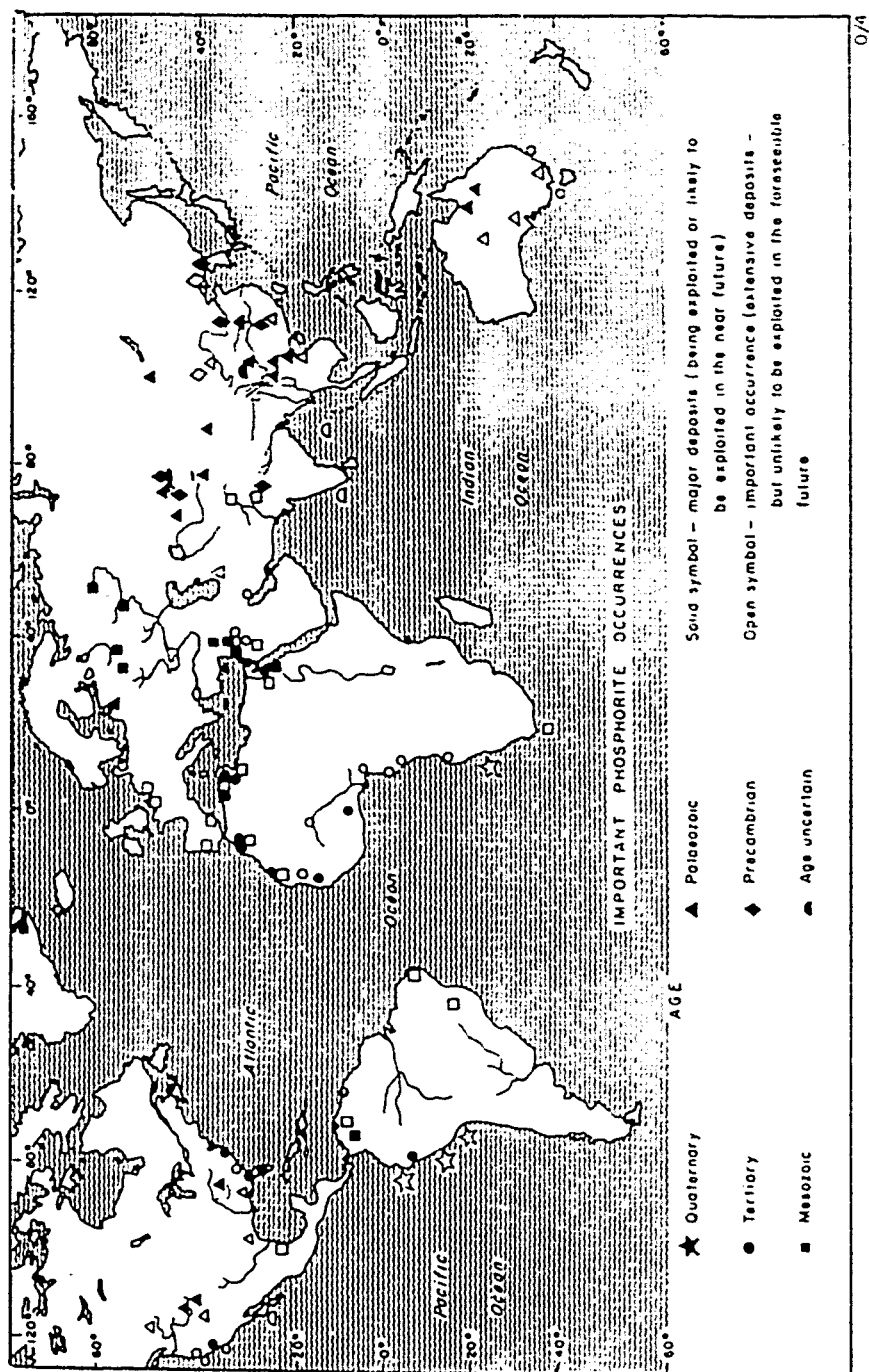


Fig. 8.1 : Distribution of major sedimentary phosphorite deposits. After, Cook, (1976), in hand book of strata bound and stratiform ore deposits (1976).

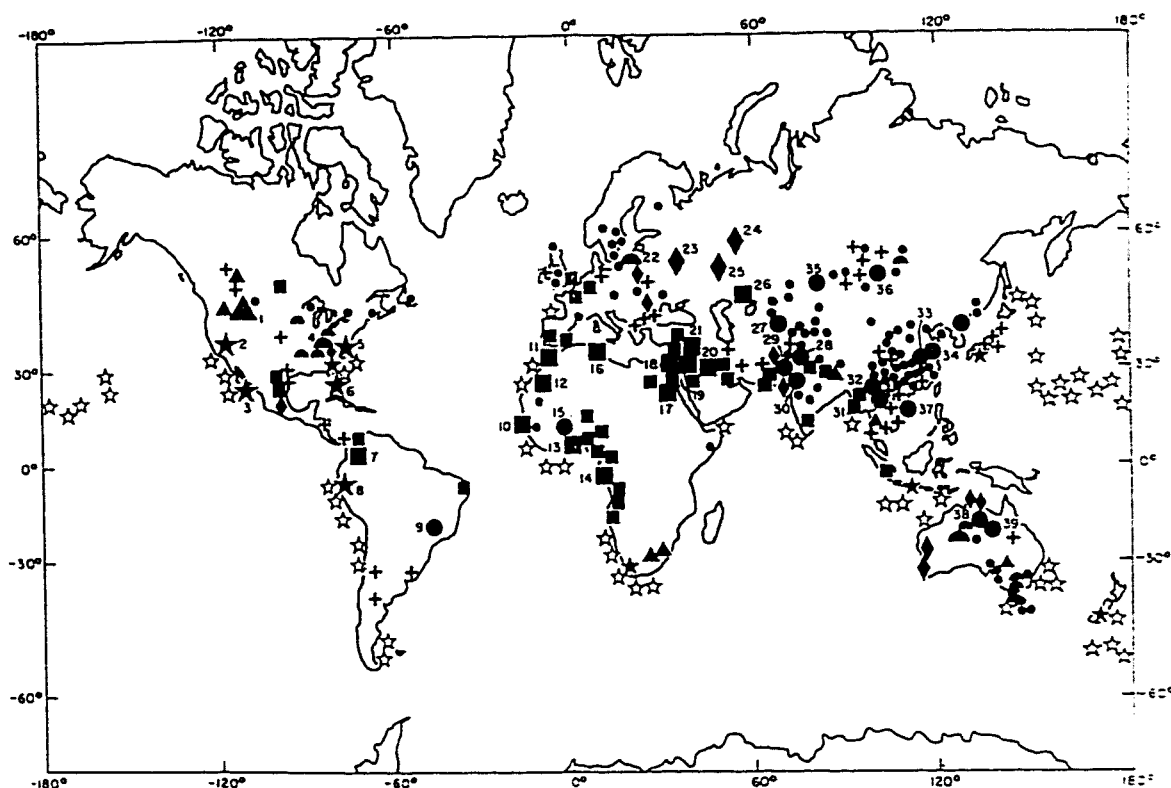


Fig.8.2: Distribution of sedimentary phosphate deposits and occurrences. Major deposits are numbered as follows: 1 Phosphoria, USA; 2 Monterey, USA; 3 Baja California, Mexico; 4 Tennessee, USA; 5 N Carolina, USA; 6 Florida, USA; 7 Cordillera, Colombia; 8 Sechura, Peru; 9 Bambui, Brazil; 10 Taiba, Senegal; 11 Khourigba etc, Morocco; 12 Bu Craa, Morocco; 13 Hahotoe, Togo; 14 Cabinda; 15 Volta and Niger; 16 Gafsa, Tunisia and Djebel Onk, Algeria; 17 Abu Tatur, Egypt; 18 Machtesh area, 19 El Hassa, Jordan; 20 Iraq; 21 Palmyra,

Syria; 22 Maadu, USSR; 23 Moscow Basin, USSR; 24 Yegorevsk, USSR; 25 Rudnichny, USSR; 26 Aktyubinsk, USSR; 27 Karatau, USSR; 28 Maldeota, India; 29 Hazara, Pakistan; 30 Rajasthan, India; 31 Laokoy, Vietnam; 32 Kunming, China; 33 Kaiyang, China; 34 Xingyang, China; 35 Abaka, USSR; 36 Hubsugul, Mongolian People's Republic; 37 Hainan, China; 38 Alexandria-Wonarah (NT), Australia; 39 Duchess etc (Qld), Australia

Phosphorites		
Minor deposits/ occurrences	Important deposits	
☆	☆	Offshore (mainly Tertiary)
★	★	Miocene - Recent
■	■	Upper Cretaceous - Eocene
◆	◆	Upper Jurassic - Lower Cretaceous
▲	▲	Permian
●	●	Ordovician
•	•	Late Proterozoic - Cambrian
+	+	Others, or age uncertain
(major deposits are numbered)		

8.1 General Factors Controlling Phosphogenesis :

The geneses of phosphorite deposits are highly complex. Many factors intervene with varying degrees in the production of these economically important deposits. The most important of these factors can be easily surveyed under the following headings :

8.1.1. The Development of Organic Life :

The development of major phosphorites at about 800-700 m.y.B.C. coincided with the first appearance of metazoans. These large-bodied organisms provided an excellent opportunity for the biochemical concentration of phosphorus in upwelling seas. An equally fundamental change occurred at about the dawn of the Cambrian period which was accompanied by massive development of phosphorites, particularly the pelletal phosphorites. This was clearly linked to the development of organisms with hard parts which did abrade to form pellets, added to organisms with phosphatic or chitinophosphatic shells such as trilobites and some inarticulate brachiopods and the fact that some shell fragments were phosphatized following burial. Some of the pellets might have been of faecal origin, but this is generally a minor component in most deposits. Throughout the remainder of the Phanerozoic, pelletal phosphorites continued to domain. Phospholipids were mentioned by Powell and others (1975) as a particular feature of the Phanerozoic phosphorites they examined, and this was taken to hint to a link between the formation of pelletal phosphorites and the gradual development of organic life on Earth. Cook and Cook (1985), pointed out that whilst the Precambrian-Cambrian boundary is the strongest evidence for a possible link between phosphogenesis and the gradual development of

organic life, similar relationships are expected around other boundaries where major biotic changes have also occurred (e.g. the Permo / Triassic or the Cretaceous / Paleogene contacts).

8.1.2. The Tectonic Setting :

Regional tectonic activity within the marine domain is critical to phosphorite sedimentation. On the one hand, severe tectonic activity cannot be conducive to the accumulation of any authigenic sediment such as phosphorites, due to the flood of terrigenous materials (including volcanic detritus), the absence of extensive shallow-water environments necessary for the formation and accumulation of extensive phosphorite deposits and the continued loss of the accumulating sediments with the continued tectonism. On the other hand, stable areas without any tectonism or only very low rates of such, are characterized by normal sequences of sedimentation of authigenic and / or fine grained terrigenous sediments. Both extremes are not conducive to the accumulation of large phosphorite deposits, and hence the optimum conditions for phosphorite deposition lies somewhere between total quiescence with its carbonate banks and tectonic belts with its big amounts of terrigenous and volcanic sediments (cf. Riggs, 1979).

8.1.3. Changes in the Sea-Level :

The concept that the formation of phosphorites is linked to changes of sea level is not new. The occurrence of phosphorites on disconformity and unconformity surfaces was noted by some of the early workers such as Mansfield (1927), who proposed that phosphoritic horizons in the Phosphoria Formation may correlate with Permian glacial

events. The phosphorite deposits occur throughout the geologic column within the transition zone between thicker and more uniform sequences of carbonate and siliciclastic or volcanoclastic sediments. Riggs (1986) mentioned that this stratigraphic succession, including the transition zone sediments, occur in concert with major changes in sea level leading into or coming out of glacial episodes. However, the major periods of phosphogenesis in both the Mesozoic and the Early Cenozoic are totally devoid of any association with glacial episodes. Indeed, Burnett (1977), was able to show that the Pleistocene phosphorites off Peru and southern Chile have radiometric ages which correspond with interglacial periods, when the oceans were warmer, sea level was higher, and there was mechanical reworking and upgrading of the phosphorites.

Riggs (1984) and Riggs and others (1985) demonstrated that a major Miocene phosphogenic episode occurred during the Miocene transgression over the Atlantic continental margin of the USA, and that phosphogenesis reached a maximum on the mid portion of the rising sea level. These authors (*op. cit.*) also showed that the duration of high stands was an important factor in providing adequate time for significant concentrations of phosphate to be deposited within the optimum environment. Vial (1987) indicated that phosphorites correlate with the maximum flooding surface, i.e. the downlap surface, and coincides with condensed sequences. A major Late Cretaceous-Early Paleogene phosphogenic episode occurred all over North Africa and the Arabian plate coinciding with high energy marine transgression.

8.1.4. Bathymetric / Topographic Control :

One of the most important variables of the phosphogenic system is the topographic (bathymetric) control which determines the basic sediment environments and its resulting geometries, the basic sediment processes, and the associated sediment system. Riggs (1979b) suggested that the appropriate regional setting of the environment of deposition is of prime importance for any significant accumulation of phosphorite. A series of structural highs with the appropriate topography, the associated shoaling environments and adjacent basins or embayments is essential for such accumulation. These must have extensive, shoaling, submarine noses or platforms off the end of the structure; where the greatest volume of phosphorite sediments accumulate. In addition, the platform has to contain significant "entrapment basins" in the form of topographic lows and / or must have a broad gentle sediment plain extending downslope, where the phosphorite sediments may accumulate. The topography may be the result of any or all of the following, regional structural deformation by folding and / or faulting, primary constructional, depositional processes during the previous period of sedimentation, subareal stream erosion, submarine erosion and scour processes, or ground water solution and collapse. Each of these mechanisms would produce a different type of topographic basin with distinctive sizes, geometries, and orientations.

Evidence of bathymetric / topographic controls on phosphorite deposition is apparent from a number of deposits particularly those of the Middle East and North Africa. Bentor (1953) showed that the Late Campanian phosphorites of Palestine are found almost exclusively in the synclinal axes of folds, which started to develop in the Turonian but

which continued to grow during Campanian sedimentation, exerting a profound influence on the distribution of phosphorites. Youssef (1965) also believed that phosphorites of Egypt and Palestine are associated with synclines that were formed on the sea floor during sedimentation, whereas adjacent anticlines are generally barren. He also believed that, the broadly lenticular nature of most of the phosphorite “beds” may be due to the partial filling of the synclines and attendant elimination of conditions favorable to the formation of phosphorite.

Wilcox (1953) related the Santonian-Early Campanian phosphatic chalk occurrences of England to synclinal troughs. Jarvis (1980a) reinterpreted these structures as elongated erosional troughs (‘cuvettes’) which exerted a major influence on the genesis and distribution of phosphorites in southern England and throughout northern France. Similarly, Russell and Trueman (1971) studied the Duchess phosphorite deposits of northern Australia and showed that its bathymetry, lithofacies and isochemical data reveal a close control of sedimentation by basinal topography. Bioclastic phosphoritic carbonates were developed on the most elevated basement highs, the chert and phosphorite beds developed on the flanks and over weaker positive basement features and the fetid micritic phosphoritic carbonates were formed in the deeper troughs. Sedimentation was, therefore, similar to that of the Mishash Formation of Palestine where active fold structures controlled the type of sediment deposited.

Riggs (1979b) reported that the Sanford highs in Florida determined (1) the locations of associated coastal environments, shelf platforms and deeper depositional basins; (2) loci, type, and abundance of phosphorite formation and accumulation; and (3) types and abundance of associated sediments. He (*op. cit.*) also believed that primary

phosphorite formed in both shallow-water environments on and around the paleotopographic highs and within deeper depositional basins, and that the type of phosphorite and associated sediments were controlled by specific environments of formation.

8.1.5. The Phosphorite Assemblages :

Many phosphorites exhibit partly rhythmical laminations and cyclical arrangements on every scale from thin-section to outcrops, and to understand the origin of these phosphorites fully, the entire assemblage of associated authigenic and diagenic minerals must also be considered.

Most of the older phosphorite deposits show pronounced lamination on a time scale of probably a few years to a few hundred years with thin laminae of phosphorites alternating with others of shale, mudstone, carbonate or chert. Bentor (1980) considered these alternations to result from local changes, such as the shifting of river mouths or of morphological features on the shallow sea-bottom, slight changes in the direction and strength of currents, small scale temperature oscillations, variations in the amount of rainfall on the nearby land and a variety of similar causes. The perfect preservation of the laminae in these organic-rich sediments might be a proof that phosphorite deposition took place in an anoxic environment.

Many phosphorite deposits are associated with chert, particularly those alternating with shale or carbonate layers. The association phosphorite-chert is by itself not surprising; as both are essentially biogenic sediments formed in zones of high productivity, but what is not clear are the causes of their cyclical deposition.

One explanation of this cyclicity is segregation after simultaneous deposition of phosphoritic and siliceous sediments. However, Bendor (1980) mentioned that chert units poor in phosphorus alternating with phosphorite units poor in silica, each meters or tens of meters thick, cannot be explained by such a mechanism.

Another explanation is that this cyclicity reflects rhythmic, eustatic or tectonic, changes in water depth at the site of deposition. All recent phosphorites form at shallow depth; the maximum for the Peru-Chile off-coast is 400 m, but most are shallower, and the same seems to be the case for older phosphorites. During deposition in shallow water, both P_2O_5 and SiO_2 are simultaneously precipitated with much higher percentages of SiO_2 than P_2O_5 , but later diagenetic evolutions can lead to a notable increase in P_2O_5 accompanied by a drastic decrease in the amount of SiO_2 .

Baturin (1971) for example, distinguishes four stages in the diagenetic evolution of phosphorites off Namibia, from the originally barely phosphatic diatomaceous ooze to hard phosphorite nodules. During this evolution the P_2O_5 -content increases from 5.10 % to 32.74 % whereas the SiO_2 -content decrease from 49.18 % to 0.15 %. A similar, but less drastic, change was reported by the same author for the recent phosphorite deposits off Chile. Under these circumstances, a silica- poor phosphorite is being formed. The elimination of amorphous silica from the sediment is not surprising, as it has been calculated that only 2 % of all the opaline silica formed in the ocean is finally incorporated into sedimentary rocks (cf. Heath, 1974). The preservation of silica in sediments is a function of the rate of deposition. Off Namibia the rate is low and silica is therefore almost quantitatively dissolved.

Assuming now that water depth increases and with it the path of P-bearing organic matter formed near the ocean surface and settling at the ocean floor. Phosphorous is readily released from decaying organic matter, but because the distance to the ocean floor is too large, little or no organic phosphorous will reach the bottom. However, the more vigorous of the opaline tests can sink to much greater depth without being dissolved. Under favorable circumstances a siliceous ooze is then deposited to be later transformed into porcellanite or chert.

Also this cyclicity might reflect rhythmic changes in the pH value at the site of deposition, favoring the deposition, at a time, of one over the other.

Again, the association between phosphorites and evaporites is most striking. Such association can be considered as a direct one through a dynamic sea water system with landward movement into an evaporative basin with phosphorite being deposited as a result of the interaction of phosphorus-rich continental brines and cold ocean waters (cf. Hite, 1976). The process of upwelling and the associated presence of cold, nearshore waters were considered to be responsible for the aridity of the hinterland and the development of coastal deserts (cf. Brongersma-Sanders, 1969). Consequently, the association of phosphogenesis with periods of global aridity, and hence, with evaporite deposition can be understood. A notable example of this correlation includes, the very extensive Cambrian salt deposits and the Permian evaporites and the vast phosphorite deposits of the two periods. However, Cook and Michael (1979) relate these correlations to plate tectonics without the need to invoke periods of global aridity. These authors (*op. cit.*) mentioned that evaporite deposition results from two processes : the movement of the area into a

low-latitude location, and the initiation of rifting, forming a salt basin which is partly connected to the open ocean. Consequently, they (*op. cit.*) concluded that whether the phosphorite is synchronous with the evaporite phase (e.g. the Phosphoria Formation), immediately follows it (e.g. the Cambrian phosphorites), or succeeds many million of years later (e.g. the Late Cretaceous-Eocene phosphorites), its deposition is dependent primarily on plate movements and the rate of sea-floor spreading.

Another important relation is between the deposition of both phosphorites and iron ores. Bushinski (1966) takes the view that “phosphorites and ironstones are antagonistic.” due to the fact that 90 % or more of the total iron ore deposits occur in Proterozoic rocks (pre-800-750 m.y.B.C.), while 90 % or more of the total phosphorite deposits occur in the latest Proterozoic and Phanerozoic (post-800-750 m.y.B.C.). Despite this, Pettijohn (1957) suggests that “the environments of phosphorites and ironstone have many factors in common.” A number of phosphorites are apparently associated with iron ores (such as the Tunisian phosphorites which are overlain by oolitic ironstones), but most phosphorites are relatively low in iron. On the East Pacific Rise, phosphorus is “scavenged” by iron oxides and apatite does not normally form as a separate mineral phase (cf. Berner, 1973). The same reasoning was used to explain the notable absence of phosphorite deposits up to the latest Proterozoic. However, the presence of some economic phosphorite deposits, and of apatite-rich bands in some banded iron formations indicates that for a limited period at least, a high P / Fe ratio prevailed in places which enabled phosphorus to form a separate mineral phase. It was not until later in the Proterozoic that the development of a more prolific (eucaryotic) fauna resulted in larger quantities of phosphorus being tied in the

biota. This, coupled with a decrease in the iron content of the deep upwelling ocean water, resulted in the association with iron becoming minimized to the extent that phosphorus was sufficiently concentrated in some sediments to form as separate deposits.

Other important associations with phosphorites include, organic matter, carbonate sediments, tillites, magnesium-rich clay minerals including montmorillonite, palygorskite and sepiolite, volcanic materials, etc. The nature of such associations will be discussed in the coming pages.

8.1.6. *Uniformitarianism :*

When recent phosphorite deposition was discovered and its environment of formation studied, hopes were raised that such information can be used for the interpretation of the genesis of the older phosphorite deposits. However, such hopes have largely been disappointed for a number of reasons expressed by Bendor (1980) as follows:

- a. There are marked differences in texture between recent and ancient phosphorites. The former occur, generally, as hard irregular bodies (“nodules”) centimeters to decimeters across, generally with a fine concentric layering, or as soft structureless masses. Pre-Miocene phosphorites have variable textures (cf. Cayeux, 1939, Trueman, 1971), but hard nodules are rarely, if ever, found in them. The vast majority of them consists of pellets (small, structureless, spherical, elliptical or irregular apatitic bodies) generally less than one millimeter across, set in a calcareous, clayey, sandy or fine grained matrix. Such pellets are generally rare in recent phosphorites,

- b. There is a difference in mineral paragenesis. Recent and Miocene phosphorites on the sea floor generally show coating or interlayers of Mn-oxide (cf. Manheim and others, 1980) and are very frequently associated with glauconite. Both features are rare in older phosphorites,
- c. There is a difference in the lithological association, recent phosphorites are not accompanied by carbonates, older one frequently are,
- d. Older phosphorites formed mostly in areas of slow deposition and represent condensed sections (cf. Jarvis, 1980), while areas of recent phosphorite deposition are distinguished by higher rates of sedimentation,
- e. Modern phosphorites form at the continental shelf or upper continental slope, and those off Namibia under stable tectonic conditions; while ancient phosphorites show a much larger variety of environmental setting, including deposition in epicontinental seas, sometimes at greater distance from the coasts (cf. Jarvis, *op. cit.*) and are frequently syn - or - post-tectonic,
- f. There are many other indications that the two types of phosphorites formed by different mechanisms. Recent ones seem to form exclusively by diagenetic processes below the sediment-water interface, while many older phosphorites (especially those with the finely laminated character) were more likely formed on the sea floor. This conclusion is strengthened by the frequent occurrence, in older phosphorites of beds made up almost exclusively of apatitic oolites, which must be considered to have formed floating above the water-sediment interface (e.g. the Phosphoria and the Karatau deposits).

The differences outlined above do not apply to all ancient phosphorites, as, some Cambrian deposits (e.g. in India) have textures similar to those of the recent phosphorites and might have formed under similar conditions. To overcome this controversy, the following points have been suggested (cf. Bentor, 1980) :

- a. There were periods in the geological past more favorable for phosphorite formation than the present one, during which phosphorites accumulated at a much vaster scale,
- b. The mechanisms of apatite precipitation at present might also have been operative periodically in the past, but additional mechanisms, not realized at the present time, seem to have been important.

As far as phosphorite genesis is concerned, a simplistic actualism does not work. Phosphorite deposition in the past probably took place in a number of ways, only one of which is operative at the present time.

8.2 Hypotheses on the Origin of Phosphorite Deposits :

The earliest record of phosphorite rocks appear to have been of the occurrences in the Estremadura region of eastern Portugal, described by Bowles (1782) as “ a vein of phosphoric stone”. Since then, the origin of phosphorite deposits has been a matter of much speculation, and hence different hypotheses have been proposed to explain their genesis (Biogenic, Biochemogenic, Chemogenic, Diagenic and Volcanogenic hypotheses).

8.2.1 The Biogenic Origin Hypothesis :

Buckland (1829) published the first detailed study of phosphorus-rich sedimentary rocks, considering them to be of coprolithic origin. Austen (1848) considered the phosphorite to be of organic origin, but argued against a direct coprolithic origin for most of the nodules in nodular phosphorites, suggesting that many of them had formed diagenetically, in analogy with chert nodules (a hypothesis supported by de la Beche, 1849).

Davies (1875), Hicks (1875) and Hudleston (1875), ascribed an organic origin to the Cambrian phosphorites of Canada and concluded that, the phosphorus was driven directly from shells, particularly trilobite carapaces.

From the abundance of organic remains in phosphorites, Murray and Renard (1891) concluded that such deposits are biogenic precipitates (a hypothesis supported by Mansfield, 1918). These authors (*op. cit.*) also observed that phosphatic nodules are apparently more abundant along coasts where great and rapid changes of temperature, arise from the meeting of cold and warm water currents. Such changes cause the mass mortality of fauna and hence provide the source of phosphorus which is redistributed and concentrated in the sediments as concretions and layers of phosphorite. However, phosphorite formation in the ocean was found to be mainly controlled by the seasonal dying of planktons (a fairly universal factor) rather than by the episodic mortality of fauna which is of local significance. Moreover, this hypothesis incorrectly interpreted the initial supply of phosphorus by currents (instead of upwelling) and the final diagenesis (without subsequent reworking) to be the basic processes of phosphatization.

McConnell (1965) believes that “organisms of various kinds are quite important in the precipitation of carbonate fluorapatite from sea water, particularly in view of the fact that certain bacteria appear to be capable of initiating similar types of precipitation.” He found that a common enzyme (carbonic anhydrase) plays an important role in the precipitation of carbonate hydroxyapatite in the oral cavity; he also reported that the same enzyme has a high activity in the mantle tissue of the phosphatic brachiopod *Lingula*.

Indeed, as phosphorus plays an essential role in the bodies of living organisms, such organisms must play a vital role in the distribution and deposition of inorganic phosphorus in the marine environment.

The role of vertebrates is fairly obvious since almost their entire skeletal structure is composed of carbonate hydroxyapatite commonly known as the biological apatite (cf. McConnell, 1973). Upon death, the nektonic marine vertebrates may contribute up to 15 percent of the phosphorite grains as teeth, bones, bone fragments and fish scales. These organisms have concentrated the phosphorus many folds from the sea waters, but their role is rarely considered to be of volumetric importance.

The role of the invertebrates is much more diverse as can be seen from the following observations (cf. Riggs, 1979) :

- a. Some living and fossil inarticulate brachiopods build their shells out of carbonate fluorapatite,
- b. Crustaceans generally have a carapace with a very high phosphorus content of 15 to 50 percent $\text{Ca}_3\text{P}_2\text{O}_8$ (cf. Clark and Wheeler, 1922),
- c. Many invertebrates have the capability of forming silt-and sand-sized phosphate concretions in their kidneys and urinary tracts, particularly under conditions of

chemical stress, which may play an important role in the production of the pelletal phosphorites (cf. McConnel & Ward, 1978; Doyle & others, 1978; Glenister & others, 1976, 1978; etc.),

- d. Some tectibranch gastropods have phosphatic hydrogel gizzard plates which contain up to 12 percent P_2O_5 (cf. Lowenstam, 1963),
- e. The low species diversity and the high population of crustaceans, polychaete worms, and other vagrant and benthic fauna in most phosphorite deposits must have played an integral part in the production of pelletal phosphorite,
- f. Empty invertebrate shells in the medium of phosphorite deposition are usually infilled with phosphorite mud, producing the very abundant internal and external molds which occur as intraclasts within phosphorite beds,
- g. Some micro and macroscopic calcareous shell materials are usually replaced by phosphorite minerals when the surrounding chemical conditions are appropriate.

Whether active or passive, the role of microorganisms in apatite precipitation is still under discussion and whether the microbial structures observed in some phosphorites are the cause or the result of the phosphogenic process is still a matter of debate.

Rizzo and others (1962) and Ennever (1963), found that bacterial cells will readily mineralize with carbonate hydroxyapatite under proper biological conditions.

Lear (1966) found that marine bacteria can regenerate inorganic phosphorus from organophosphorus compounds in zooplankton, phytoplankton, and fish meal.

Hodson (1973) concluded that microorganisms are responsible for the following critical transformations of phosphorus : altering the solubility of inorganic compounds of phosphorus; mineralizing organic compounds with the release of orthophosphates;

converting the inorganic available anion into cell protoplasm, an immobilization process analogous to nitrogen fixation, and bringing about an oxidation or reduction of inorganic phosphorus compounds. Particularly important to the phosphorus cycle in nature are the microbial mineralization and immobilization reactions. Since bacteria-like rods have been found to be major fossil components of many varieties of phosphorite grains, it is logical to assume that they have played some role in the formation of phosphorite deposits.

Cook (1976) reported that phytoplankton can concentrate phosphorus to a very high degree, but incorporation of phytoplankton in sediments would produce nothing more than a slightly phosphoritic organic-rich sediment, and therefore decay and other forms of post-depositional modification are required before a phosphorite can result.

Burnett (1977) found that opaline diatom frustles were commonly covered with apatite. The author (*op. cit.*) considered it conceivable, but unlikely, that the frustles and other "small undetected fragments of calcite served as 'seeds' for epitaxial growth of apatite."

Riggs (1979) was among the first to interpret the globular microstructures in the Florida phosphorites as coccoidal type bacteria. The structures were found attached to phosphorite grains and in cavities.

O'Brine and others (1981) described similar microstructures in Holocene to Pliocene phosphorites from the east Australian continental shelf. These authors (*op. cit.*) found bacterial structures occurring as isolated coccoidal cells scattered in the matrix or attached to phosphorite grains, fossil shells, and glauconites.

Soudry and Lewy (1988) proposed a microbial mat model for the genesis of certain nodular phosphorite horizons in the Negev, southern Palestine, and suggested that the

Palestinian phosphorites were formed through the reworking of microbial mats deposited in sabkhas of the Late Cretaceous age. However, as the bacterial structures are present solely in the binding material around the phosphorite grains or in cavities, it could have been produced during weathering, in association with percolating ground water which reactivated microbial processes in the sediments. The structures were formed, therefore, very late in the history of these rocks, and were not a result of a primary mat-forming process.

Abed and Fakhouri (1990), examined samples representing granular and laminated phosphorites from the Late Cretaceous deposits of Jordan, by SEM for microbial structures. They identified two kinds of structures : globular clusters and sheaths and empty cylindrical and / or spherical sheaths. Globular structures and sheaths, postulated to have been formed by bacterial activity or possibly as inorganic precipitates, have been found only within cavities and in the cementing phosphoritic material around phosphorite grains of the granular phosphorites. These structures were interpreted to have originated in association with the percolation of ground-water late in the history of the sediments, rather than as a consequence of primary grain- forming processes. Organic-rich phosphorite grains were believed to have acted as a food source for the bacteria and were, therefore, the cause of the microbial structures and not the result of them. On the other hand, empty cylindrical and / or spherical sheaths, interpreted to be of primary, cyanobacterial (blue-green algae) origin, were readily observed in the laminated phosphorites. These phosphorites were interpreted to have been deposited as algal mats in shallow, subtidal to intertidal environments.

Lamboy (1990), carried out petrographic study on the Late Cretaceous phosphatic chalks of northern France and reported that phosphorites occur predominantly as mineralized microbial remains and are localized in two kinds of structures which are interpreted as having microbial origins :

- a. Laminae within phosphatic crusts and forming the cortices of coated grains;
- b. Individual ovoid bacteria and small microbial colonies having botryoidal surfaces and radial fibrous internal structures. These are observed in phosphatized chalks, chambers of foraminiferans and bryozoans, fragments of echinoderm tests, and coprolithes and fecal pellets.

The microbial community which formed the crusts and grain coatings were believed to be developed by surface accretion, whereas the other community grew solely in the intergranular porosity of grains and in the extragranular porosity of semilithified sediments. Finally, Lamboy (*op. cit.*) reported that “ Comparison with other phosphorites indicates that the microbial structures observed in phosphatic chalks may also be identified in other deposits. It is concluded that microbial activity exerts a major control on phosphogenesis in many phosphorites.” This idea is supported by many other authors, e.g., Krajewski (1981 a, b, 1983, 1984); Delamette (1988); Föllmi, (1990), etc.

8.2.2 The Biochemogenic Origin Hypothesis :

Cayeux (1936) considered phosphorites to be a biochemical product formed, for instance by the action of microorganisms.

Youssef (1965) proposed a biochemical mode of formation controlled by sea floor configuration for bedded deposits of marine phosphorites. Due to him, decaying organisms

on the bottom of depressions of an otherwise open sea produce ammonium phosphate and ammonia. Nitration bacteria oxidize ammonia into nitrates that act as fertilizers for the phytoplanktons on which other nektons and planktons flourish. On death, the biota fall to the bottom of the sea-floor depressions, where the amounts of soluble phosphorus increase in due course beyond the needs of the animals and plants living above. The sheltered depressions preserve the solutions from dissipation in the open sea. The ammonium phosphate reacts with Ca ions or with precipitating CaCO_3 to give calcium phosphate. The common occurrence of bituminous material and pyrite in phosphorites and the common association of phosphorites and black shales indicate anaerobic conditions (negative Eh) in an environment with restricted circulation. Restriction of circulation is a necessary requirement for the concentration rather than for the deposition of phosphorites. The relatively concentrated solutions of phosphates would react with the CaCO_3 precipitating in the medium, or with any Ca ion in solution, to produce the practically insoluble $\text{Ca}_3(\text{PO}_4)_2$. The phosphatized shells present in phosphorites and the phosphatization of the contact between phosphorites and the underlying beds indicate that phosphates were present in a soluble form for a period of time long enough to permit replacement. Restriction of circulation may be effected locally on the bottom of the open sea by the development of series of anticlines and synclines on the sea floor during deposition of the phosphorite - bearing formations. Other forms of depressions on the bottom could provide similar conditions, and all types of depressions would be sheltered from most currents and waves if the sea were deep enough. The broadly lenticular nature of most of the phosphorite "beds" may be due to the partial filling of the synclines and attendant

elimination of conditions favorable to the phosphorite formation. Doubly plunging synclines would explain variations in thickness both along and across the strike.

Youssef (*op. cit.*), believed that the ultimate source of the phosphorus ion is the land, and that phosphorites are common in areas whose climates were warm at the time of their formation. Warm climates promote the exuberance of life, a prerequisite to the concentration of soluble phosphates. The author (*op. cit.*) also concluded that phosphorites were deposited in a medium with pH around 7.8 (the limestone fence), however, Blackwelder (1916) favored low pH (7-7.5) and restricted basins for phosphorite precipitation, a hypothesis supported by Krumbein and Garrels (1952). The latter authors (*op. cit.*) though inclined to place the phosphorite environment at pH values between 7 and 7.8, state that “the exact position of the environment is somewhat equivocal.”

Senin (1970), studied the recent phosphorite deposits of off Southwest Africa and concluded that these deposits are of biochemical origin because of “...the high biological productivity of this region, the extraordinarily high concentrations (of organic carbon) for bottom sediments, the significant coprolite content and the high concentrations of P in certain biogenic sediments.” Southwest Africa is an area of well developed upwelling, and in upwelling areas, phytoplanktons are likely to be an important biochemical agent. However, Berger (1911) considered the possibility of bacteria as the agent and McConnell (1965) suggested that enzymes may play an important role.

8.2.3 The Chemogenic Origin Hypothesis :

Kazakov (1937) proposed that phosphorites formed as a result of direct inorganic precipitation of apatite, from ascending phosphorus-rich deep ocean waters. A decrease in the partial pressure of CO₂, accompanied by an increase in pH and temperature, and a consequent decrease in phosphate solubility, were suggested as the mechanisms of precipitation. This chemical sedimentation of phosphorites was described by Kazakov (*op. cit.*) to take place in the upper and middle portions of the shelf (i.e. at a depth of about 50 - 200 m) where calcite precipitates first and then apatite. Such precipitation does not said to take place within the photosynthetic zone, where any available phosphorus would be taken up by the abundant phytoplanktons.

In a partial agreement with Kazakov, Gulbrandsen and Roberson (1973) show that the lowest concentrations of phosphorus in marine waters are at the surface and these rapidly increase to a maximum at a depth of about 1000 m with only a small and variable decrease with continued increasing in depth. Such distribution was explained by these authors (*op. cit.*) as follows : “The thin surface layer is where photosynthesis takes place and is the zone of phosphorus consumption. Below this zone is the zone of rapid phosphorus regeneration where the phosphorus maximum is attained; it is where phosphorus is returned to solution upon the dissolution and oxidation of organic excrement and dead organisms. The deep zone receives regenerated phosphorus from the organic matter that passes through the zone of phosphorus maximum and constitutes a large reservoir of phosphorus that is brought to the surface for reuse in the life cycle by the major mixing processes of the oceans.”

Kazakov's "upwelling hypothesis" provided an elegant integrated theory which explained many of the features of phosphorites, notably the regular facies distributions associated with many phosphorites, and particularly the distribution of carbonates in relation to phosphorite deposits. Most modern theories of phosphorite formation are modifications of Kazakov's model of direct inorganic precipitation of marine apatite from sea water, although some authors reject it completely.

After studying the Phosphoria Formation, Mckelvey and others (1953) stated that the facies changes and composition of these deposits reflect marine deposition of phosphorites controlled primarily by depth, temperature, pH and CO₂ content of the water, much as previously indicated by Kazakov (1937). These authors (*op. cit.*) however differed in that calcite does not precipitate before apatite but after and that phosphorites form at depths of 200 - 1000 m (not at 50 - 200 m as previously proposed by Kazakov). Their main argument is that phosphorites generally include organic matter that would have been oxidized at depths shallower than 200 m, and that Phosphorites on the present sea bottom at various localities over the world are found at depths of 400 - 1000 m or more.

Mckelvey and others (1959) showed that the mechanism of upwelling is more than adequate to produce the very considerable phosphate in phosphorites.

Sheldon (1964a) mentioned that virtually all important phosphorites were deposited within 40° north or south of the paleoequator and within this longitudinal range most cold currents are associated with coastal upwelling. Coastal upwelling may occur in response to seaward-moving surface water (divergent upwelling) or the movement of a current over a topographic high (dynamic upwelling). Such upwellings generally occur on

the western continental coasts, as well as on the north coasts in the northern hemisphere and the south coasts in the southern hemisphere.

Freas and Eckstrom (1968) summarized the conditions conducive to upwelling as follows :

- a. " In situations where ocean currents flow parallel or offshore and are enhanced by strong prevailing winds blowing in the same direction,
- b. In situations where ocean currents flow up onto a positive submarine topographic feature,
- c. In the belts of trade winds at low latitudes between 0° and 25° ,
- d. Along the north and west coasts in the northern hemisphere, and the south and west coasts in the southern hemisphere at latitudes between 0° and 25° ,
- e. Along coasts of land masses with dry climates,
- f. Along the coasts in the belt of westerlies approximately between 20° and 40° ,
- g. In large ocean basins with unrestricted circulations and open connection to polar seas."

As a result of one or more of these conditions cold deep water, rich in phosphorus and other nutrients, is brought to the surface. There is strong evidence particularly from the sedimentary facies distribution pattern to suggest that phosphorites of the west coast type such as those of the Phosphoria Formation and the Lesser Karatau are associated with large-scale divergent upwelling. Other deposits such as those of Florida and some of the Middle East deposits are clearly associated with topographic highs which are likely to have produced dynamic upwelling (cf. Cook, 1976).

Indeed, there are reasonable grounds for regarding upwelling as being the major source of phosphorus for many deposits. The greatest difficulty in applying the upwelling hypothesis is for deposits which are obviously of very shallow water origin with a maximum water depth of a few tens of meters. Some of these deposits may owe their origin primarily to a fluvial or estuarine source, but these deposits are likely to be of comparatively small areal extent. Small-scale, dynamic upwelling can occur in very shallow depths provided the current is sufficiently strong, though it is likely to be a very much less potent source of nutrient than deep upwelling currents. Entrainment of bottom waters by seaward-flowing surface waters in estuaries can induce localized upwelling and this mechanism could possibly also act as a further source of phosphorus in very shallow seas. Phosphorus-rich water upwelling on the edge of the shelf can be swept across that shelf and hence can be an additional process by which nutrient-abundant conditions can prevail in shallow water (cf. Cook, 1976).

Attempts to relate the distribution of marine phosphorites to ocean circulation and, in particular to coastal and oceanic upwelling, have been made by Brongersma-Sanders (1957), Sheldon (1964a), Mckelvey (1967), and Baturin (1971a, b). Mckelvey (1967) for example, drew attention to the fundamental differences between phosphorite deposits forming in different oceanographic environments. Using an idealized ocean model (fig. 8.3) Mckelvey (*op. cit.*) argued that phosphorite forming in an area of coastal upwelling with divergence in the eastern boundary currents are typically, associated with cherts and black shales, while phosphorites forming in the warmer waters of the western boundary

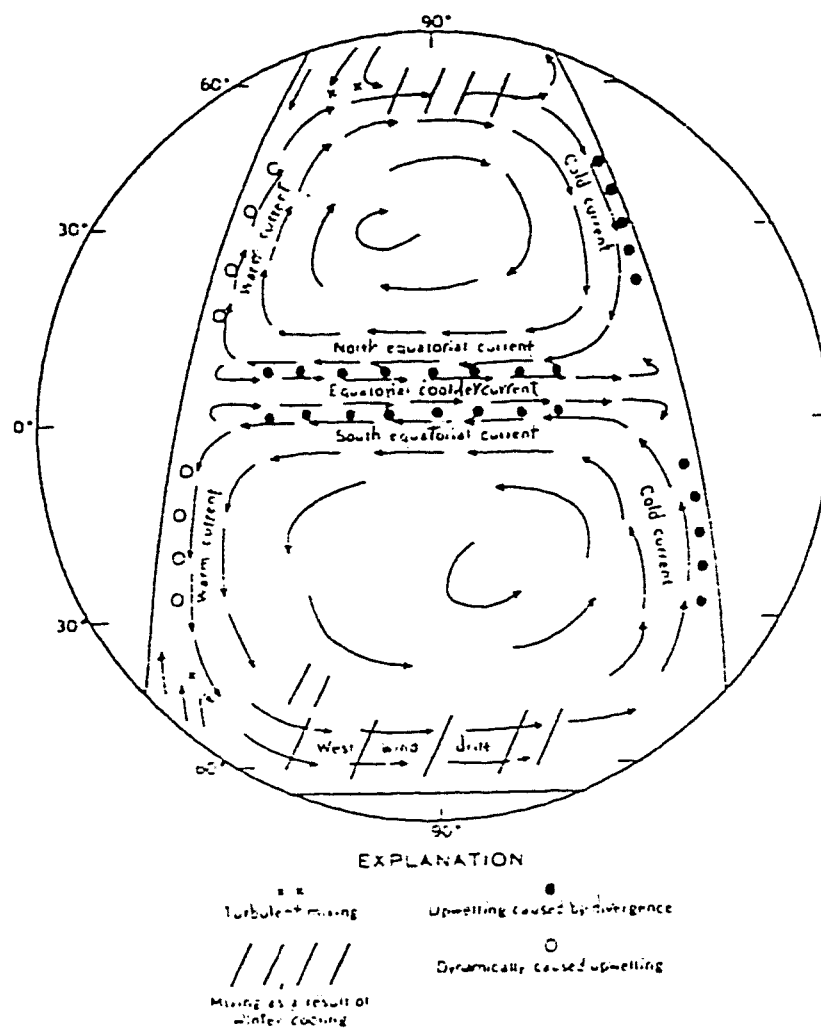


Fig. 8.3 : Surface currents in an idealized ocean, showing areas of ascending nutrient water. After, Mckelevy (1967).

currents consist of phosphatic limestones and sandstones. The latter, normally, are less extensive and are generally of lower grade, unless subsequently enriched by reworking and / or chemical weathering.

Baturin and others (1972), reported the occurrence of soft phosphatic nodules in organic rich diatomaceous oozes, currently accumulating on the continental margins of a number of countries such as Southwest Africa, Peru, Chile and Namibia. Continental margins have long been known to be classic examples of wind-induced coastal upwelling regions, with intense biological productivity in surface waters. Below the sediment water interface, these authors (*op. cit.*) reported that precipitation of (and probably replacement by) apatite is currently taking place. Initially the apatite is in the form of soft pellets and nodules of gel-like calcium phosphate, incorporating phosphatic particles. As lithification proceeds, a further increase in the phosphorus content of the pellets and nodules takes place. Further upgrading occurs as a result of mechanical reworking of these sediments. The occurrence of phosphatic nodules in varying degrees of lithification in the same ooze samples was taken by these authors (*op. cit.*) to indicate that their formation proceeds relatively fast in a highly reducing environment, and to support their convection that the origin of phosphorite is connected with upwelling waters as previously suggested by Kazakov (1937). Nevertheless, apatite most probably forms exclusively within the pore waters of the sediments, not in the overlying waters as previously suggested by Kazakov (*op. cit.*).

Veeh and others (1973, 1974), Burnett (1977), Burnett and others (1980) confirmed the occurrence of modern phosphorite nodules along a number of continental margins and reported the same mode of formation with minor modifications. In his study

of the geochemistry and origin of phosphorite deposits from off Peru and Chile, Burnett (1977) concluded that apatite forms authigenically as a direct chemical precipitate from its solutions (rather than by replacement of previously existing materials) within the pore waters of sediments and not in the overlying waters as previously suggested by Kazakov (1937). His conclusions were based on the following considerations :

- a. the phosphorus concentration in the pore waters may be several times greater than in the overlying waters,
- b. there is no reasonable mechanism to raise the Ca / Mg ratio in sea water to the point where apatite may precipitate, but diagenetic reactions could significantly deplete anoxic pore waters of Mg^{+2} ,
- c. surfaces for apatite nucleation are more readily available within the sediments than within the bottom waters.

Burnett (*op. cit.*) also pointed out that the conditions necessary for apatite precipitation from sea water are essentially the same for calcium carbonate precipitation (cf. Gulbrandsen, 1969). The ascension of cold CO₂-enriched waters into a warmer, shallow sea, with the subsequent loss of CO₂ and the rise in pH, would favor the precipitation of both calcium carbonate and apatite. Since the dissolved carbonates in sea water are several orders of magnitude higher than the phosphates, a coprecipitation of apatite and calcite would surely result in the apatite being completely overwhelmed by the calcium carbonate. In order to precipitate large quantities of apatite with only negligible amounts of calcite, it is necessary that the dissolved phosphorus content be raised high enough so that the calcium ion is being controlled by apatite rather than by carbonate equilibria. Burnett (*op. cit.*) concluded that, a more realistic model would require apatite to

precipitate from pore waters of anoxic sediments rather than from the overlying ocean waters. The concentration of the initially precipitated apatite into indurated phosphorite rocks is probably brought about by physical processes, such as winnowing and reworking. These processes could possibly occur in response to changes in the sedimentary environment, such as those brought about by tectonic activity or eustatic changes in sea level.

This hypothesis is supported experimentally by the works of both Bachra and others (1965) and Martens and Harriss (1970), where the Mg^{2+} ions were proved to inhibit the precipitation of apatite, probably because Mg^{2+} competes with Ca^{2+} for sites in the apatite structure. In view of these results, it is difficult to explain how apatite could possibly form in the ocean, where Mg^{2+} is commonly abundant. Some threshold value for the Ca / Mg ratio above which crystalline apatite may precipitate was suggested by Martens and Harriss (*op. cit.*). This ratio remains almost invariant in normal sea water, even in near-shore areas. Pore-water compositions, however, are known to vary greatly from sea-water values. It seems plausible, therefore, that diagenetic reactions occurring within anoxic sediments could raise the Ca / Mg ratio to the point where apatite may precipitate.

Drever (1971) suggested that Mg^{2+} may replace Fe^{3+} in clays under anoxic conditions. The Fe^{3+} is then reduced and combines with sulfides. Other mechanisms to remove interfering Mg^{2+} ions may include ion exchange, substitution of Mg^{2+} for Ca^{2+} in carbonates (dolomitization), and the authigenic formation of Mg-rich silicates, such as sepiolite or chlorite. Indeed, Burnett (1977) found that only those sediments which contain dolomite, chlorite, or sepiolite on the Peru-Chile shelf also contain detectable apatite. He

believes that the diagenetic reactions that take up Mg^{2+} ions would be favorable for the precipitation of apatite.

For the past 30 years, the “Upwelling Hypothesis” has been the favored theory for phosphogenesis, but its applicability and indeed the whole idea of the ocean being the primary source of the phosphorus have been questioned by a number of authors such as Pevear (1966) who advocated a fluvial source for the phosphorites of the southeastern United States. This author (*op. cit.*) calculated that in the estuary of the relatively small Altamaha River, Georgia, enough phosphorus is available to form a bottom layer of apatite, 5 m thick over the entire estuary in 1 million years. Similarly, Bushinskii (1966) proposed that the continents, via the rivers, are the main source of phosphorus in the ocean, suggesting a direct fluvial / estuarine origin for the phosphorite without passing through what could be regarded as a marine intermediary. Nevertheless, it is unlikely that these conditions operated throughout an extensive phosphogenic province such as the Tethyan Late Cretaceous-Eocene province, which is obviously of continental shelf, marine origin.

Smirnov and others (1962) considered the sea water to be slightly undersaturated with phosphorous, but still concluded that the removal of CO_2 will precipitate apatite. however the diffusion of CO_2 from upwelling sea water is too slow to produce a significant amount of apatite as an inorganic precipitate.

From experimental observations Bushinskii (1966) remarked that any phosphorite precipitate would be so fine grained that there would be little possibility of its settling onto the sea floor in areas with any current activity. This idea is echoed by Senin (1970) who also noted that if the phosphorite was a fine inorganic precipitate it would be associated

with the fine pelitic sediments of the shelf, whereas he found the highest phosphorus concentrations in the Holocene sandy sediments accumulating off the Southwest African Coast.

Using radiometric dating, Kolodny (1969) and Kolodny and Kaplan (1970) found that the present-day ocean-floor phosphorites are generally not forming today (were dated to be older than 800,000 years using uranium isotopes), but are a relict dating from times when conditions were more favorable. However, because this study did not include the two areas where coastal upwelling, and hence organic productivity is most intense (the areas off Peru-Chile and off Southwest Africa), such conclusion is considered to be of partial nature (cf. Burnett and Veeh, 1977).

The lack of modern phosphorite sediments along the western margins of ocean basins has commonly been attributed to the general lack of upwelling (cf. Mckevey and Chase, 1966 and Tooms and others, 1969). However, in recent studies, well-developed upwelling currents were observed at numerous places along the coast of Brazil (between Cabo Frio and Royal Charlotte Bank) where concentrations of biogenic suspensates mostly result from topographically induced, and coastal upwelling, and reach levels comparable with those reported for northwest Africa (cf. Milliman and others, 1975 and Summerhayes and others, 1976). However, in such areas the P_2O_5 content of local bottom sediments was found to be less than 0.1 %, and never greater than 0.2 %, suggesting a lack of phosphorite mineral formation (cf. Milliman and others, 1975).

These observations led Riggs (1979) to conclude that the correlation of the distribution of known occurrences of sea-floor phosphatic sediments with known upwellings appear to be somewhat fortuitous. Some upwellings are associated with no

apparent phosphatic sediments, some have minor concentrations of modern phosphorite disseminated through the sediments, while many occur in conjunction with major concentrations of lithochemical phosphorites (i.e., reworked from older preexisting phosphorite sediments which either crop out on the submarine shelf or occur on the adjacent land). Therefore, it might be logical to accept the conclusion that, despite the fact that upwelling is an important oceanic process, it alone does not appear to explain the origin of major phosphorite deposits. The mechanism of phosphorite formation is probably much more complicated than the simple chemical precipitation of calcium phosphate from a nutrient-rich upwelling current system.

Bentor (1980), reported that, Kazakov's inorganic mechanism for the precipitation of apatite has now been abandoned for a number of reasons, that can be summarized as follows :

- a. " The rate of diffusion of CO_2 by decrease of pressure is very much lower than the velocity of upwelling currents,
- b. Supersaturation of phosphorus would occur in or near the photic zone, where it would rapidly be taken up by organisms,
- c. Deep ocean water is not "rich in phosphorus" and most probably considerably undersaturated. It would indeed be a strange coincidence if the relatively small physical changes caused by upwelling in the rising water-mass would cause supersaturation. There are, in fact, many areas of upwelling in the present ocean in which no phosphorite forms today,
- d. Martens and Harris (1970) showed in laboratory experiments that apatite precipitation is critically dependent on the $\text{Mg}^{2+} / \text{Ca}^{2+}$ - ratio in the aqueous

solution. By adding soluble phosphate to Mg-free sea water apatite crystallized readily, but by applying the same procedure to normal sea water with a Mg^{2+} / Ca^{2+} - ratio of 5.3 they obtained only an amorphous Ca-phosphate precipitate with a molar Ca / P-ratio of 1.35 (instead of 1.67 for apatite). This precipitate did not change to apatite during the eight months of their experiments, but quickly transformed to apatite when immersed in Mg-free sea water. This effect, known as the Mg-inhibition, is the result of distortion of the embryonic apatite lattice by Mg^{2+} -replacing Ca^{2+} , a distortion strong enough to inhibit further crystal growth. This effect seems to rule out altogether apatite crystallization from open sea water.”

The concept of inorganic precipitation of apatite from the water column in areas of upwelling seems, therefore, unrealistic at least for the present ocean. Nevertheless, the idea

Bentor (*op. cit.*) considered Kazakov's theory to be an excellent case-not rare in science-of a correct idea proposed for the wrong reasons, and reported that “Most workers today would probably agree that oceanic upwelling is an important, possibly a necessary, certainly not a sufficient factor in phosphogenesis.” Two points, frequently misunderstood, should, however, be stressed :

- a. Upwelling does not supply “phosphorus-rich water.”, its effect is to counteract P-depletion of surface water by biological activity by providing a steady, although dilute (rarely more than 70-100 ppb) supply of phosphorus (and other nutrients),

- b. Upwelling does not imply the rise of water from very great depths. Thus, the source of upwelling off the Namibian coast is only about 200 m deep (cf. Clvert and Price, 1971); in fact, water in the zone of regeneration of organic matter, just below the photic zone, is slightly richer in P than deep-ocean water.

8.2.4 *The Diagenic Origin Hypothesis :*

Collet (1905) ; Murray and Philippi (1908) and Cayeux (1934) recognized the association of phosphorites with the nutrient-rich upwelled water and high biological productivity, and advocated the replacement of calcium carbonate by calcium phosphate to be the principal mechanism of phosphorite formation, a hypothesis supported by Parker and Siesser (1972); Parker (1975) and Birch (1979b).

Grabau (1919) also reported the common association of phosphorites with limestones or limy sediments and hence, the replacement of such carbonates was considered to be the principal mechanism of phosphorite formation, although such association is sometimes lacking. Moreover, carbonate sediments that accumulate slowly and undergo long exposure to phosphatization on the sea bottom, are generally characterized by low phosphorus content

Clark (1924) mentioned the diagenetic origin of phosphorite deposits by the mechanism of differential solution of admixed calcite and calcium phosphates, an idea completely rejected by Ames (1959), although, Bushinsky (1935, 1964), reported the replacement of calcite and aragonite by phosphate solutions, and the effect of carbonate grain size on the relative rate of such replacement.

Both Klement and others (1942) and Arnold (1950) experimentally indicated that, in contrast to (F,OH,Cl)-apatite, the carbonate phosphates do not precipitate from aqueous solutions. Thus, supersaturation would only result in the precipitation of (F,OH, Cl)-apatite. In this respect, carbonate apatites resemble closely the so-called primary dolomites which are exclusively products of early diagenesis.

In a series of classical experiments, Ames (1959) showed that calcite powder through which a dilute phosphate solution is percolated at room temperature easily converts into apatite, an evidence that phosphatization can operate in nature (e.g. phosphatization of foraminiferal and other shells is widespread), but the same author (*op. cit.*) considered the differential dissolution of limestones, leaving an apatite-rich residue to be an unlikely source of phosphorites. He (*op. cit.*) limited the apatite replacement of CaCO_3 , to conditions such as :

- a. A non-depositional environment,
- b. Limy sediments or limestones, available for replacement,
- c. Ca-saturated sea water, in order that the limestone present be in near-equilibrium with the sea water,
- d. $\text{pH} \geq 7$,
- e. PO_4^{-3} concentration of at least 0.1 ppm.

Ames (*op. cit.*) believed that limestone replacements can also occur during the diagenesis of phosphatic shales that contain calcite nodules or intercalations, or are adjacent to limestones in the sedimentary sequence. The alkaline phosphatic solutions oozing out from the phosphatic shales were found to replace calcite with a carbonate apatite of variable compositions. Relative replacement rates were a function of the solution

pH, the PO_4^{3-} content in relation to the HCO_3^- concentration, and the calcite grain sizes (surface area). Finally, from stability relations in the system $\text{Na}_3\text{PO}_4\text{-CaCO}_3\text{-H}_2\text{O}$, Ames (*op. cit.*) concluded that “apatite replacement of carbonates is the most probable mode of formation of large marine phosphorite deposits, due to the operation of the replacement mechanism with PO_4^{3-} and Ca^{++} concentrations far below those required for apatite precipitation”.

Ever since Ames' (1959) experiments, replacement of calcite (or aragonite) as a mode of apatite formation has been stressed by many authors, and some, including Ames (1959, 1960), have gone so far as to claim this as the only mode of sedimentary apatite formation. Two comments seem appropriate here :

- a. Ames stated that the conversion of calcite to apatite takes place by PO_4^{3-} replacing CO_3^{2-} in the calcite lattice. This seems an impossibility as the calcite lattice with its triangular CO_3^{2-} -groups does not have enough room to accommodate the tetrahedral PO_4^{3-} -groups. Moreover, the Ca^{2+} -distribution in the calcite lattice is entirely different from that in apatite where part of the Ca^{2+} -ions occurs in 9-fold coordination,
- b. The controversy of primary crystallization versus replacement, is largely an artificial one, as in both cases the system has to be saturated with apatite. For replacement to occur the original Ca-mineral has to be unstable (cf. Bentor, 1980).

Nathan and Lucas (1972) obtained the same results as those of Ames (1959, 1960) by using other Ca-minerals such as gypsum. These authors (*op. cit.*) found that apatite crystallized not within the gypsum crystals but in their solution cavities, and that the

resultant apatite didn't carry any sulfate ions, while in most sedimentary apatites a small but variable amount of SO_4^{-2} replaces PO_4^{-3} . The sulfate content of apatite in phosphorites is an indicator of paleosalinity (reflecting the environmental conditions of deposition), as high values are taken to indicate an evaporitic environment. The degree of replacement of PO_4^{-3} by SO_4^{-2} depends on the sulfate content of the aqueous phase in equilibrium with phosphate during its formation (cf. Smirnov, 1966; Smirnov and others; 1962 and Gulbrandsen, 1969). Nevertheless, McArthur (1978) suggested that all marine carbonate-fluorapatites initially have the same sulfate content, and that variations found are due to later weathering.

The association between phosphorite and organic matter seems to have an important bearing on the genetic interpretation of many (if not all) phosphorite accumulations of economic importance. Phosphorus is apparently removed from the pore water of decaying bodies during the diagenetic transformation of organic matter (i.e. during microbial sulfate reduction) and is incorporated in fluorapatite (cf. Gaudette and Lyons, 1978). Consequently, organic matter, sulfides and / or sulfates (gypsum) are common accessory minerals of phosphorite deposits. This might confirm the hypothesis that phosphorites were formed in an early diagenetic reducing environment.

The diagenetic mobilization of phosphorus and the formation of apatite concentrations from interstitial waters is the model proposed by Bushinskii (1966) and favored by both Price and Calvert (1978) and Kolodny (1980). Based on a geochemical study of phosphorites from the Namibian shelf, Price and Calvert (*op. cit.*) concluded that : "the origin of phosphorite is believed to be the result of the diagenetic precipitation of phosphorus within sediments..". Indeed, the absence of any clear correlation between the

petrographic types of phosphorite deposits and their chemical composition (cf. Gulbrandsen, 1966) points to an early diagenetic environment for the genesis of phosphorite (cf. Nathan and Nielsen, 1980).

Diagenetic phosphorites are commonly associated with eustatic / tectonic instability of continental margins (cf. Summerhayes, 1970; Pasho, 1972; Parker, 1975; Birch, 1979b; Cullen, 1980) and with unconformities in the rock record. Since the phosphorus content of upwelled water is frequently above that required for initiation of diagenetic phosphatization, other factors must be critical to the formation of these rocks. The replacement process is temperature dependent and therefore increased solar radiations in the shoaling waters of transgressive and regressive seas may have facilitated mineralization on wide, flat-lying shelves where diagenetic phosphorites predominate. These conditions, combined with generally warmer seas of the Paleogene (cf. Tooms and others, 1969), may account for the apparent increase in phosphorite mineralization during this period (cf. Summerhayes, 1970).

Indeed, both primary and replacement apatites occur in nature, and sometimes in the same deposit (cf. Manheim and others, 1975 and Burnett, 1977).

Birch (1980) proposed a model of penecontemporaneous phosphatization by diagenetic and authigenic mechanisms for the phosphorites of the western margin of South Africa. In that model, authigenic phosphorite and phosphorus-rich materials form in shallow, restricted, lagoonal or estuarine environments, in low latitudes ($<40^{\circ}$) adjacent to a hot, arid hinterland. Intense, wind-induced upwelling of nutrient-rich water results in the generation of vast quantities of siliceous phytoplankton which, on decay, greatly enrich the bottom water in phosphates. Apatite is precipitated directly from the water column to form

layered or massive phosphorites, or apatite may grow or precipitate within interstices in the sediment to form phosphatic packstones. Phosphorite pellets probably form by accretion at the water / sediment interface if suitable nuclei are available or granular material may be produced by fragmentation of newly formed phosphatic packstone during periodic storms. The authigenic process is greatly facilitated by solar heating in the shallow lagoonal environment, by reduced terrigenous supply and possibly by the activity of microorganisms. The model also suggests that phosphorites and phosphorus-rich sediments formed diagenetically are located on open shelves and offshore topographic highs (banks, ridges, seamounts) which are dominated by carbonate sedimentation. The deposition of calcareous zooplankton is related to diffuse, divergent upwelling of nutrients-rich water. Insufficient P is released by decay of calcareous zooplankton on the open shelf for the precipitation of apatite, but, lime mud mantling the sea floor is phosphatized in the solar-heated shoaling waters of a P-rich transgressive sea, and all the components of the bottom sediment are lithified into a thin, near-continuous capping of phosphorus-rich rock, the composition of which varies according to the prevailing sedimentological environment. Both the onland authigenic and the offshore diagenetic materials are dated as Late Miocene / Early Pliocene. This suggests that the calcareous sediment on the open shelf was being phosphatized at the same time as the authigenic varieties were being formed in adjacent lagoons and estuaries or probably slightly later during a regressive phase. A mixing of authigenic and diagenetic forms of phosphorite may occur during transgressive / regressive cycles due to superimposition of environmental regimes (cf. Birch, *op. cit.*).

8.2.5 The Volcanogenic Origin Hypothesis :

Mansfield (1940) proposed a volcanogenic origin for phosphorite deposits. He (*op. cit.*) considered fluorine to play a vital role in the precipitation of phosphorite and suggested a correlation between times of volcanism (when fluorine-rich gases are common) and phosphorite deposition. The author (*op. cit.*) proposed a time and space association between volcanism and phosphorite deposition in the South Atlantic Coastal Plain using the extensive deposits of bentonites and Fuller's Earth as evidence. This link between phosphogenesis and volcanism was also proposed by a number of Soviet geologists, notably Shatskii (1955); Strakhov (1960) and Brodskaya and Ilyinskaya (1968, 1970).

In support of this view, Bidaut (1953) attributed the Dinantian phosphorites of the Pyrenees (southern France) to the action of submarine fumaroles rich in fluorine. However, as pointed out by Kazakov (1950), the amount of fluorine in sea water is very much greater (in proportion to PO_4) than is needed for the production of carbonate fluorapatite.

Miller (1964) proposed a volcanic source for the anomalous fluorine and phosphorus in phosphorite deposits as well as the volcanic shards which occur in some deposits. He (*op. cit.*) believed that the location of phosphorite deposition is primarily determined by the location of volcanic arcs and the ocean currents.

Bushinski (1964) stated that rich concentrations of dissolved phosphates, in addition to upwellings of the sea water and fluvial supply from the land, may be derived from submarine hydrothermal sources or volcanic exhalations. During periods of increased

tectonic activity, such a source might act as a “supercharger” supplying enough new materials to the chemical system to bring about a totally abnormal period of sedimentation, abnormal in terms of the chemical and biochemical environment and the resulting sediment system. Such magmatic and / or hydrothermal solutions exhausted from a major oceanic fracture system or crustal boundary could represent such a supercharger if it occurred adjacent to or through a shallow-water continental-shelf system. In addition, consideration should be given to the potential chemical exhalations, including phosphorus, which might be driven from the baking of organic-rich sea floor sediments by intrusive or extrusive igneous activity associated with fracturing. If the previous conditions are fulfilled, the oceanic current systems and associated upwellings become very important mechanisms. They mix and move the supercharged waters up into the shallow-water shelf environments. The somewhat enriched toxic waters could modify the chemical and environmental conditions, stressing the organic populations and producing abnormal authigenic sediment systems. The type and degree of development of authigenic sediments formed (dolomite, glauconite, phosphorite, etc.) depend upon the composition of the enriched solutions and their duration and volume, as well as the physical dynamics of the entire upwelling system. However, as stated by, Riggs (1979) “The evidence for such supercharger, at this point in time, is all indirect, but it is an important hypothesis which demands further work”.

Rooney and Kerr (1967) found that the mineral assemblage “zeolite / clinoptilolite / montmorillonite” is ubiquitous in the Miocene Pungo River phosphorites of North Carolina, and proposed a volcanic source for glass shards which, due to them, were subsequently altered to this mineral assemblage. These authors (*op. cit.*) explained the associated dolomites as a product of seepage refluxion of limestones by heavy magnesium-

rich brines in the depositional lagoon, and attributed the source of phosphorus to widespread ashfalls of long duration which killed a large number of marine organisms whose subsequent decay contributed the phosphorus.

However, Cathcart (1968) observed that clinoptiolite is a comparatively minor component in the Miocene Pungo River phosphorites, forming only 0-5 % of the total sediment, and hence concluded that there is no compelling evidence to indicate a significant volcanic association in any of the major sedimentary phosphorite deposits. Moreover, stratigraphic and petrographic work by Snyder and others (1984) and Riggs and Mallette (1990) demonstrated that the clinoptiolite was formed in foraminiferal tests through diagenesis, associated with the development of condensed stratigraphic sections.

Bostrom and others (1968), reported that pelagic sediments on active ridges are enriched in numerous elements including phosphorus, and that such element enrichment is probably due to carbonatitic volcanism associated with the degassing of the mantle, which could also explain the occurrence of hydrothermal dolomite in the ridge sediments.

Lowe (1971) studied the Miocene deposits of California, and reported that volcanism might have had a double effect : because of the ash produced and its alteration to bentonite, and hence, the reduction of the Mg content of sea water and the increase in its pH value, the crystallization of carbonate fluorapatite was stimulated.

Berner (1973) found that the P_2O_5 content in the predominantly montmorillonite clays on the East Pacific Rise ranged between 0.18 % and 3.39 %, values which are considerably higher than those of the normal marine sediments. Such magnesium-rich montmorillonite clays were believed by this author (*op. cit.*) to have formed from the

submarine weathering of volcanic glass and to have been responsible for the absorptive removal of phosphorus from sea water.

Kharin (1974) reported that periods of intense volcanism cause an increase in the phosphorus content of sea water, and therefore stimulate the development of plankton which, in turn, will provide phosphorus for sedimentation.

Many authors (e.g. Hathaway and others, 1970 and Weaver and Beck, 1979) believe that, the magnesium-rich clay minerals including montmorillonite, palygorskite, and sepiolite along with the zeolite clinoptilolite which are important components of the Miocene phosphorite sediments of Florida are the result of the alteration of volcanic ash, as 90 feet of a 300-feet-thick Miocene section on the continental shelf off Florida represent material of volcanic origin.

Cook (1979) proposed an indirect relationship between phosphogenesis and volcanism and stated that, although the direct input of large amounts of volcanogenic phosphorus into the sedimentary system and / or the initiation of mass mortalities as a result of massive ash falls may be of some significance locally, there is no evidence that they are capable of producing large phosphorite deposits.

8.3 Genesis of The Studied Phosphorite Deposits :

8.3.1 Factors Controlling Phosphogenesis in Northwestern Saudi Arabia :

A biochemical mode of formation, controlled by sea floor configuration, is here proposed for the phosphorite deposits of northwestern Saudi Arabia. The phosphogenic system under which these deposits had been forming was characterized by both a specific

tectonic setting and structural framework, added to an abnormal abundance of organic life and a particular set of environmental conditions of deposition that can be summarized as follows :

8.3.1.1 The Tectonic Setting :

It is believed that the development of certain tectonic settings on the sea floor can lead to conditions that are either favorable or unfavorable for the flourishing of life. These same conditions can also cause restriction of circulation on the bottom of an otherwise open sea, and hence, can prevent the products of decay of the once flourished life (among them soluble phosphates) from dissipation. Tectonically, the phosphorite deposits of northwestern Saudi Arabia were laid down on the passive margin of the Afro / Arabia Continent. This passive margin helped in providing a certain degree of restriction.

Towards the end of the Jurassic, incipient rifting and large-scale strike-slip faulting were active upon a large part of the west-Tethyan realm, leading to the early stages of the separation of Arabia from Africa.

The movement of the newly-formed Arabian plate was partly accommodated by the sinistral, strike-slip motion along the Gulf of Aqaba-Dead Sea lineament. The most obvious structural features created by these tensional stresses are a tightly spaced set of normal faults and horst and graben structures, sub-parallel to the Red Sea coast. These structural trends have greatly influenced the depositional environment during the Late Mesozoic-Early Cainozoic times, by creating a lobate shoreline of broad embayments with northwest trending axes particularly in the Sirhan-Turayf area of northwestern Saudi Arabia and its northward extension in Central Jordan.

8.3.1.2 The Structural Framework :

The detailed stratigraphic work on the phosphorite deposits of northwestern Saudi Arabia has revealed the important role played by the structural framework of the region in the accumulation of such economically important deposits. This has determined the basic environmental conditions of deposition and has largely dictated the resulting geometries, the basic sediment processes, and the associated sediment system.

The proper regional setting has defined the limits of this phosphorite belt as part of the larger Mediterranean phosphogenic province which extends from Morocco to Iraq.

Within this appropriate regional setting, there was a series of structural highs (with the associated shoaling environments) and adjacent basins. The production, deposition and accumulation of phosphorite deposits was directly related to these structures, of particular importance of which was the Ha'il Arch Complex. This is a broad, block-faulted NNW-SSE trending series of structures, which controlled the regional dip in the region, restricted the circulation and shaped the sea floor into a series of plunging anticlines and synclines. These folds are associated with and traversed by a large number of major and minor faults, mainly of the Red Sea trend (NNW-SSE) and the Aqaba trend (NNE-SSW).

These structures contained an extensive shoaling submarine platforms (where the greatest volume of phosphorite sediments were produced) and adjacent closed to semi-closed basins where most the economically important phosphorite deposits did accumulate.

The area was characterized by intermediate but changing tectonism, somewhere between total quiescence with its carbonate banks (e.g. the area to the east of Ha'il arch)

and extreme mountain building with its deluge of terrigenous and volcanic sediments, such two systems are not suitable at all for phosphorite formation.

A particular topographic setting might produce conditions on the sea floor similar to those resulted from tectonism, and such favorable topography might have prevailed during the sedimentation of phosphorite deposits. However, favorable topography not directly resulting from tectonism cannot alone explain the widespread occurrence of phosphorites. Structures, on the other hand, repeat themselves much more regularly and frequently than do non-tectonic topographic features. Moreover, the presence of favorable structural elements in the region have been reported.

Topographic depressions (synclines) of the sea floor, whether structural or not, are believed here to be the favored sites for phosphorite deposition. The structural framework of the area and its effect on phosphorite accumulation is explained in more detail in chapter 4.

8.3.1.3 Sea Level Changes :

the phosphorite deposits of northwestern Saudi Arabia are known to occur on disconformity surfaces which indicate their direct relationship with the past sea level changes. Phosphorite deposits abound at the base of each of the three carbonate formations of the Hibr Group, reflecting high-energy marine transgressions at the start of each of the repetitive cycles, where lag deposits of phosphorite and organic (bioclastic) fragments were formed mainly by the reworking of primary deposits. The duration of each of those high sea stands was an important factor in providing the adequate time for

phosphogenesis to take place within the optimum environment, and hence led to the formation of such vast phosphorite deposit.

8.3.1.4 Upwelling :

The investigated area is an example of a fossilized upwelling regime in a warm, subtropical ocean under an arid climate. The sedimentary rocks are light-colored, chalky limestones / cherts and phosphorites with abundant teeth, bone fragments, coprolithes and other faunal remains that are diagnostic for the upwelling regime. Bone fragments' accumulations usually result during mass mortality events which are currently observed in upwelling zones (cf. Brongersma-Sanders, 1957).

Low values of cerium in apatite grains derived from phosphorites was taken to reflect the influence of deep-ocean water (cf. Bendor, 1980), and hence its direct relationship with oceanic upwelling. Indeed, phosphorite deposits of northwestern Saudi Arabia and of nearby countries, such as Syria are highly deficient in Ce (cf. Kemper and Zimmerle in Thiel and Suess, 1983) and this was taken to support the assumption that their deposition could have taken place in areas of oceanic upwelling, a hypothesis supported by the following observations :

- a. The presence of rather cool water faunas at low paleolatitudes,
- b. The observed evidence for local oxygen deficiency,
- c. The abundance of siliceous microfossils in the basin of deposition,
- d. The abundance of phosphoritic fish relics.

Such upwelling was caused by the vertical upward interaction of coastal currents, winds and the coriolis effect and is thought to be the major mechanism for recycling the

deep supply of phosphorus and other nutrients back to the surface and to represent areas of high primary organic productivity.

8.3.1.5 *Organisms :*

Organisms, particularly the planktonic ones, have played an important role in the genesis of the phosphorite deposits of northwestern Saudi Arabia. These have acted as bioconcentrating agents for the phosphorus and other nutrients associated with the upwelling currents. On death, the bodies of such organisms fell to the sea bottom and found their way to the depressions either directly or drifted into them from the intervening elevations.

Decaying organisms in depressions at the sea-bed did produce ammonium phosphate and ammonia, among other constituents, the latter was oxidized by the nitrification bacteria into nitrates which, together with the soluble phosphates, acted as fertilizers for the phytoplanktons on which other nektons and planktons flourished. On death, the biota fell to the sheltered, partly restricted sea floor depressions, where the amounts of soluble phosphates resulting from their decaying increased in due course beyond the needs of animals and plants living above, and hence became subjected to further concentration prior to deposition. Restriction of circulation was a necessary requirement for the concentration rather than for the deposition of phosphorites.

The proposed role of organisms in the genesis of phosphorite deposits of northwestern Saudi Arabia is also supported by the results of the chemical analyses and by the obvious similarity of elemental concentrations in both the phosphorites and organic matter (see chapter 7).

8.3.1.6 Surficial Weathering :

Surficial weathering with its solubilizing and leaching away of cementing carbonates was an important factor for the development of the economic phosphorite deposits of northwestern Saudi Arabia. The removal of carbonates from these phosphorite deposits softened the formations, upgraded the P_2O_5 content, removed carbonate materials which are deleterious to the treatment of the final concentrate, and made the mining and the beneficiation easier. A notable example of such effect is provided by the Hazm-al-Jalamid Phosphorite deposit. Examination of the few deep boreholes that penetrated unoxidized rocks beyond the Jalamid area, showed that the unweathered phosphoritic rocks of the Thaniyat Turayf Phosphorite Member are organic-rich and dolomitic. Much of the Jalamid ore, in its original unweathered state, probably contained less than 10 % P_2O_5 , well below the present ore-grade material (Mineral Resources of Saudi Arabia, 1994). Surficial weathering of the ore resulted in oxidation of the organic matter, in partial to complete dedolomitization, and in variable degrees of leaching of its calcite content, which enhanced the grades to between 15 and 27 % P_2O_5 . Of these enriching processes, the dedolomitization has been particularly important. The ground water in the region is normally sulfate-rich and this sulfate content was probably originated by the oxidation of pyrite and sulfur in organic matter associated with the phosphorite deposits. The sulfate-rich ground water dissolved the dolomite; caused the secondary precipitation of calcite from the solution quickly and more-or-less in place, whereas the magnesium and sulfate ions did migrate out of the system. Complete dedolomitization of dolomitic phosphorite deposits formed a porous high grade phosphorite partially cemented by secondary sparry

calcite. Leaching of the sparry calcite by meteoric water turned the compact calcareous ore into a semi-friable to friable one, depending on the degree of leaching. As a result of this process approximately 25 % of the Jalamid Phosphorites are friable or semi-friable.

8.3.2 Formation of Sedimentary Apatite :

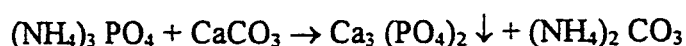
The carbonate fluorapatite of the phosphorite deposits of northwestern Saudi Arabia might have been formed by the contribution of any of three main ways : biogenesis, direct precipitation or epigenesis.

8.3.2.1 Biogenesis :

This means that the apatite minerals were mainly formed by the accumulation of phosphatic skeletons and skeletal fragments. The tests of many inarticulate brachiopods (e.g. *Obolus*, *Lingula*, etc.), whether complete or in the form of debris, consist of francolite, and hence, the calcium phosphate content of phosphorite beds depends directly on their accumulation and their favorable fossilization. The same applies to the debris of skeletons of fish and other marine or coastal vertebrates, which are also rich in phosphate minerals. However, such debris can undergo more rapid diagenetic changes, mainly by the conversion of the initial carbonate hydroxylapatite into carbonate fluorapatite, and hence biogenesis (the direct biological formation of phosphorite minerals) seems less frequent, although it might be of local importance.

8.3.2.2 Direct Precipitation :

The relatively concentrated solutions of ammonium phosphates entrapped in depressions (synclines) of restricted circulation might have reacted with the CaCO_3 precipitating in the medium, or with any Ca ions in solution, to produce the practically insoluble $\text{Ca}_3(\text{PO}_4)_2$ according to the following equation :



Such reaction might have also taken place between the dissolved ammonium phosphates and the solid CaCO_3 . An important product of the reaction is the ammonium carbonate. If this substance were produced in rather large quantities, it would raise the pH value and the ammonia liberated from its dissociation might become dangerous even for the nektons and planktons. Such a condition might not be attained, however, because of the slowness of the reaction and the possibility of active oxidation of the product by the nitrification bacteria.

The anaerobic conditions in the localized depressions may well explain the general absence of remains of bottom dwelling organisms. The rare shells that are sometimes found in these deposits probably were derived from nearby relatively elevated portions of the sea floor (anticlines or any other topographic highs) by the action of mild waves and currents.

The above mentioned process might have continued with the continuation of restriction of circulation on the sea bottom. Interruption of the cycle could have been caused by the shallowing of the sea and the consequent aeration and continuous agitation of the water in the depressions. This could have prevented the concentration of the decaying products to the degree necessary for the deposition of calcium phosphate.

Interruption could have also resulted from the partial filling of the gentle depressions by phosphorite deposits, leading to open circulation on the sea bottom, while renewal of the tectonic setting could again cause deposition of phosphorites. This explains the very common recurrence of phosphorite beds in the region. This phenomena would be difficult to explain if the depressions in which the phosphorites accumulated were of non-tectonic origin.

The broadly lenticular nature of the phosphorite deposits (figs. 7.7 , 7.11 , 8.4) may be due to both the partial filling of the synclines and the gradual elimination of conditions favorable to phosphorite formation. Doubly plunging synclines would explain variations in the thickness both along and across the strike. Faulting and displacement might also be an acceptable cause.

The obvious similarity between the present structure of phosphorite-bearing formations and their configuration during deposition of phosphorite beds support the view of synclines being the favored structures for phosphorite deposition (figs. 7. 7, 7. 11, 8.4)

8.3.2.3 Epigenesis or Phosphatization :

Apatite formation is here attributed to the replacement of calcium carbonate (either calcite or aragonite). The phosphatization of calcareous material (either organic or non-organic) was, most probably, due to the presence of the PO_4 ion in easily soluble form for a time long enough to permit replacement.

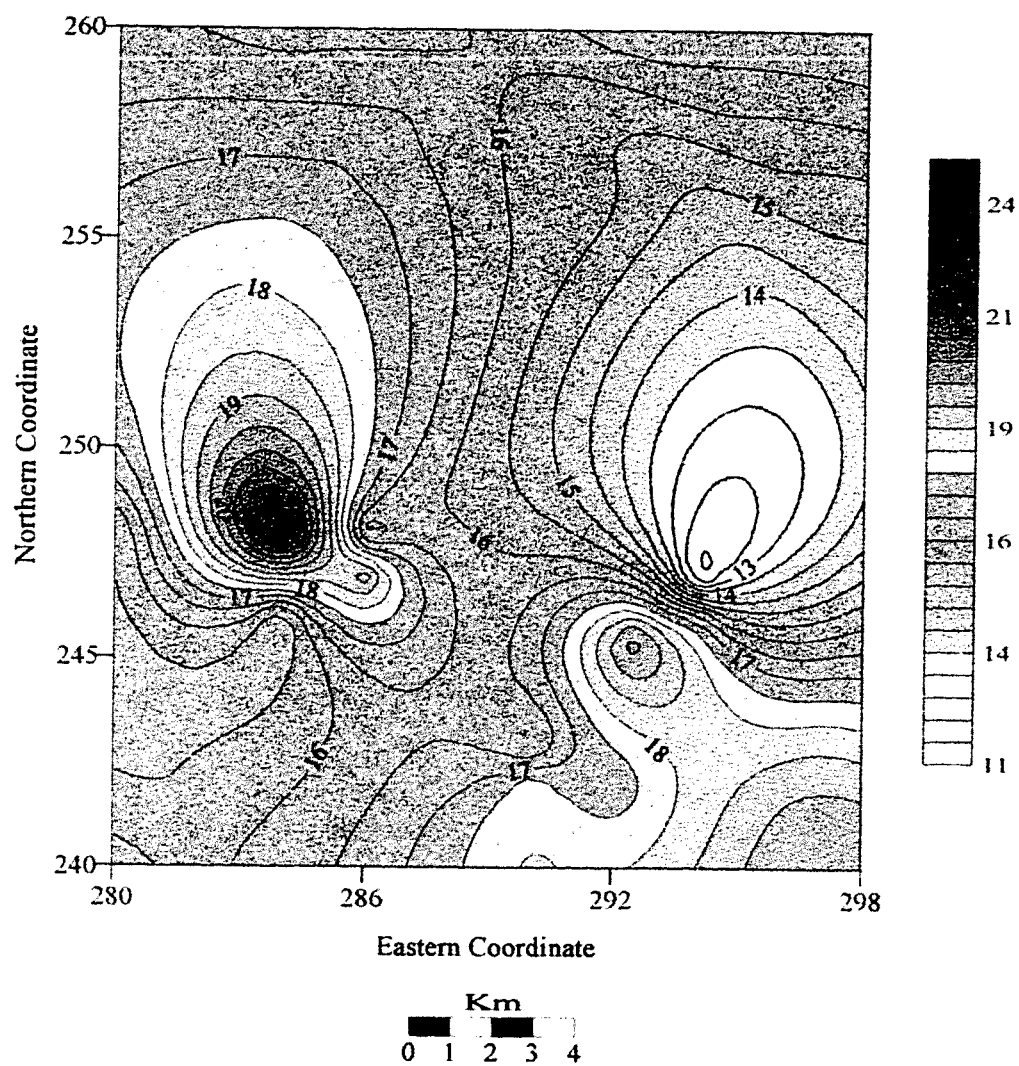


Fig. 8.4 : Iso-tenor Map for the Zone 3 Phosphorite in the Hazm Al-Jalamid area based on P_2O_5 %.

Of the three modes of possible formation discussed above, direct precipitation and epigenesis was the most common . It is important to mention that, the controversy of primary crystallization versus replacement, is largely an artificial one. In both cases the system has to be saturated with respect to apatite, but, for replacement to occur the original Ca mineral has to be unstable. Both processes have contributed with varying degrees to the formation of the phosphorite deposits of northwestern Saudi Arabia.

8.3.3 A Proposed Model for the Genesis of The Studied Phosphorite Deposits :

Based on the previous discussions, the following 9-stage genetic scheme is proposed for the formation of the phosphorite deposits of northwestern Saudi Arabia :

- a. Proper tectonic setting and structural framework,
- b. Restricted circulation, suggested by many features of the phosphorite deposits, was provided by the prior folding of the floor of the open sea into shallow anticlines and synclines,
- c. Influx of nutrient-rich water, provided generally by upwelling, into a shallow marine region with a slow rate of terrigenous deposition, and often a warm arid climate,
- d. Development of a high productivity zone with a prolific biota,
- e. Accumulation, upon death, of the remains of the biota in the bottom of the sheltered, semi-restricted depressions;
- f. Development, upon decay of the soft parts of the accumulated dead biota, of a phosphorus rich solution in the depressions,

- g. Formation of sedimentary apatite either by direct precipitation or by phosphatization in the presence of phosphorus rich solutions. Locally, some might have formed by biogenesis,
- h. Development of phosphorite particles by a number of possible ways such as : reworking, epigenesis of pre-existing non-phosphoritic particles, filling of cavities or porous media, phosphatization of faecal pellets and direct precipitation on a suitable surface (quartz or calcite grain, bone lathes, etc.),
- i. Reworking, winnowing and sorting and, therefore, concentration of the formed phosphorite deposits in response to changes in current patterns or relative sea level. Of particular importance was surficial weathering with its solubilizing and leaching away of cementing carbonates.

CHAPTER NINE

SUMMARY AND CONCLUSIONS

Selected samples from the Early Paleogene phosphorite-bearing succession of northwestern Saudi Arabia were thin sectioned for the petrographical and mineralogical description of the ore. These samples were also processed for geochemical analysis, including trace elements' microanalysis, radiometric measurements and interpretation of the obtained data. Such analyses have led to a number of interesting conclusions that can be summarized as follows :

1. The phosphorite deposits of northwestern Saudi Arabia are economically important in terms of tonnage, grade, and trace elements. The P_2O_5 content ranges from 15-39 %, with several trace elements including K, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Sr, Y, Mo, Cd, Hg, Pb, Th and U. These trace elements range in concentration from a few ppm to several hundred ppm. Despite their low concentrations, some of these trace elements are of equal importance to the phosphorite ore, if not of greater value. A uranium content of up to 200 ppm and a vanadium content of up to 3000 ppm have been recorded and such values can warrant the exploitation of the ore for these trace elements alone. No direct relationship between the concentration of these trace elements and the average chemical composition of sea water or the P_2O_5 content was

observed. The relationship between the concentrations of these trace elements and the P_2O_5 content is not strictly proportional; even when the correlation is good. Likewise, the existence of an intercorrelated group of elements without tie with any major element or mineral phase can lead to the assumption that these elements (which have no special affinity for each other) must have been collected by their common affinity for another substance which had already disappeared. The known association of such elements as V, Ni, Cr and Zn with organic matter, together with the abundant signs of biological activity of macro-as well as -microorganisms indicate that organisms, especially plankton, played an important role in the genesis of the studied phosphorites, and that the described trace element associations show that the first trap for these elements was a biological one, becoming then biochemical. Only the final arrangement of the trapped elements in a very specific environment is chemical.

2. The studied phosphorite deposits belong to the pelletal phosphorites (with occasional phosphorite nodules and coprolithic materials), are mostly friable to consolidated, fairly to poorly sorted, fine to coarse grained, and rarely granular. The main components are phosphorite pellets, ovules, nodules, coprolithic material, phosphatized fossils (e.g. bone and other fossil fragments, particularly fish remains), with minor oolites and rare compound pellets.

The pellets occur in a number of widely varying forms, owing to differences in texture, structure, endogangue and diagenetic history. Certain pellets are homogenous in appearance, with practically no endogangue. Others, though almost entirely apatitic, have very clear inclusions such as calcite, dolomite or quartz grains, fossil fragments

(e.g. bone fragments, diatomaceous, radiolarian, foraminiferal and other fossil debris) all epigenized with phosphorite. A pellet may contain several grains, but only one generally takes a central position, around which the apatite is distributed in one or more layers. Some pellets show marginal replacement of apatite by calcite, dolomite or silica, while the outer edge of others is covered by a cortex of hyaline apatite a few microns in thickness. Compound pellets are not uncommon.

Ovules are abundant, and show little or no internal structure, but are well rounded with a low degree of sphericity. Oolites are rather less developed and form mainly around nuclei of foreign materials.

Coprolites, are common and have different shapes and sizes. Indeed, most of the encountered pellets can be of faecal origin, and so are many nuclei. Other biogenic remains are also common, such as : fish scales and teeth, bone fragments, worm tubes, as well as foraminifer, radiolarian, diatomaceous, bryozoan, ostracod, sponge, echinoid and molluscan remains.

The matrix is mainly composed of carbonate minerals, but clayey matrix cannot be excluded. The layered nature of the clayey matrix suggests its simultaneous deposition with the pellets.

Carbonate (either calcite or dolomite) dominates as a cement, although silica cement also occurs, in particular, at the Thaniyat Turayf area. Silicification of carbonate cement is also well documented. In some instances due to either winnowing or leaching, there is virtually no matrix, and the rock is composed of a sparsely cemented friable mass of pellets.

The endogangue materials show a wide range of variation, being composed of quartz, calcite or dolomite grains, fossil fragments, or carbonaceous material. Similarly the exogangue materials are also highly variable, being either of calcareous or siliceous composition.

A carbonate exogangue is very common in the Jalamid phosphorites. being predominantly calcitic, but dolomite is also present and is sometimes the most abundant mineral. Chert is also well recorded in the exogangue, particularly where silicification has taken place.

Clastic quartz grains are frequent in the exogangue of the Thaniyat Turayf phosphorites. The grains are angular to subangular, suggesting immediate reworking from a nearby source, most probably the underlying Zallum or Tawil Sandstones.

3. In the present study, a P_2O_5 content of 18 % is selected as the borderline between phosphorite and phosphoritic rocks, the former with 45 % or more phosphorite minerals, and the latter with less than that. 19 % P_2O_5 corresponds to 46.7 % phosphorous minerals, while 20 % P_2O_5 corresponds to 49.16 % phosphorous minerals, a figure close to 50 %.
4. The Jalamid phosphorite deposit occurs at the base of the Paleocene Jalamid Formation, which is predominantly composed of a phosphorite-bearing carbonate / chert section. Two main phosphorite horizons and a third one of only local importance have been recorded. The deposit is composed primarily of phosphoritic peloids and intraclasts embedded in a well crystallized sparry calcitic to dolomitic, finely crystalline matrix and cement. Minor quartz grains, chert fragments, rare gypsum and bassanite as

well as minor amounts of metayuyamunite (a yellow secondary calcium-uranium vanadate mineral $\{Ca(UO_2)_2(VO_4)_2 \cdot 3-5H_2O\}$) have been recorded. The dominant phosphorite minerals present include francolite (carbonate-fluorapatite), $\{Ca_5(PO_4CO_3)_3F\}$ and dahllite (carbonate hydroxyapatite), $\{Ca_5(PO_4,CO_3,(OH)_3(F,OH))\}$, which is produced by the partial replacement of F by OH in francolite (and hence the amount of fluorine is less than 1 %). As the average grade of the ore is in the range 19-21 % P_2O_5 , it is concluded that the substitution of PO_4^{-3} by CO_3^{-2} could never have been of any important role as the process usually lowers the P_2O_5 % to less than 17 %.

Typical phosphorite grains range in diameter from 50 to 300 microns, averaging 215 microns. SEM observations (backscattered electrons) indicate that the grains have highly varying concentrations of elements, and hence are polygenetic and / or have had differing diagenetic histories. SEM observations and physical tests also indicate that the phosphorite grains break cleanly from the matrix, whether this is of sparry calcite, dolomitic micrite, or of mixed character. This can facilitate the liberation of the soft phosphorite pellets upon crushing the ore without destroying them which makes the ore amenable to beneficiation by the process of floatation.

In the zone 1 phosphorite, apatite has an average of 46.35 %, dolomite of 36.69 %) and calcite of 13.14 %. The 3 components together account for an average of 96.18 % of the total minerals present.

In the zone 2 phosphorite, apatite has an average of 46.88 %, dolomite of 22.57 and calcite of 24.48. The 3 components together account for an average of 93.93 % of the total minerals present.

The overall average mineralogical composition of the Jalamid phosphorites (of 46.56 % apatite, 30.91 dolomite and 17.78 % calcite, = 95.25 %) reflects the restricted to semi-restricted nature of the basin of deposition. Such environmental conditions of deposition encouraged the high rate of chemical precipitation (carbonate material) and the very little amounts of detrital sediments (< 5 %) which was probably transported to the basin largely by wind. The scarcity of detritus material also reflect the chalky nature of the underlying strata over which the Jalamid phosphorites were deposited. Reworking here could only produce calcareous material. The average composition also reflects the effect of diagenetic changes (such as surficial weathering) in the enhancement of the phosphorous content via dedolomitization and calcite leaching.

5. The Thaniyat Turayf phosphorite deposits occur at several levels in the Thaniyat Turayf Phosphorite Member at the base of the Jalamid Formation. The member consists of phosphorite, sand, chert, shale, and finely crystalline dolomite. Here, the phosphorite beds contain numerous quartz grains which are the principal non-phosphoritic fraction and which are sometimes so abundant that the rock can easily be named sandy phosphorites or even phosphoritic sandstone. The majority of the quartz grains are sharply angular to subangular, but some are rounded to sub-rounded, and were formed by the reworking of the underlying sandstone units.
6. A simple and straightforward mineralogical classification for phosphorite deposits is here suggested, based on the following :

- i. The term phosphate and its derivatives is avoided as it belongs strictly to the chemical field,
- ii. The term “phosphorite” and its derivatives is adopted here to designate sedimentary rocks with different phosphorus content,
- iii. The term “collophanite” is also abandoned and the appropriate minerals of the apatite family are used instead,
- iv. Phosphorite minerals other than the apatite family (e.g. aluminum phosphate, iron phosphate minerals, etc.) are considered within the definition of phosphorites.
- v. A P_2O_5 content of 18 % is selected to represent the borderline between phosphorite rocks (with 45 % or more phosphorite minerals) and phosphoritic rocks (having less than 45 % phosphorite minerals),
- vi. The P_2O_5 content is regarded to be the controlling factor in the classification and nomenclature of the phosphorite rock, regardless of the type and amount of phosphorite minerals present. A minimum of 18 % P_2O_5 is strictly required for a rock to be termed phosphorite. Between 8 % and 18 % P_2O_5 , the primary petrographic term to be used is that of the non-phosphorite fraction, with “phosphoritic” as a qualifier (e.g. phosphoritic limestone, phosphoritic clay, phosphoritic sandstone, etc.). If the P_2O_5 content ranges between 1 % and 8 %, the primary petrographic term to be used is that for the non-phosphorite fraction, with “slightly phosphoritic” as a qualifier (e.g. slightly phosphoritic limestone, slightly phosphoritic clay, slightly phosphoritic sandstone, etc.). Below 1 % P_2O_5 was completely ignored. A summary of the classification and nomenclature

together with the corresponding percentage of phosphorite mineral is shown in the following table:

P₂O₅ %	Phosphorite Minerals %	Nomenclature
< 1	< 2.5	Ignored
1-8	2.5-20	"Slightly phosphoritic" + non-phosphoritic fraction
8-18	20-45	"Phosphoritic" + non-phosphoritic fraction
≥ 18	≥ 45	Phosphorite

- vii. The amount of phosphorite minerals may differ for different deposits having the same P₂O₅ content, hence, the content of phosphorite minerals may slightly differ from those recorded here, however, this makes no difference as the P₂O₅ content is regarded as the controlling factor in our classification and nomenclature.
- viii. Phosphorite rock is defined here as "any rock of sedimentary origin that contains a minimum P₂O₅ content of 18 %." A prefix provides a means of naming rocks with other phosphorite minerals, such as aluminophosphorite, ferriphosphorite, uranophosphorite, etc.
- ix. The non-phosphoritic fraction is termed the "endogangue" when it is inside the grains, nodules or other phosphorite particles, and the "exogangue" when it is outside. The siliceous or carbonate coating that more or less encloses certain grains may be called the "epigangue."
- x. The proposed terminology is as descriptive as possible and does not indulge into the disputes of genesis,

- xi. Based on this classification, the Jalamid phosphorous-rich ore falls well within the phosphorite category ($\geq 18\%$ P_2O_5 and $\geq 45\%$ phosphorite minerals) with carbonate (calcite and dolomite) as the dominant non-phosphoritic fraction. The Thaniyat phosphorite deposits falls well within the phosphorite category, but some of its beds can be more specifically designated as siliceous or sandy phosphorites, and others as phosphoritic sandstone.
7. The mineralogical, petrographical and geochemical analyses of the ore as well as its stratigraphical relationships suggest a biochemical origin, in a partially restricted continental shelf. Such partial restriction was mainly provided by a large number of swells and basins of the Arabian type that were apparently active prior to the deposition of the phosphorite sequence, and hence provided the necessary configuration of the sea-bottom during the deposition of the ore. The following 9-stage genetic scheme is proposed for the formation of phosphorite deposits of northwestern Saudi Arabia :
- a) Proper tectonic setting and structural framework,
 - b) Restricted circulation, suggested by many features of the phosphorite deposits, was provided by the prior folding of the floor of the open sea into shallow synclines and anticlines,
 - c) Influx of nutrient-rich water, provided generally by upwelling, into a shallow marine region with a slow rate of terrigenous deposition, and often a warm arid climate,

- d) Development of a high productivity zone with a prolific biota;
- e) Accumulation, upon death, of the remains of the biota on the bottoms of the sheltered, semi-restricted depressions,
- f) Development of a phosphorus rich solution, upon the decay of the soft parts of the accumulated dead biota, in the depressions,
- g) Formation of sedimentary apatite either by direct precipitation or by phosphatization in the presence of the phosphorus rich solution,
- h) Development of phosphorite particles by a number of possible ways such as : reworking, epigenesis of pre-existing non-phosphoritic particles, filling of cavities or pores, phosphatization of faecal pellets and direct precipitation on a suitable surface (quartz or calcite grain, bone lathes, etc.),
- i) Reworking of the deposited phosphorites by being subjected to weathering and erosion processes or through the action of groundwater.

8. Reworking and other diagenetic changes have played an important role in the development of the studied deposits.

9. The Phosphorite deposits of northwestern Saudi Arabia are generally associated with the axes of the synclinal folds and further exploration should concentrate in such structures.

REFERENCES

- Abed, A.M. & Fakhouri, K. 1990. Role of microbial processes in the genesis of Jordanian Upper Cretaceous phosphorites. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 193-203.
- Aksoy, A., Naqvi, A.A., Khiari, F.Z., Abujarad, F., Al-Ohali, M. & Sumani, M. 1994. Elemental analysis using natural gamma-ray spectroscopy. *Nuclear Instruments and Methods in Physics Research A* 353, pp. 558-561.
- Algarra, A.M. & Navas, A.S. 1995. Phosphate stromatolites from condensed cephalopod limestones, Upper Jurassic, Southern Spain. *Sedimentology*, 42, pp. 893-919.
- Alsharhan, A. & Nairn, A. 1990. A review of the Cretaceous formations in the Arabian Peninsula and Gulf, Part 3 : Upper Cretaceous (Aruma Group) stratigraphy and paleogeography. *Jour. Petro. Geo.*, 13, pp. 247-266.
- Altschuler, Z.S. 1973. The weathering of phosphate deposits : Geochemical and environmental aspects. In : *Environmental phosphorus Handbook*. Wiley, New York, pp. 33-96.
- Altschuler, Z.S. 1980. The geochemistry of trace elements in marine phosphorites : Part I. characteristic abundances and enrichment. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) *Marine Phosphorites-Geochemistry, Occurrence, Genesis*. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 19-30.
- Altschuler, Z.S., Cathcart, J.B. & Young, E.J. 1964. The geology and geochemistry of the Bone Valley Formation and its phosphate deposits, west central Florida. A Guidebook for field No. 6, *Geol. Surv. Prof. Pap.*, 575-B, B1-B9.
- Altschuler, Z.S., Clark, R.S. & Young E.J. 1958. Geochemistry of uranium in apatite and phosphorite. *U.S. Geol. Surv. Prof. Pap.*, 314-D, pp. 45-90.
- Ames, L.L. 1959. The genesis of carbonate-apatite. *Econ. Geol.*, 54, pp. 829-841.
- Ames, L.L. 1960. Some cation substitutions during the formation of phosphorite from calcite. *Econ. Geol.*, 55, pp. 354-362.

Andrei, V.I. 1994. Cenomanian phosphorites in the former Soviet Union. *Sediment. Geol.*, 94, pp. 109-127.

ARAMCO, 1952*a*. Gravity meter map : "Jawf-Sakaka" sheet. Plan B-1574-B. 1 : 5000,000-scale. In Data File RF-Df-00-05.

ARAMCO, 1952*b*. Gravity meter map : "Wadi-Sirhan" sheet. Plan B-1575-B. 1 : 500,000-scale. In Data File RF-Df-00-05.

Arda, O., Saltoglu, T., Alparslan, E. & Akyuz, T. 1976. Geochemical and mineralogical analysis of the Mazidagi phosphates containing uranium, vanadium, fluorine and other trace elements; and views on the probability of uranium recovery. *Bull. Miner. Res. Explor. Inst. Turkey*, 87, pp. 33-48.

Arnold, P.W. 1950. The nature of precipitated calcium phosphates. *Trans. Faraday Soc*, 46, pp. 1061-1072.

Austen, R.A.C. 1848. On the position in the Cretaceous series of beds containing phosphate of lime. *Quarterly Journal of the Geological Society of London*, 16, pp. 256-262.

Axelrod, S., Metzger, A. & Rohrllich, V. 1980. The petrography of Palestinian Phosphorites as related to their beneficiation. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) *Marine Phosphorites-Geochemistry, Occurrence, Genesis*. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 153-165.

Bachra, B. N., Travtz, O.R. & Simon, S.L. 1965. Precipitation of calcium and carbonates and phosphates-III : The effect of magnesium and fluoride ions on the spontaneous precipitation of calcium carbonates and phosphates. *Archives Oral Biology*, 10, pp. 731-738.

Balson, P.S. 1990. Episodes of phosphogenesis and phosphorite concretion formation in the North Sea Tertiary. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 125-137.

Basham, I. 1984. XRF and XRD analyses of Sirhan-Turayf Phosphates. British Geological Survey Analytical Report, London, U.K. In Data File RF-Df-00-05.

Bashir, S. 1977. Radioactivité et état d'équilibre radioactif de quelques phosphates jordaniens : Leues caractères pétrologiques, minéralogiques, cristallographiques et géochimiques. Thèse de docteur ingénieur, Institut National Polytechnique de

Lorraine, Ecole National Supérieure de Géol. Appliquée et de Prospection Minière, Nancy.

Baturin, G.N. 1971. Formation of phosphate sediments and water dynamics. *Oceanology*, 11, pp. 372-376.

Baturin, G.N. 1971. Stages of phosphorite formation on the ocean floor. *Nature Phys. Sc.*, 232, pp. 61-62.

Baturin, G.N. 1982. Phosphorites on the sea floor : Origin, Composition and Distribution. *Developments in Sedimentology*, 33, pp. 279-295.

Baturin, G.N., Merkulova, K.I. & Chalov, P.I. 1972. Radiometric evidence for recent formation of phosphatic nodules in marine shelf sediments. *Mari. Geol.*, 13, pp. 37-41.

Bayliss, D.D. 1981*a*. Riofinex Phosphate Project, Saudi Arabia : Review and re-examination of ditch samples, picked slides, and washed residues previously analyzed by Robertson Research International Ltd. Prepared by the Geoscience Consulting Unit Ltd., U.K. and issued as Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-01-13, Jiddah.

Bayliss, D.D. 1981*b*. Lithostratigraphy and biostratigraphy of the Sirhan-Turayf Phosphate Area. Prepared by the Geoscience Consulting Unit Ltd., U.K. and issued as Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-01-25, Jiddah.

Bayliss, D.D. 1982*a*. Review of Robertson Research International Report No. 4427. Report prepared by Poltec Ltd., U.K. In Data File RF-OF-01-25, Jiddah.

Bayliss, D.D. 1982*b*. Sirhan-Turayf Phosphate Project : Lithostratigraphy and biostratigraphy of outcrop and borehole sections (P-series holes and U.S.G.S. Wt-Borehole Sections). Thaniyat and Wadi Sirhan Area Subdivisions. Prepared by Poltec Ltd., U.K. and issued as Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-02-17, Jiddah.

Bayliss, D.D. 1982*c*. A Review of the Lithostratigraphy and biostratigraphy of the Sirhan-Turayf Phosphate Area. Prepared by Poltec Ltd., U.K. and issued as Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-03-06, Jiddah.

Bayliss, D.D. 1983. A Review of the Lithostratigraphy and biostratigraphy of the Sirhan-Turayf Phosphate Area. Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-03-6, Jiddah.

Bayliss, D.D. 1984. A paleontological and petrological study of nineteen borehole samples and fifteen field samples from northwestern Saudi Arabia, Sirhan-Turayf Phosphate Area. Prepared by Poltec Ltd., U.K. In Data-File RF-DF-00-05.

Bender, F. 1974. Geology of Jordan : Contrib. Regional Geol. of the Earth. Suppl. (ed.) in English, 7, with minor revisions, Gebreuder Borntraeger, Berlin-Stuttgart.

Bentor, Y.K. 1953. Relations entre la tectonique et les dépôts de phosphates dans le Neguev Palestine. 19th Session of the International Geological Congress, Algiers, 1952, Section II, 93, pp. 93-101.

Bentor, Y.K. 1979. Modern phosphorites-not sure guide for the interpretation of ancient deposits : Rep. In : Burnet, W.C. & Sheldon, R.P. (eds.) Marine Phosphorite Sediments Workshop. Honolulu, pp. 29.

Bentor, Y.K. 1980. Phosphorites-The unsolved problems. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 3-18.

Berge, J.W. & Jack, J. 1982. The phosphorites of west Thaniyat Turayf, Saudi Arabia. Econ. Geol., 77, pp. 1912-1922.

Berggren, W.A. 1969. Cenozoic chronostratigraphy, planktonic foraminiferal zonation and the radiometric time-scale. Nature, 224 (5224), pp. 1072-1075.

Berggren, W.A. 1971. Tertiary boundaries. In : Funnel, B.F. & Reidle, W.R. (eds.) Micropaleontology of the Ocean. Cambridge Univ. Press, pp. 693-809.

Berggren, W.A. 1972. A Cenozoic time scale, some implications for regional geology and paleobiogeography. Lethaia, 5, pp. 195-215.

Berner, R.A. 1973. Phosphate removal from sea water by absorption on volcanogenic ferric oxides. Earth Planet. Sci. Letters., 18, pp. 77-86.

Birch, G.F. 1979b. Phosphatic rocks in the western margin of South Africa. Jour. Sed. Pet., 49, pp. 93-110.

Birch, G.F. 1980. A model of penecontemporaneous phosphatization by diagenetic and authigenic mechanisms from the western margin of Southern Africa. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry,

Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 79-100.

Blackwelder, E. 1916. The geologic role of phosphorus. *Am. Jour. Sci.*, 4th Ser, 42, pp. 285-298.

Blow, W.H. 1969. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. *Proc. Intern. Conf. Planktonic Microfossils*, 1st, 2, pp. 199-421.

Blow, W.H. 1979. *The Cainozoic Globigerinida*. Brill, E.J., Leiden, 3 vols., 1413 pp.

Boris, F.F. & Patrick, G. 1995. Can REE patterns and U-Th variations be used as a tool to determine the origin of apatite in clastic rocks?--comment. *Sediment. Geol.*, 96, pp. 281-282.

Bostrom, K., Tallbacka, L. & Joensuu, O. 1968. Evidence for carbonatitic volcanism on active oceanic ridges (abs.). *Am. Geophys. Union Trans.*, 49, pp. 364.

Boujo, A., Faye, B., Giot, D., Lucas, J., Manivit, H., Monciardini, C. & Prévôt, L. 1980. The early Eocene of the lake of Guiers (western Senegal)-reflections on some characteristics of phosphate sedimentation in Senegal. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) *Marine Phosphorites-Geochemistry, Occurrence, Genesis*. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 207-213.

Bramkamp, R.A., Brown, G.F., Hom, D.A. & Layne, N.M. Jr. 1963*a*. Geology of the Wadi As-Sirhan Quadrangle, Saudi Arabia. U.S.G.S., Misc. Geol. Inv. Map 1-200A, DGMR, Jiddah, Saudi Arabia.

Bramkamp, R.A., Ramirez, L.F., Steineke, M. & Reiss, W.H. 1963*b*. Geology of the Jawf-Sakakah Quadrangle, Saudi Arabia. U.S.G.S., Misc. Geol. Inv. Map 1-201A, DGMR, Jiddah, Saudi Arabia.

Brasier, M.D. 1990. Phosphogenic events and skeletal preservation across the Precambrian-Cambrian boundary interval. 1990. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 289-303.

Breger, D.L. 1911. Origin of Lander oil and western phosphate. *Mining Eng. World*, 35, pp. 631-633.

Brodsкая, N.G. & Ilyinskaya, M.N. 1968. Phosphate accumulation in volcanic regions. In : Sedimentology and useful fossils of past volcanic regions, 2. Proceedings of The Geological Institute, USSR Academy of Sciences, 196, pp. 193-292.

Brodsкая, N.G. & Ilyinskaya, M.N. 1970. Principal genetic types of phosphate deposits associated with an endogenic source of phosphorous. In : State and problems of Soviet Lithology. All Union Lithological Conference, 8th Report, 3, pp. 257-262.

Brongersma-Sanders, M. 1969. Permian wind and the occurrence of fish and metals in the Kupferschiefer and Marl Slate. 15th Inter-University Geol. Cong., Univ. of Leicester, Proc., pp. 61-71.

Bruinsma, J.W., Cater, M.C., Futyan, A. & Morley, R. 1978. Sedimentological and biostratigraphical studies of selected borehole and field samples from the Sirhan-Turayf Basin, northwestern Saudi Arabia. Report NO. 623 prepared by Robertson Research (Singapore) Private Ltd., and issued by the Riofinex Geological Mission as Open-File Report RFO-1979-3, Jiddah.

Buckland, W. 1829. On the discovery of coprolites, or fossil faces, in the Lias at Lyme Regis. Transactions of the Geological Society of London, 3, pp. 223-236.

Buday, T. 1980. The regional geology of Iraq : Stratigraphy and paleogeography. Organization of Minerals, Baghdad, 445 pp.

Burnett, W.C. 1977. Geochemistry and origin of phosphorite deposits from off Peru and Chile. Geol. Soc. America Bull., 88, pp. 813-823.

Burnett, W.C. & Veeh, H.H. 1977. Uranium-series disequilibrium studies in phosphorite nodules from the west coast of South America. Geochim. Cosmochim. Acta, 41, pp. 755-764.

Burnett, W.C., Veeh, H.H. & Soutar, A. 1980. U-series, Oceanographic and Sedimentary evidence in support of recent formation of phosphate nodules off Peru. In : Bendor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 61-71.

Bushinski, G.I. 1935. Structure and origin of phosphorites of the U.S.S.R. J. Sed. Petr., 5, pp. 81-92.

Bushinski, G.I. 1964. Shallow water origin of phosphorite sediments. In : van Straiten, L.M. (ed.) Deltaic and shallow marine deposits. Amsterdam, Elsevier, pp. 62-70.

Bushinski, G.I. 1966. The origin of marine phosphorites. *Lithology and Mineral resources*. Consultants Bureau, New York, N.Y., pp. 292-311.

Calvert, S.E. & Price, N.B. 1971. Upwelling and nutrient regeneration in the Benguela current. *Deep-Sea Res.*, 18, pp. 505-523.

Capetta, H. & Riddler, G.P. 1985. Age-determination on a selection of fish-remains from phosphorite beds in the Sirhan-Turayf region. Riofinex International Report. In Data-File RF-Df-00-05.

Cater, M.C. 1978. Biostratigraphy of field samples from TAPLINE road sections between Badanah and Turayf, Saudi Arabia, and from the P.1 borehole near Turayf, Saudi Arabia. Report NO. 2365. Prepared by Robertson Research International Limited (UK) and issued by the Riofinex Geological Mission as Open-file Report RFO-1979-40. Jiddah.

Cater, M.C., Futyan, A. & Morley, R., 1978. The biostratigraphy of selected borehole and field samples from the Sirhan-Turayf basin, northern Saudi Arabia. Report NO. 4182. Prepared by Robertson Research International Ltd. (UK).

Cathcart, J.B. 1968. Florida-type phosphorite deposits of the United States : origin and techniques for prospecting. *U.N. Mineral Resource., Develop. Ser.*, 32, pp. 178-186.

Cathcart, J.B. 1968. Texture and composition of outcropping phosphorite in the Turayf Region, northwestern Saudi Arabia. *U.S.G.S. Prof. Paper* 600-C.

Cathcart, J.B., 1966. Phosphate deposits in the Jawf-Sakakah Basin, Saudi Arabia, Part III : Preliminary observations on the textures and composition. *U.S. Geol. Survey, Tech. Letter* 83, pp. 22.

Cayeux, L. 1934. The phosphatic nodules of Agulhas-Bank. *Ann. S. Afr. Mus.*, 31, pp. 105-136.

Cayeux, L. 1936. Phosphates sédimentaires et bactéries. *Comptes rendus*, 203, pp. 1198-1200.

Cayeux, L. 1939. Les phosphates de Chaux sédimentaires de France. *Serv. de la Carte Géol. de la France*, Paris, I, 350 pp.

Choudhuri, R. 1990. Two decades of phosphorite investigations in India. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 305-311.

Christie, R.L. 1978. Sedimentary phosphate deposits : an interim review. Geol. Survey of Canada, Paper 78-20, 9 pp.

Clark, F.W. 1924. The data of geochemistry. U. S. Geol. Surv. Bull. 770.

Clarke, R.S. & Altschuler, Z.S. 1958. Determination of the oxidation state of uranium in apatite and phosphorite deposits. *Geochim. Cosmochim. Acta*, 13, pp. 127-142.

Clegg, I.H. 1981. Mineral exploration in the Kingdom of Saudi Arabia by mining companies under concession, 1971-1980. DGMR-OF-01-12.

Collenette, P.C. 1977. Revised Phosphate Project in the northern region. Memorandum from the technical advisor, 13 March, 1977 (23 Rabbi Awal, 1397H). In Data-File Rf-Df-00-05.

Collet, L.W. 1905. Les concrétions phosphatées de l' Agulhas-Bank . *Proc. Roy. Soc. Edin.*, 25, pp. 862-893.

Compton, J.S., Hall, D.L., Mallinson, D.J. & Hodell, D.A. 1994. Origin of dolomite in the phosphatic Miocene Hawthorn Group of Florida. *Jour. Sedi. Resear.*, A64 (3), pp. 638-649.

Cook & Cook, J.R. 1985. Marine biological changes and phosphogenesis around the Cretaceous-Tertiary boundary. *Science Géologiques, Mémoire*, 77, pp. 105-108.

Cook, P.J. 1972. Petrology and geochemistry of the phosphate deposits of northwestern Queensland, Australia. *Econ. Geol.*, 67, pp. 1193-1213.

Cook, P.J. 1976. Sedimentary phosphate deposits. In : Wolf, K.H. (ed.) *Handbook of stratabound and stratiform ore deposits*. Amsterdam, Elsevier Pub. Co., 7, pp. 505-535.

Cook, P.J. and McElhinny, M.W. 1979. A re-evaluation of the spatial and temporal distribution of sedimentary phosphate deposits in the light of plate tectonics. *Economic Geology*, 74, pp. 315-330.

Cook, P.J., Shergold, J.H., Burnett, W.C. & Riggs, S.R. 1990. Phosphorite research : a historical overview. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 1-22.

Cullen, D.J. 1980. Distribution, Composition and Age of submarine phosphorites on Chatham Rise, east of New Zealand. In : Bendor, Y.K. & Scripps Institution of

Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 139-148.

Dabous, A.A. 1994. The geochemistry of uranium and thorium isotopes in the Western Desert of Egypt. *Geochim. Cosmochim. Acta*, 58 (21), pp. 4591-4600.

Davies, D.C. 1875. The phosphorite deposits of North Wales. *Quarterly Journal of the Geological Society of London*, 31, pp. 357-364.

De La Beche, H. 1849. Phosphate of lime in green sand and marl. *American Journal of Science*, 58, pp. 422-424.

Delamette, M. 1988. L'évolution du domaine helvétique entre Bauges et Morcles de l'Aptien supérieur au Turonien. Séries condensées, phosphorites et circulations océaniques. In : Publications du Département de Géologie et de Paléontologie de l'Université de Genève, 5.

Deputy Ministry for Mineral Resources. 1981. Technical work program, 1401-1402H, Jiddah.

Deputy Ministry for Mineral Resources. 1981. Technical work program, 1402-1403H, Jiddah.

Deputy Ministry for Mineral Resources. 1983. Technical work program, 1403-1404H, Jiddah.

Deputy Ministry for Mineral Resources. 1984. Technical work program, 1405H, Jiddah.

Deputy Ministry for Mineral Resources. 1985. Technical work program, 1406H, Jiddah.

Dill, H.G. 1994. Can REE patterns and U-Th variations be used as a tool to determine the origin of apatite in clastic rocks?. *Sediment. Geol.*, 92, pp. 175-196.

Donnelly, T.H., Shergold, J.H., Southgate, P.N. & Barnes, C.J. 1990. Events leading to global phosphogenesis around the Proterozoic / Cambrian boundary. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 273-287.

Doubinger, J. 1978. Dinokystes et Acritarches des sédiments phosphates de Ganntour (Maroc). *Sci. Géol. Bull.*, 31, pp. 3.

Eirik, J.K. & Richard, J.W. 1994. High closure temperatures of the U-Pb system in large apatites from the Tin Mountain pegmatite, Black Hills, South Dakota, U.S.A. *Geochim. Cosmochim. Acta*, 58 (18), pp. 3845-3853.

El-Asa'ad, G. 1983*a*. Lithostratigraphy of the Aruma Formation in central Saudi Arabia. *Jordanian Geological Association, Special Publication 1*, pp. 72-86.

El-Asa'ad, G. 1983*b*. Bio-and chronostratigraphy of the Aruma Formation in central Saudi Arabia. *Jordanian Geological Association, Special Publication 1*, pp. 87-111.

El-Asa'ad, G. 1987. Rudist fauna from the Late Cretaceous of central Saudi Arabia. *Journal of the College of Science, King Saud University*, 18, pp. 53-71.

El-Kammar, A.M., Zayed, M.A. & Amer, S.A. 1979. Rare Earths of the Nile Valley Phosphorites, Upper Egypt. *Chem. Geol.*, 24, pp. 69-81.

El-Khayal, A.A. 1974. Planktonic foraminiferal biostratigraphy of the lower Tertiary Hibr Strata of northwestern Saudi Arabia. *Fac. Sci. Bull., Riyadh Univ.*, 6, pp. 174-194.

El-Naggar, Z.R. & Al-Rifa'iy, I. 1972*a*. Microfacies analysis of the type Magwa Formation of Kuwait, Arabia. *Proceedings of the 8th Arab Petrol. Congr., Algeria*, Paper 95 (B-3), pp. 1-101.

El-Naggar, Z.R. & Al-Rifa'iy, I. 1972*b*. Stratigraphy and Microfacies of the type Magwa Formation of Kuwait, Arabia, part 1 : Rumaila Limestone Member. *Amer. Assoc. Petro. Geol. Bull.*, 56, pp. 1465-1493.

El-Naggar, Z.R. & Dawood, A.M. 1979. Pre-historic life (In Arabic). *Scientific Puyb. House, Kuwait*, 160 pp.

El-Naggar, Z.R. & Kamel, S. 1988. Biostratigraphical analysis of the Late Cretaceous-Early Paleogene succession in the Turayf area, northwestern Saudi Arabia. *Revista Espanola De Micropaleontologia*, xx (3), pp. 329-353.

El-Naggar, Z.R. 1966. Stratigraphy and planktonic foraminifera of the Upper Cretaceous-Lower Tertiary succession in the Esna-Idfu region, Nile Valley, Egypt. *Bull. Brit. Mus. (Nat. His.), Geol., Suppl. 2*, 291 pp.

El-Naggar, Z.R. 1967*a*. Correlation of the various planktonic foraminiferal zonations of the Paleocene. *Abstracts. 1st. Intern. Conf. Planktonic Microfossils (Geneva)*, pp. 31-32.

El-Naggar, Z.R. 1967b. The occurrence of *Globorotalia inconstans* (Subbotina) in the Type Heersian of Belgium and the position of the Heersian in Paleocene Stratigraphy. Rev. Micropal., 10, pp. 97-106.

El-Naggar, Z.R. 1969. New suggestions for the division and correlation of Paleocene strata by the use of Planktonic foraminifera. Proc. 1st. Intern. Conf. Planktonic Microfossils (Geneva, 1967), 2, Brill, Leiden, pp. 202-224.

El-Naggar, Z.R. 1971. On the classification, evolution and stratigraphical distribution of the Globigerinacea. Proc. Intern. Conf. Planktonic Microfossils, 2nd., 2, pp. 421-479.

El-Naggar, Z.R., Saif, S.I. & Abdennabi, A. (Ms.). Stratigraphical analysis of the phosphate deposits in northwestern Saudi Arabia, Final Report submitted to SANCST, Riyadh.

El-Naggar, Z.R., Saif, S.I. & Abdennabi, A. 1982. Stratigraphical analysis of the phosphate deposits in northwestern Saudi Arabia, Progress Reports 1-4 submitted to SANCST, Riyadh, 120 pp.

El-Nakhal, H. & El-Naggar, Z.R. 1990. Stratigraphy and Planktonic Foraminifera of the Aruma Group (Cretaceous) in Kuwait, Arabia. Damascus University Journal, 6, pp. 13-52.

El-Nakhal, H. 1973. Stratigraphy and planktonic foraminifera of the Late Cretaceous-Early Paleogene succession in Kuwait. Unpublished Ph.D. thesis, Kuwait University, Kuwait, 566 pp.

Ennever, J. 1963. Microbiologic calcification. New York. Acad. Sci. Annals., 109, pp. 4-13.

Föllmi, K.B. 1990. Condensation and phosphogenesis : example of the Helvetic mid-Cretaceous (northern Tethyan margin). In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 237-252.

Föllmi, K.B. 1995. 160 m.y. record of marine sedimentary phosphorus burial : Coupling of climate and continental weathering under greenhouse and icehouse conditions. Geology, 23 (6), pp. 503-506.

Fakhry, A.A., El-Beheri, K.M. & Eid, M.A. 1989. Preliminary study on the vertical distribution of rare earths in an Egyptian phosphorite deposit. Jour. of the Less-Common Metals, 148, pp. 59-65.

Fischer, A.G. & Jerome, D. 1973. Geochemistry of minerals containing phosphorus. In : Environmental Phosphorus Handbook, 141-152. Wiley, New York, London, Sydney and Toronto.

Fleischer, M. 1956. Minor elements in some sulfide minerals. Econ. Geol. 50th Anniv., pp. 970-1024.

Fox, A. & Brown, R. 1968. The geology and reservoir characteristics of Zakum oil field, Abu Dhabi. Second Technical Symposium of the Society of Petroleum Engineers of AIME (Saudi Arabia Section, Dhahran), pp. 39-66.

Freas, D.H. & Eckstrom, C.L. 1968. Areas of potential upwelling and phosphorite deposition during Tertiary, Mesozoic and Late Paleozoic time. U.N. Mineral Resource., Develop. Ser., 32, pp. 228-238.

Freas, D.H. 1964. Stratigraphy and sedimentation of phosphorite in the central Florida phosphate district. (Abstr.). Econ. Geol., 59, 1619.

Fuller, A.O. 1979. Phosphate occurrences on the western and southern coastal areas and continental shelves of Southern Africa. Econ. Geol. 74, 221-231.

Futyan, A. & Nicolson, C.A. 1979. Saudi Arabia phosphate stratigraphic study : Stratigraphical, petrological and micropaleontological studies of 195 field samples from the Wadi-Sirhan Basin, northern Saudi Arabia (2 vols.). Report NO. 2427 prepared by Robertson Research International Ltd. (UK) and issued by the Riofinex Geological Mission as Open-File Report RFO-1979-41, Jiddah.

Futyan, A. & Nicolson, C.A. 1980a. Biostratigraphical and lithological study of 285 ditch cuttings and core samples from the Wadi Sirhan-Turayf area, northern Saudi Arabia. Report NO. 2497 prepared by Robertson Research International Ltd. (UK) and issued by the Riofinex Geological Mission as Open-File Report RFO-1980-4, Jiddah.

Futyan, A. & Nicolson, C.A. 1980b. Biostratigraphical and lithological study of 319 ditch cuttings and core samples from the Wadi Sirhan-Turayf area, northern Saudi Arabia. Report NO. 4427 P / F prepared by Robertson Research International Ltd. (UK) and issued as Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-01-12, Jiddah.

Futyan, A. 1979. Literature study and synthesis of the stratigraphy and sedimentation of the East Mediterranean Upper Cretaceous and Lower Tertiary Phosphate Deposits. Report NO. 2409 prepared by Robertson Research International Ltd. (UK) and issued by the Riofinex Geological Mission as Open-File Report RFO-1979-5, Jiddah.

Futyan, A. 1980a. Biostratigraphic and petrographic study of selected samples from P21 and P43 wells from the Wadi Sirhan-Turayf Area, northern Saudi Arabia. Report NO. 4471 P / F prepared by Robertson Research International Ltd. (UK). In Data-File RF-DF-00-05.

Futyan, A. 1980b. Biostratigraphical and petrographical study of cuttings samples from P44, P46 to P48 and P56 to P61 boreholes, drilled in Thaniyat-Wadi Sirhan area, northern Saudi Arabia. Report NO. 4495 P / F prepared by Robertson Research International Ltd. (UK) and issued as Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-01-11, Jiddah.

Futyan, A., Nicolson, C.A. & Attewell, R.A. 1979. Saudi Arabia Phosphate stratigraphic study : Stratigraphical, petrographical and micropaleontological studies of wells and field sections from the Sirhan-Turayf Phosphate Area, northern Saudi Arabia (3 vols.). Report NO. 2406 prepared by Robertson Research International Ltd. (UK) and issued by the Riofinex Geological Mission as Open-File Report RFO-1979-38, Jiddah.

Gardner, J.V. 1973. Eastern equatorial Atlantic : Sea-surface temperature and circulation response to global climatic changes during the past 200,000 years (abs.). Geol. Soc. America Abstracts with Programs, 5, pp. 629.

Gaudette, H.E. & Lyons, W.B. 1978. Phosphate geochemistry in nearshore carbonate sediments : Evidence of apatite formation : Abstr. In : Friedman, G.M. (ed.) Tenth Intern. Congr. Sedimentology, 1, pp. 238.

Gaudette, H.E. & Lyons, W.B. 1980. Phosphate geochemistry in nearshore carbonate sediments : A suggestion of apatite formation. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 215-225.

Gimmel'farb, V.M., Karsil'nikova, A.A. & Tushina, A.M. 1959. Classification des phosphorites. Dokl. (Proc.) Acad. Sci. USSR., 128 (6), pp. 1258-1261.

Giresse, P. 1980. Phosphorus concentrations in the unconsolidated sediments of the tropical Atlantic shelf of Africa south of the equator-oceanographic comments. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 101-116.

Giresse, P. 1980. The Maastrichtian phosphate sequence of the Congo. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry,

Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 193-205.

Glenn, C.R. 1990. Depositional sequences of the Duwi, Sibāiyya and Phosphate Formations, Egypt : phosphogenesis and glauconitization in a Late Cretaceous epeiric sea. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 205-222.

Goldberg, E.D., Koide, M., Schmitt, R. A. & Smith, H.V. 1963. Rare earth distribution in the marine environment. J. Geophys. Res., 68, pp. 4209-4217.

Gony, J.N. 1971. Etude cristallographique du phosphate uranifère de Bakouma (République Centr Africaine). Commis. Energ. At. {Fr.}, Rapp., CEA-R-4003.

Grabau, A. W. 1919. Prevailing stratigraphic relationships of the bedded phosphate deposits of Europe, North Africa, and North America (abstract). Bull. Geol., Soc. Am., 30, pp. 104.

Granges International Mining. 1980. Geology, in Vol. 3 of Thaniyat Phosphate Project, final exploration report (6 Vols.), Stockholm.

Gulbrandsen, R. 1977. Byproduct resources in phosphate ore of southeastern Idaho. Geol. Soc. America Abstracts with Programs, 9, pp. 728.

Gulbrandsen, R.A. & Roberson, C.E. 1973. Inorganic phosphorus in sea water. In : Griffith, E.J., Beeton, A., Spencer, J.M. & Mitchell, D.T. (eds) Environmental phosphorus handbook, New York, John Wiley and Sons, pp. 117-140.

Gulbrandsen, R.A. 1966. Chemical composition of phosphorites of the Phosphoria formation. Geochim. Cosmochim. Acta, 30, pp. 769-778.

Gulbrandsen, R.A. 1969. Physical and chemical factors in the formation of marine apatite. Econ. Geol., 64, pp. 375-382.

Gulbrandsen, R.A., Roberson, C.E. & Neil, S.T. 1984. Time and the crystallization of apatite in seawater. Geochim. Cosmochim. Acta, 48, pp. 213-218.

Høgdahl, O. 1967. Distribution of the rare earths in sea water. Prog. Rept., 4, to NATO, Central Instit. for Ind. Res., Blindern, 34 pp.

Hassan, M., Hossin, A. & Combaz, A. 1976. Fundamentals of the differential Gamma-ray log interpretation technique. Transactions, SPWLA.

Hathawayt, J.C., McFarlan, P.F. & Ross, D.A. 1970. Mineralogy and origin of sediments from drill holes on the continental margin off Florida. U.S Geological Survey, Professional Paper, 581-E, 26 pp.

Heath, G.R. 1974. dissolved silica and deep-sea sediments. In : Hay, W.W. (ed.) studies in Paleo-Oceanography. Society of Economic Paleontologists and Mineralogists, Special Publication, 20, pp. 155-181.

Heggie, D.T., Skyring, G.W., O'Brine, G.W., Reimers, C., Herczeg, A., Moriarty, D.J.W., Burnett, W.C. & Milnes, A.R. 1990. Organic carbon cycling and modern phosphorite formation on the East Australian continental margin : an overview. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 87-117.

Heinsalu, H.N. & Ilyin, A.V. 1990. Early Ordovician shelly phosphorites of the Baltic Phosphate Basin. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 253-259.

Hicks, H. 1875. On the occurrence of phosphates in the Cambrian rocks. Quarterly Journal of the Geological Society of London, 31, pp. 368-383.

Hite, R.J. 1976. Possible genetic relationships between evaporites, phosphorites and iron-rich sediments (abs.). Internat. Geol. Cong., 25th, 3, pp. 835.

Hodson, P.H. 1973. The role of phosphorus in bacteria and viruses. In : Griffith, E.J., Beeton, A., Spencer, J.M. & Mitchell, D.T. (eds.) Environmental phosphorus handbook. New York, John Wiley and Sons, pp. 451-474.

Howard, P.F. & Hough. M.J. 1979. On the geochemistry and origin of the D tree, Wornarah, and Sherrin Creek phosphorite deposits of the Georgina Basin, northern Australia. Econ. Geol., 74, pp. 260-284.

Howard, P.F. 1979. Phosphate. Econ. Geol. 74, 192-194.

Howard, P.F. 1990. The distribution of phosphatic facies in the Georgina, Wiso and Daly River Basin, Northern Australia. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 261-272.

Hudleston, W.H. 1875. On the chemical analyses of the Cambrian rocks (appendix to paper by Henry Hicks). Quarterly Journal of the Geological Society of London, 31, pp. 376-385.

Irvine, R. & Anderson, W.S. 1891. On the action of metallic and other salts on carbonate of lime. Royal Soc. Edinburgh Proc., 17, pp. 42-52.

Jacques, L., El Mâti, E. & Liliane, P. 1990. Experimental study of the substitution of Ca by Sr and Ba in synthetic apatites. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 33-47.

Jane, S.T., Rolf, S.A., Michael, L.III. & Fred, T.M. 1995. Crystal chemistry, and thermodynamic and kinetic properties of calcite, dolomite, apatite, and biogenic silica : applications to petrologic problems. Sediment. Geol. 95, pp. 11-37.

Jarvis, I. 1980a. Geochemistry of phosphatic chalks and hardgrounds from the Santonian to early Campanian (Cretaceous) of northern France. Journal of the Geological Society of London, 137 (6), pp. 705-722.

Jarvis, I. 1980b. The initiation of phosphatic chalk sedimentation-the Senonian (Cretaceous) of the Anglo-Paris basin. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 167-192.

Kamel, S. 1985. Stratigraphical and microfacies analysis of the Late Cretaceous-Early Paleogene phosphate-bearing succession in Turayf area, Saudi Arabia. Unpublished M.Sc. Thesis, KFUPM, Saudi Arabia.

Kazakov, A.V. 1937. The phosphorite facies and the genesis of phosphorites. Int. Geol. Congr., 17th Sess., pp. 95-113.

Kazakov, A.V. 1950. The fluorapatite system of equilibrium in conditions of formation of sedimentary rocks. Akad. Nauk. S.S.S.R. Geol. Ser., 144 (40), pp. 1-21.

Kember, E. & Zimmerle, W. 1983. Facies patterns of a Cretaceous / Tertiary subtropical upwelling system (Great Syrian Desert) and an Aptian / Albian bored upwelling system (NW Germany). In : Theide, J & Suess, E (eds) part B, "Coastal Upwelling". Plenum Press, New York, pp. 501-533.

Kharin, G.S. 1974. The phosphatic rocks of the submarine Jan Mayan ridge (North Atlantic) and their relation to volcanism. Lith. Miner. Resour. U.S.A, 9 (1), pp. 32-35.

Kidder, D.L. & Eddy-Dilek, C.A. 1994. Rare earth element variation in phosphate nodules from mid-continent Pennsylvanian Cyclothems. Jour. Sedi. Resear., A64 (3), pp. 584-592.

Killeen, P.G. & Carmichael, C.M. 1970. Gamma-ray spectrometer calibration for field analysis of thorium, uranium and potassium. *Canad. Jour. Earth Scie.*, 7, pp. 1093-1098.

Klement, R., Hüter, F. & Köhrer, K. 1942. Bildet sich carbonatapatit in Wasserigen Systemen. *Zeitschr. Elektrochemie*, 48, pp. 334-336.

Klup, J.L., Turekian, K. & Boyd, D.W. 1952. Strontium content of limestones and fossils. *Bull. Geol. Soc. Am.*, 63, pp. 701-716.

Kluyver, H.M., Berg, V.B., Ryder, J.R. & Van Eck, M.V. 1981. Sirhan-Turayf phosphate project : Results of work carried out under the Phosphate Agreement, 29th Dhul Hijjah 1398-30th Jumad Thani 1401 A.H. (29th Nov. 1978-4th May 1981). Open-file Rep. RF-TR-01-5, DGMR, Jiddah, Saudi Arabia, 77 pp.

Kolodny, Y. & Kaplan, I.R. 1970. Uranium isotopes in seafloor phosphorites. *Geochim. Cosmochim. Acta*, 34, pp. 3-24.

Kolodny, Y. 1969. Are marine phosphorites forming today?. *Nature*, 224, pp. 1017-1019.

Kolodny, Y. 1980. The origin of phosphorite deposits in the light of occurrences of recent sea-floor phosphorites (extended abstract). In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) *Marine Phosphorites-Geochemistry, Occurrence, Genesis*. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 249.

Krajewski, K. 1981a. Phosphate microstromatolites in the High-Tatric Albian Limestones in the Polish Tatra Mountains. *Bulletin de Académie polonaise des Sciences, Série des Sciences de la Terre*, 29, pp. 175-183.

Krajewski, K. 1981b. Phosphate pisolite structures from condensed limestones of the High-Tatric Albian (Tatra Mts.). *Annales de la Société Géologique de Pologne*, 51, pp. 339-352.

Krajewski, K. 1983. Albian pelagic phosphate-rich macrooncooids from the Tatra Mts., Poland. In : Peryt, T.M. (ed.) *Coated Grains*. Springer Verlage, Berlin, pp. 344-357.

Krajewski, K. 1984. Early diagenetic phosphate cements in the Albian condensed glauconitic limestone of the Tatra Mountains, Western Carpathians. *Sedimentology*, 31, pp. 443-470.

Krumbein, W.C. & Garrels, R.M. 1952. Origin and classification of chemical sediments in terms of pH and oxidation-reduction potential. *Jour. Geology*, 60, pp. 1-21.

Lamboy, M. 1990. Microbial mediation in phosphogenesis : new data from the Cretaceous phosphatic chalks of northern France. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 157-167.

Lear, D. W. 1966. Bacterial participation in phosphate regeneration in marine ecosystem (abs.). *Dissert. Abstr.*, 27, pp. 357-B.

Lehr, J.R., McClellan G.H., Smith, J.P. & Frazier, A.W. 1967. Characterization of apatites in commercial phosphate rocks. In : *Coll. Int. Phos. Miner. Solids*. Toulouse, 2, pp. 29-44.

Lehr, J.R., McClellan, G.H., Smith, J.P. & Frazier, A.W. 1967. Characterization of apatites in commercial phosphate rocks. In : *Coll. Int. Phos. Miner. Solids*. Toulouse, 2, pp. 29-44.

Lewy, Z. 1990. Pebbly phosphate and granular phosphorite (Late Cretaceous, southern Palestine) and their bearing on phosphatization processes. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 169-178.

Longinelli, A. 1984. Oxygen isotopes in mammal bone phosphate : A new tool for paleohydrological and paleoclimatological research?. *Geochim. Cosmochim. Acta*, 48, pp. 385-390.

Lowe, D.R. 1971. The relationship between silicic volcanism and the formation of some sedimentary phosphorites. *Proc. VII Forum Geol. Ind. Mineral. Geol. Phosphate, Dolomite, Limestone Clay Deposits*, Tampa, Florida, pp. 217-225.

Lozej, C-P. 1985. Sirhan-Turayf Phosphate Project : A contribution to the regional stratigraphy. Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-15, Jiddah.

Lucas, J., Flicoteaux, R., Nathan, Y., Prévôt, L. & Shahr, Y. 1980. Different aspects of phosphorite weather. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) *Marine Phosphorites-Geochemistry, Occurrence, Genesis*. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 41-51.

Lucas, J., Prévôt, L., Ataman, G. & Gündoğdu, N. 1980. Mineralogical and geochemical studies of the phosphatic formations in southeastern Turkey (Mazidagi-Mardin). In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 149-152.

Luther, S.M., Dudas, M.J. & Rutherford, P.M. 1993. Radioactivity and chemical characteristics of Alberta Phosphogypsum. Water, Air, and Soil Pollution, 69, pp. 277-290.

Manheim, F.T., Pratt, R.M. & McFarlin, P.F. 1980. Composition and origin of phosphorite deposits of the Black Plateau. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 117-137.

Manheim, F.T., Rowe, G.T. & Jipa, D. 1975. Marine phosphorite formation off Peru. J. Sed. Petr., 45, pp. 243-251.

Mansfield, G.R. 1918. The origin of the western phosphates of the United States. Am. J. Sci., 4 Ser., 46, pp. 591-598.

Mansfield, G.R. 1927. Geography, geology and mineral resources of part of southern Idaho. U.S Geological Survey Bulletin, 152.

Mansfield, G.R. 1940. The role of fluorine in phosphate sedimentation. Am. J. Sci., 238, pp. 863-879.

Martens, C.S. & Harriss, R.C. 1970. Inhibition of apatite precipitation in the marine environment by magnesium ions. Geochim. Cosmochim. Acta, 34, pp. 621-625.

McArthur, J.M. & Herczeg, A. 1990. Diagenetic stability of the isotopic composition of phosphate oxygen : palaeoenvironmental implications. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 119-124.

McArthur, J.M. 1978. Systematic variations in the contents of Na, Sr, CO₃ and SO₄ in marine carbonate-fluorapatite and their relation to weathering. Chem. Geol., 21, pp. 89-112.

McArthur, J.M. 1980. Post-Depositional alteration of the carbonate-fluorapatite phase of Moroccan phosphorite. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 53-60.

McClellan, G.H. & Lehr, J.R. 1969. Crystal chemical investigation of natural apatites. *Am. Mineral.*, 54, pp. 1374-1391.

McClellan, G.H. & Van Kauwenbergh, S.J. 1990. Mineralogy of sedimentary apatites. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 23-31.

McConnell, D. 1965. Precipitation of phosphates in sea water. *Econ. Geol.*, 60 (5), pp. 1059-1062.

McConnell, D. 1973. *Apatite : its crystal chemistry, mineralogy, utilization and geologic and biologic occurrences*. New York, Springer-Verlage, Vienna, 111 pp.

McKelvey, V. E. & Chas, L. 1966. Selecting areas favorable for subsea prospecting. *Exploiting the oceans*, 2nd Ann. Marine Technology Soc. Conf., Trans., pp. 44-60.

McKelvey, V.E. 1956. Uranium in phosphate rock. *U.S. Geol. Surv. Prof. Paper*, 300, pp. 477.

McKelvey, V.E. 1967. Phosphate deposits. *U.S Geological Survey Bulletin*. 1252-D, pp. 1-21.

McKelvey, V.E., Swanson, R.W. & Sheldon, R.P. 1953. The Permian phosphorite deposits of western United States. 19th Session of the International Geological Congress, Algiers, 1952, Section II, pp. 45-64.

McKelvey, V.E., Williams, J.S., Sheldon, R.P., Cressman, E.R., Cheney, T.M. & Swanson, R.W. 1959. The Phosphoria Park City and Shedhorn Formations in the Western phosphate field. *U.S Geological Survey, Professional Paper*, 313-A.

McPheat, V.E., Tuffley, J.R. & Allen, R.J. 1985. Sirhan-Turayf Phosphate Project : Preliminary laboratory-scale characterization, beneficiation and suitability test work. Australian Mineral Development Laboratories (AMDEL) Report No. 1592, OD6 / 953 / 2, Adelaide, South Australia. In Data-File RF-OF-00-05.

Medrano, M.D. & Piper, D.Z. 1992. A normative-calculation procedure used to determine mineral abundances in rocks from the Montpelier canyon section of the Phosphoria Formation, Idaho : A tool in deciphering the minor-element geochemistry of sedimentary rocks. *U.S. Geolo. Surv. Bull.* 2023-A.

Meissner, C.R. Jr. & Ankary, A. 1972. Phosphorite deposits in the Sirhan-Turayf basin, Saudi Arabia, *Mín. Res. Rep. Inv.* 2, DGMR, Jiddah, Saudi Arabia, 27 pp.

Meissner, C.R. Jr. 1967. Phosphate rock at West Thaniyat, Sirhan-Turayf basin, Saudi Arabia. U.S.G.S., Tech. Let., 94, DGMR, Jiddah, Saudi Arabia, 8 pp.

Meissner, C.R. Jr., Mytton, J.W., Riddler, G.P. & Van Eck, M. 1986. Geologic Map of the Ash Shuwayhitiyah Quadrangle Sheet 30D, Saudi Arabia. Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report U.S.G.S.-OF-06-1, Jiddah.

Miller, L.J. 1964. The origin of sedimentary phosphate (abs.). Econ. Geol., 59, pp. 1619.

Milliman, J.D., Summerhayes, C.P. & Barrette, H.T. 1975. Oceanography and suspended sediment off the Amazon River. Jour. Sed. Pet., 45, pp. 189-206.

Mineral Resources of Saudi Arabia, annual report 1994. Deputy Ministry for Mineral Resources, Jiddah.

Moshrif, M.A. & Kelling, G. 1984. Stratigraphy and sedimentary history of upper Lower and Middle Cretaceous rocks, Central Saudi Arabia. Min. Res. Bull. 28, DMMR, Jiddah, Saudi Arabia, 28 pp.

Murray, J. & Philippi, E. 1908. Die Grundproben der deutschen Tiefsee Expedition 1898-1899 auf dem Dampfer "Valdivia". Wiss. Ergeb. Dtsch. Tiefsee-Exped., 10, pp. 181-187.

Murray, J. & Renard, A.F. 1891. Scientific Results, H.M.S. Challenger, Deep Sea Deposits. Longman, London, pp. 391-400.

Mytton, J.W. 1966a. Phosphate deposits in the Jawf-Sakakah basin, Saudi Arabia, Part 1 : Turayf Area. U.S.G.S., Tech. Let., 62, DGMR, Jiddah, Saudi Arabia, 20 pp.

Mytton, J.W. 1966b. Phosphate deposits in the Jawf-Sakakah basin, Saudi Arabia, Part 11 : Thaniyat Turayf and Quraymiz, U.S.G.S., Tech. Let., 74, DGMR, Jiddah, Saudi Arabia, 19 pp.

Nathan, Y. & Lucas, J. 1972. Synthèse de l'apatite à partir du gypse : application au problème de la formation des apatites carbonatées par précipitation directe. Chem. Geol., 9, pp. 99-112.

Nathan, Y. & Nielsen, H. 1980. Sulfur isotopes in phosphorites. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 73-78.

Nathan, Y. 1990. Humic substances in phosphorites : occurrence, characterization and significance. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 49-59.

Nathan, Y., Soudry, D. & Avigour, A. 1990. Geological significance of carbonate substitution in apatites : Palestine phosphorites as an example. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 179-191.

Notholt, A.J. 1983. A review and assessment of the Sirhan-Turayf phosphate project. Open-file Rep. RF-Of-03-10, DGMR, Jiddah, Saudi Arabia.

Notholt, A.J. 1994. Phosphate rock : Factors in economic and technical evaluation. In : Whateley, M.K. & Harvey, P.K. (eds.) *Mineral Resource Evaluation II : Methods and Case Histories*. Geological Society, London, Special Publication, 79, pp. 53-65.

O'Brien, G.W., Harris, J., Milnes, A. & Veeh, H. 1981. Bacterial origin of East Australian continental margin phosphorites. *Nature*, 294, 442-444.

O'Brien, G.W., Milnes, A.R., Veeh, H.H., Heggie, D.T., Riggs, S.R., Cullen, D.J., Marshall, J.F. & Cook, P.J. 1990. Sedimentation dynamics and redox iron-cycling : controlling factors for the apatite-glaucinite association on the East Australian continental margin. In : Notholt, A.J.G. & Jarvis, I. (eds) *Phosphorite Research and Development*. Geological Society, London, Special Publication, 52, pp. 61-86.

Odin, G.S. & Letolle, R. 1980. Glaucinitization and phosphatization environments : A tentative comparison. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) *Marine Phosphorites-Geochemistry, Occurrence, Genesis*. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 227-237.

Outerbridge, W.F. & Meissner, Jr. 1985. Opal claystone associated with phosphate rock in northwestern Saudi Arabia. Deputy Ministry for Mineral Resources, Jiddah, Open-File Report, USGS-Of-05-20.

Owen, R.M. & Naser, S.N. 1958. Stratigraphy of the Kuwait-Basra area. In : *Habitat of Oil*. Amer. Assoc. Petrol. Geol. Symposium, pp. 1252-1278.

Parker, R.J. & Siesser, W.G. 1972. Petrology and origin of some phosphorites from the South African continental margin. *Jour. Sed. Pet.*, 42, pp. 434-440.

Parker, R.J. 1975. The petrology and origin of some glauconitic and glauco-conglomeratic phosphorites from the South African continental margin. *Jour. Sed. Pet.*, 45 (1), pp. 230-242.

Pasho, D.W. 1972. Character and origin of marine phosphorites. Geol. Dept. Univ. of Southern California, Geol. Publication, 72-S, pp. 1-88.

Peers, C.L. 1983. Mineralogy and chemical analyses of Turayf samples 988001-988003. Geomet Services Reports 7 / 2 / 83 and SPS 2809, Chessington, U.K. In Data-File RF-DF-00-05.

Peers, C.L. 1984. Mineralogical examination of phosphate samples ex Turayf, Saudi Arabia. Geomet Services Report MER-89, Chessington, U.K. In Data-File RF-DF-00-05.

Petromin-Graenges International Mining. 1980. Thaniyat Phosphate Project : Final Exploration Report-6 vols. Stockholm.

Pettijhon, F.J. 1975. Sedimentary Rocks. 3rd ed., Harper and Row Publishers, New York.

Pettijhon, F.M. 1957. Sedimentary rocks. 2nd ed., Harper and Row, New York, Evanston and London, 718 pp.

Porter, K.G. 1981. Zooplankton fecal pellets link fossil fuel and phosphate deposits. Science, 212, pp. 931-933.

Powell, T.G., Cook, P.J. & McKirdy, D. 1975. Organic geochemistry of phosphorites : relevance to petroleum genesis. Am. Assoc. Petro. Geol. Bull., 59, pp. 618-632.

Powers, R.W. 1968. Lexique Stratigraphique International, Saudi Arabia. Center National de la Recherche Sci., Paris, 3, Fascicule 10 b1, 173 pp.

Powers, R.w., Ramirez, J.F., Redmond, C.D. & Elberg, E.L. 1966. Geology of the Arabian Peninsula-Sedimentary geology of Saudi Arabia. USGS Prof. Paper 560-D.

Prévôt, L. & Lucas, J. 1979. Comportement de quelques éléments traces dans les phosphorites. Sci. Géol. Bull., 32.

Prévôt, L. & Lucas, J. 1980. Behavior of some trace elements in phosphatic sedimentary formations. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 31-39.

Price, N.B. and Calvert, S.E. 1978. The geochemistry of phosphorites from the Namibian shelf. Chem. Geol., 23, pp. 151-170.

Pritchard, P.W. 1978. Sirhan Phosphate Project. Progress Report Number 1 : Initial review of the project. Report NO. 474 prepared by Robertson Research (Australia) Pty. Ltd. and issued by the Riofinex Geological Mission as Open-File Report RFO-1979-39, Jiddah.

Riddler, G.P., Khallaf, H.M. & Farasani, A.M. 1983. Exploration for phosphate in the Sirhan-Turayf region northwest Saudi Arabia. Open-file Rep. RF-Of-03-22, DGMR, Jiddah, Saudi Arabia.

Riddler, G.P., Van Eck, M., Aspinall, N.C., McHugh, J.J., Griffin, M.B. & Farasani, A.M. 1985a. Sirhan-Turayf Phosphate Project : Lithostratigraphy of the Turayf group. Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-2, Jiddah.

Riddler, G.P., Van Eck, M., Aspinall, N.C., McHugh, J.J., Parker, T.W., Farasani, A.M. & Dini, S.M. 1986. Delineation and Evaluation of the Al-Jalamid Phosphorite Deposit. Saudi Arabian Deputy Ministry for Mineral Resources Technical Record RF-TR-06-3, Jiddah.

Riddler, G.P., Van Eck, M., Aspinall, N.C., Mchugh, J.J., Parker, T.W., Farasani, A.M. and Dini, S.M. 1986. Sirhan-Turayf phosphate project : An assessment of the phosphate resource potential of the Sirhan-Turayf region. Saudi Arabia Deputy Ministry for Mineral Resources, Jiddah, Technical Record RF-TR-06-02.

Riggs, S.R. & Mallette, P.M. 1990. Patterns of phosphate deposition and lithofacies relationships within the Miocene Pungo River Formation, North Carolina continental margin. In : Burnett, W.C. & Riggs, S.R. (eds.) Phosphate Deposits of the World : 3, Neogene to Modern Phosphorites. Cambridge University Press, Cambridge.

Riggs, S.R. 1979. Petrology of the Tertiary Phosphorite System of Florida. Econ. Geol., 74, pp. 195-220.

Riggs, S.R. 1979. Phosphate sedimentation in Florida-A model phosphogenic system. Econ. Geol., 74, pp. 285-314.

Riggs, S.R. 1984. Paleooceanographic model of Neogene phosphorite deposition, US Atlantic continental margin. Science, 223, pp. 123-131.

Riggs, S.R. 1986. Proterozoic and Cambrian phosphorites-specialist studies : phosphogenesis and its relationship to exploration for Proterozoic and Cambrian phosphorites. In : Cook, P.J. & Shergold, J.H. (eds.) Phosphate Deposits of the World : 1, Proterozoic and Cambrian phosphorites. Cambridge University press, Cambridge, pp. 352-368.

Riggs, S.R., Synder, S.W., Hine, A.C., Ellington, M.D. & Mallette, P.M. 1985. Geological framework of phosphate resources in Onslow Bay, North Carolina continental shelf. *Econ. Geol.*, 80, pp. 716-738.

Riofinex Geological Mission. 1977a. A preliminary review of mineral opportunities in Saudi Arabia. Open-File Report RF-1977-1 prepared for the Directorate General of Mineral Resources, Saudi Arabia.

Riofinex Geological Mission. 1977b. Annual Report, program year 1396-1397H. Report for the period 19th Ramadan, 1396 to 29th Jumad Thani, 1397H (13th September, 1976 to 16th June, 1977). Saudi Arabian Directorate General of Mineral Resources Open-File Report RF-1977-4, Jiddah.

Riofinex Geological Mission. 1979a. Annual Report, program year 1397-1398H. Report for the period 1st Rajab, 1397 to 29th Jumad Thani, 1398H (17th June, 1977 to 5th June, 1978). Saudi Arabian Directorate General of Mineral Resources Open-File Report RF-1978-2, Jiddah.

Riofinex Geological Mission. 1979b. Investigation of the Upper Cretaceous and Tertiary phosphatic sedimentary rocks of northern Saudi Arabia. Interim Report to the end of programme year 1398-1399H. Saudi Arabian Directorate General of Mineral Resources Open-File Report RFO-1979-13, Jiddah.

Riofinex Geological Mission. 1979c. Computing by Riofinex Limited in Saudi Arabia. Saudi Arabian Directorate General of Mineral Resources Open-File Report RFO-1979-1, Jiddah.

Riofinex Geological Mission. 1980. Annual Report, program year 1399-1400H. Report for the period 1st Rajab, 1399 to 29th Jumad Thani, 1400H (27th May, 1979 to 14th May, 1980). Saudi Arabian Directorate General of Mineral Resources Open-File Report RF-1980-21, Jiddah.

Riofinex Geological Mission. 1982. Annual Report, program year 1400-1401H. Report for the period 1st Rajab, 1400 to 30th Shawal, 1401H (15th May, 1980 to 30th August, 1981). Saudi Arabian Directorate General of Mineral Resources Technical Record RF-TR-02-1, Jiddah.

Riofinex Geological Mission. 1983. Annual Report, program year 1401-1402H. Report for the period 1st Dhul Qidah, 1401 to 30th Shawal, 1402H (31st August, 1981 to 19th August, 1982). Saudi Arabian Directorate General of Mineral Resources Technical Record RF-TR-03-1, Jiddah.

Riofinex Geological Mission. 1984. Quarterly Report for the period 1st Shawal to 30th Dhul Hijjah, 1404H (30th June to 25th September, 1984). Saudi Arabian Directorate General of Mineral Resources Quarterly Report RF- QR-04-4, Jiddah.

Riofinex Geological Mission. 1985. Quarterly Report for the period 1st Moharram to 30th Rabbi Awal, 1405H (26th September to 22 December, 1984). Saudi Arabian Directorate General of Mineral Resources Quarterly Report RF- QR-05-1, Jiddah.

Rizzo, A.A., Marlin, G.R., Scott, D.B. & Mergenhagen, S.E. 1962. Mineralization of bacteria. *Science*, 135, pp. 439-441.

Rooney, T.P. & Kerr, P.F. 1967. Mineralogical nature and origin of phosphorite, Beaufort county, North Carolina. *Bull. Geol., Soc. Am.*, 78, pp. 731-748.

Rosenkrantz, A. 1960. Danian Mollusca from Denmark. 21st Int. Geol. Congr., Copenhagen, 5, pp. 193-198.

Russell, R.T. & Trueman, N.A. 1971. The geology of the Duchess Phosphate deposits, northwest Queensland, Australia. *Econ. Geol.* 66, pp. 1186-1214.

Ryder, J.M. & Kluyver, H.M. 1983. Detailed logs and cross sections, phase I drilling, P1-86, Sirhan-Turayf area, volumes 1 and 2. Deputy Ministry for Mineral Resources Open-File Report RF-OF-03-12.

Sander, N. 1962. Aperçu Paléontologique et stratigraphique de Paléogène en Arabie Séoudite orientale. *Revue de Micropaléontologie*, 3, pp. 3-40.

Saraswat, A.C., Sankaran, A.V., Varada Raju, M.N., Taneja, P.C. & Bargaje, V.G. 1970. Geochemical data on the uraniferous phosphorites of Mussoorie, Dehradun district, Uttar Pradesh, India. In : *Proceedings of the second seminar on Geochemical prospecting methods and techniques*. *Miner. Resou. Dev. Ser.*, 38, pp. 179-187., United Nations, New York,

Sassi, S. 1974. La sédimentation phosphateé au Paléocène dans le Sud et le Centre-Ouest de la Tunisie. Thèse doctoratés sciences, Université de Paris-Sud.

Senin, Y.M. 1970. Phosphorus in bottom sediments of the Southwest African Shelf. *Lithology and Mineral resources*. Consultants Bureau, New York, N.Y., pp. 8-20.

Serra, O., Baldwin, J. & Quirein, J. 1980. Theory, interpretation and practical applications of natural gamma ray spectroscopy. SPWLA 21st Annual Logging Symposium.

Shatskii, N.S. 1955. Phosphorite bearing formations and classification of phosphorite deposits. Report on Conference on Sedimentary Rocks, 2. USSR Academy of Sciences, Moscow.

Sheldon, R.P. 1959. Geochemistry of uranium in phosphorites and the black shales of the Phosphoria Formation. U. S. Geol. Surv. Bull., 1984-D, pp. 83-115.

Sheldon, R.P. 1964. Exploration for phosphorite in Turkey-A case history. Econ. Geol., 59, pp. 1159-1175.

Sheldon, R.P. 1964a. Paleolatitudinal and paleogeographical distribution of phosphorite. U.S. Geological Survey, Professional Paper, 501-C, pp. 106-113.

Sheldon, R.P. 1965. Discovery of phosphate rock in Saudi Arabia and recommended program for further study. U.S.G.S., Tech. Let., 22, DGMR, Jiddah, Saudi Arabia, 9 pp.

Sheldon, R.P. 1967. Discovery of phosphate rock in Saudi Arabia and recommended program for further study. U.S.G.S. Tech. Letter 22.

Sheldon, R.P. 1980. Episodicity of phosphate deposition and deep ocean circulation-A hypothesis. In : Bentor, Y.K. & Scripps Institution of Oceanography (eds) Marine Phosphorites-Geochemistry, Occurrence, Genesis. Society of Economic Paleontologists and Mineralogists, Special Publication, 29, pp. 239-247.

Sisodia, M.S. & Chauhan, D.S. 1990. The influence of magnesium ions during the formation of stromatolitic phosphorites of Udaipur, Rajasthan, India. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 313-320.

Slansky, M. 1974. Notes on phosphate deposits in Saudi Arabia and recommendation for further exploration. B.R.G.M., Rep-74-JED-22, DGMR, Jiddah, Saudi Arabia, 10 pp.

Slansky, M. 1986. Geology of sedimentary phosphate. Elsevier, New York, Amsterdam and Oxford. 210 pp.

Smirnov, A.I. 1958. The problem of the genesis of phosphorites (Engl. transl.). Akad. Sci. U. S.S.R. (Geochem.), 119, pp. 53-56.

Smirnov, A.I. 1966. In physical methods of investigation of minerals of sedimentary rocks. Nauka, Moscow.

Smirnov, A.I., Ivinskaya, R.B. & Zalavina, T.P. 1962. Experimental data on the possibility of chemical precipitation of phosphates from sea water. In : *Geology of phosphorite deposits*. Gosgortekhnizdat, Moscow. (In Russian).

Smith, G.H. 1983. Reconnaissance exploration for phosphate in the Thaniyat-Quraymiz district. Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-Of-03-3.

Smith, M.R. 1976. Phosphate Project : Sirhan-Turayf Basin, Saudi Arabia Tentative Programme. Riofinex Internal Correspondence. In Data-File RF-DF-00-05.

Snyder, S.W., Hale, W.R., Riggs, S.R., Spruill, R.K. & Waters, V.J. 1984. Occurrence of clinoptilolite as moldic fillings of foraminiferal tests in continental margin sediments. *Geological Society of America, Abstracts with programs*, 16, 662.

Soudry, D. & Lewy, Z. 1988. Microbially influenced formation of phosphate nodules and megafossil molds Negev, Southern Palestine. *Palaeogeography Palaeoclimatology*, 64, pp. 15-34.

Spencer, S. & Shannon, JR. Rare Earths and Thorium. In : Stanely, J. (ed.) *Industrial Minerals and Rocks*, 5th edition, 2, pp. 1109-1117.

Steineke, M. & Bramkamp, R.A. 1952. Mesozoic rocks of Eastern Saudi Arabia (abs.). *Amer. Assoc. Petrol., Geol. Bull.*, 36, pp. 909.

Steineke, M., Bramkamp, R.A. & Sander, N.J. 1958. Stratigraphic relations of Arabian Jurassic Oil. In : *Habitat of Oil*. Amer. Assoc. Petrol. Geol. Symposium, pp. 1294-1329.

Stokes, W.L. 1982. *Essentials of Earth history*. 4th ed., Prentice-Hall, Inc., Englewood Cliffs. N.J. 07632.

Strakhov, N.M. 1960. *Fundamentals of the theory of lithogenesis*. USSR Academy of Sciences, Geological Institute, Moscow.

Summerhayes, C.P. 1970. Phosphate deposits on the Northwest African continental shelf and slope. Unpubl. Ph.D. thesis, Univ. of London, 282 pp.

Summerhayes, C.P., de Melo, V. & Barreto, H.T. 1976. The influence of upwelling on suspended matter and shelf sediments off southern Brazil. *Jour. Sed. Pet.*, 46, pp. 819-828.

Thralls, W.H. & Hasson, R.C. 1956. Geology and oil resources of Eastern Saudi Arabia. Intern. Geol. Congr. 21st, Mexico, 2, pp. 9-32.

Tooms, J.S., Summerhayes, C.R. & Cronan, D.S. 1969. Geochemistry of marine phosphate and manganese deposits. *Oceanogr. Mar. Biol. Ann. Rev.*, 71, pp. 49-100.

Tooms, J.H. S., Summerhayes, C.P. & Cronan, D.S. 1969. Geochemistry of marine phosphate and manganese deposits. In : Barnes, H. (ed.) *Oceanography Marine Biology Ann. Rev.*, 7. Millport, Scotland, Hafner Pub. Co., pp. 49-100.

Torrent, H. 1975. Preliminary investigation of the availability of water supplies for the phosphate deposits of West Thaniyat and Turayf. BRGM, 76-JED-1, Jiddah.

Trueman, N.A. 1971. A petrological study of some sedimentary phosphorite deposits. *Aust. Mineral. Develop. Lab. Bull.*, 11, pp. 1-72.

Uwah, E.J. & Rosenberg, R.J. 1993. Measurement of radioelement contents of rocks of Ugep, S.E. Nigeria, by gamma-ray spectrometric and instrumental neutron activation analysis techniques. *Appl. Radiat. Isot.*, 44 (5), pp. 855-858.

Vail, P.R. 1987. Seismic stratigraphy interpretation utilizing sequence stratigraphy. Part 1, Seismic stratigraphy interpretation procedure. In : Bally, A.W. (ed.) *Atlas of Seismic Stratigraphy. Am. Assoc. Petro. Geol., Studies in Geology*, 27, pp. 1-10.

Van Bellen, R.C., Dunnington, R.W. & Morton, D.M. 1959. *Lexique stratigraphique international*, 3, Asie, fasc. 10a, Iraq (Mesozoic and Paleozoic), 333 pp. Paris, Centre Recherche Scientifique, Internat. Geol. Cong. Comm. Stratigraphy.

Van Eck, M. 1985b Sirhan-Turayf Phosphate Project : Lithostratigraphy of the Aruma Formation. Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-05-23, Jiddah.

Van Eck, M. 1986. The phosphorite resource of the Umm Wu'aal area. Riofinex International Report. In Data-File RF-DF-00-05.

Van Eck, M., Riddler, G.p, Mchugh, J.J. and Farasani, A.M. 1984. Sirhan-Turayf phosphate project : The discovery of a significant phosphorite resource in the Al-Jalamid area. Saudi Arabia Deputy Ministry for Mineral Resources, Jiddah, Open-File Report RF-OF-04-19.

Van Hinte, J.E. 1976. A Cretaceous time scale. *Amer. Assoc. Pet. Geol. Bull.*, 60, pp. 498-516.

Van Kauwenbergh, S.J. & McClellan, G.H. 1990. Comparative geology and mineralogy of the southern United States and Togo phosphorites. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 139-155.

Veeh, H.H., Calvert S.E. & Price, N.B. 1974. Accumulation of uranium in sediments and phosphorites on the South West African shelf. *Mar. Chem.*, 2, pp. 189-202.

Veeh, H.W., Burnett, W.C. & Soutar, A. 1973. Contemporary phosphorites on the Continental margin of Peru. *Science*, 181, pp. 844-845.

Veeh, H.W., Calvert, S.E. & Price, N.B. 1974. Accumulation of uranium in sediments and phosphorites on the South West African shelf. *Marine Chemistry*, 2, pp. 189-202.

Wasimuddin, M. 1985. Stratigraphical and microfacies analysis of the Late Cretaceous-Early Paleogene phosphate-bearing succession in northwestern Saudi Arabia (Thaniyat Turayf and southern Turayf areas). Unpublished M.Sc. Thesis, KFUPM, Saudi Arabia.

Weaver, C.E. & Beck, K.C. 1977. Miocene of the S. E. United States : a model for chemical sedimentation in a pre-marine environment. In : *Developments in Sedimentology*, 22 : Amsterdam, Elsevier Pub. Co., 234 pp.

Wedepohl, K.H. 1969. *Handbook of geochemistry*. Berlin, Springer-Verlag.

Wilcox, N.R. 1953. The origin of beds of phosphatic chalk with special reference to those at Taplow, England. 19th Session of the International Geological Congress, Algiers, 1952, Section II, 93, pp. 119-134.

Youssef, M. I. 1958. Association of phosphates with synclines and its bearing on prospecting for phosphates in Sinai. *The Egyptian Jou. Geol.*, II (2), pp. 75-87.

Youssef, M. I. 1965. Genesis of bedded phosphates. *Econ. Geol.*, 60, pp. 590-600.

Zaghloul, Z.M. & Mabrouk, B. 1964. On uranium in Dakhla and Mahamid phosphate deposit. *Jour. Geol. U.A.R.*, 8 (2), pp. 79-81.

Zanin, Y.N., Zverev, K.V. & Solotchina, E.P. 1990. Clay minerals and phosphorite genesis in the Upper Cretaceous of the northern Siberian Platform. In : Notholt, A.J.G. & Jarvis, I. (eds) Phosphorite Research and Development. Geological Society, London, Special Publication, 52, pp. 223-235.