SEDIMENTATION OF SAQ SANDSTONE, CENTRAL SAUDI ARABIA

BY

OMAR ASSAF AL-HARBI

A thesis submitted for the Degree of Master of Science
at
The University of Glasgow

Department of Geology
University of Glasgow
Scotland.

May, 1987

ACKNOWLEDGEMENTS

I wish to thank all those who have assisted me with the preparation of this thesis - in particular, Professor B.E. Leake, Head of Department, for the use of departmental facilities.

I am deeply grateful to Dr B.J. Bluck for his continuous help, encouragement and supervision, without which this research would not have been possible.

Thanks are also extended to Dr C.M. Farrow for his help with XRF and computer facilities.

I would also like to express my thanks to Mr R. Morrison, Chief Technician, Mr D. McLean for photography and the technical staff of the Department of Geology for their help.

Finally, my thanks to Mrs B Mackenzie for typing the thesis.

DECLARATION

This thesis is the result of independent research at the Department of Geology, University of Glasgow. Any published or unpublished results of other workers have been given full acknowledgement in the text.

1987

ABSTRACT

The Cambro-Ordovician Saq Sandstone, over 600m thick, is a quartz-arenite and rests unconformably on the Arabian Shield from the Al-Qassim region in the South to the Jordan Border.

Quartz generally comprises more than 95% of the sandstone and 91% of the quartz is monocrystalline quartz. Both chemistry and petrography studies indicate this Formation to be very mature sandstone.

The Saq Sandstone is abundantly cross-stratified and contains marine fossils. It is considered to have formed on an open marine tidal shelf. The cross-strata are sometimes seen to form into major sand bars, and beach deposits occur within the sequence.

The palaeoflow is unimodal, and is the result of asymmetrical tides operation on a sloping shelf.

The palaeoflow, which is to the NE, is therefore seen as the main direction of sediment dispersal and is the direction in which the Cambrian sandstones in this whole area are replaced by mudstones.

The Saq Sandstone was derived from a pre-existing sandstone since it contains detrital chert.

In the process of becoming mature, there are probably many cycles of reworking before final deposition.

There is some 50 Million years difference between the last recorded thermal event affecting the Arabian Shield and the deposition of this sandstone. This suggests that the development of a craton can occur in less than 50 Million years.

CONTENTS

		Page No.
ACKNOWLEDGEMENTS	... ...	
ABSTRACT	... ...	
DECLARATION	... ...	
CONTENTS	... ...	i
LIST OF FIGURES	... ...	iv
LIST OF TABLES	... ...	viii
LIST OF PLATES	... ...	x
CHAPTER ONE	- Introduction	1
	Samples	7
	Aim and Scope of Study	7
CHAPTER TWO	- Saq Sandstone Petrography and Provenance	16
	Mineralogical Classification of Sandstone	16
	Framework Mineralogy	17
	Quartz Petrography	18
	Non-undulatory Monocrystalline Quartz	19
	Undulatory Monocrystalline Quartz	20
	Polycrystalline Quartz	20
CHAPTER THREE	- Geochemistry of Saq Sandstone ...	36
	Procedure	36
	Wet Chemical Analysis	36
	Chemical Composition of Upper and Lower Saq Sandstone	37
	SiO_2	37
	Al_2O_3 vs SiO_2	38
	TiO_2 vs SiO_2	38

		Page No.
	Na_2O vs SiO_2	39
	CaO vs SiO_2	39
	MnO vs SiO_2	40
	K_2O vs SiO_2	40
	Fe_2O_3+FeO vs SiO_2	41
	Al_2O_3 vs K_2O	41
	Al_2O_3/SiO_2 vs Fe_2O_3+FeO+MgO ...	41
	P_2O_5	42
	Discrimination Function analysis and Tectonic setting	42
	Trace Element Geochemistry ...	43
	La vs Th	43
	Th vs Zr	43
	La+Y+Ce vs Ni+Cr vs Sr ...	44
	Ba, Co, Cu, Zn	44
	Ga, Pb, U	46
	Discussion	47
CHAPTER FOUR	- Grain Size Analysis	84
	Median	84
	Graphic Mean	84
	Inclusive Graphic Standard Deviation	85
	Inclusive Graphic Skewness ...	85
	Kurtosis	86
	Bivariate Discriminate Plots ...	88

Page No.

CHAPTER FIVE - Cross-stratification and Dispersal in Saq Sandstone 104

Techniques 105

Cross-stratification of Lower Saq Sandstone 105

Dip of Cross-stratification ... 106

Thickness of Cross-stratification 106

Basal Unit of Lower Saq Sandstone 106

Cross-stratification of Upper Saq Sandstone 107

Dip of Cross-stratification ... 107

Thickness of Cross-stratification 107

Interpretation 108

Structure of Sedimentary bar in Lower Saq Sandstone. 111

CHAPTER SIX - Heavy Minerals in Saq Sandstone ... 125

Method 126

Opaque Minerals 127

Zircon 127

Tourmaline 127

Rutile 127

Apatite 128

Epidote 128

Sphene 128

CHAPTER SEVEN - Depositional Environment & Palaeogeographical Setting of Saq Sandstone ... 133

CHAPTER EIGHT - Conclusions 148

REFERENCES 150

LIST OF FIGURES

		Page No.
FIGURE 1	Outcrops of Cambro-Ordovician Saq Sandstone in Saudi Arabia and adjacent countries.	8
FIGURE 2	Sedimentary geology of Palaeozoic of Saudi Arabia	9
FIGURE 3	Geological map of the area of study.	10
FIGURE 4	Geological map of Arabian Shield illustrating sample localities.	11
FIGURE 5	Isopach map of Saq Sandstone.	12
FIGURE 6	Composite columnar section of Saq Sandstone.	13
FIGURE 7	Columnar section for Jabal Saq (Saq Sandstone).	14
FIGURE 8	Location map of Saq Sandstone showing sample localities	15
FIGURE 9	Reference diagrams for petrographic data (1) QFL diagram (after McBride 1963) for classification of sandstone: (2) QFL diagram: (3) QmFLt diagram (after Dickinson _et al_. 1983) to decipher the provenance ...	26
FIGURE 10	QFL diagram showing the composition of Lower Saq Sandstone	27
FIGURE 11	QFL diagram to decipher the provenance of Upper Saq Sandstone	28
FIGURE 12	QFL diagram to decipher the composition of Lower Saq Sandstone	29
FIGURE 13	QFL diagram to decipher the provenance of Upper Saq Sandstone	30

Page No.

FIGURE 14 QmFLt diagram to decipher the provenance of Lower Saq Sandstone. 31

FIGURE 15 QmFLt diagram to decipher the provenance of Upper Saq Sandstone. 32

FIGURE 16 Al_2O_3 vs SiO_2 71

FIGURE 17 TiO_2 vs SiO_2 72

FIGURE 18 Na_2O vs SiO_2 73

FIGURE 19 CaO vs SiO_2 74

FIGURE 20 MnO vs SiO_2 75

FIGURE 21 K_2O vs SiO_2 76

FIGURE 22 Fe_2O_3 + FeO vs SiO_2 77

FIGURE 23 Al_2O_3 vs K_2O 78

FIGURE 24 Fe_2O_3+FeO+MgO vs Al_2O_3/SiO_2 ... 79

FIGURE 25 Plot of discriminant scores along Function I vs Function II for Upper and Lower Saq Sandstone. 80

FIGURE 26 Th vs La 81

FIGURE 27 Th vs Zi 82

FIGURE 28 Ni + Cr vs Y + La + Ce Vs Sr.. 83

FIGURE 29 Cumulative-frequency curve of beach sand, drawn on probability paper. ... 93

Page No.

FIGURE 30 Cumulative curves of Upper Saq Sandstone. 94

FIGURE 31 Cumulative curves of Lower Saq Sandstone. 95

FIGURE 32 Cumulative curves of Lower Saq Sandstone. 96

FIGURE 33 Histograms of selected samples from Lower Saq Sandstone. 97

FIGURE 34 Histograms of selected samples from Lower Saq Sandstone. 98

FIGURE 35 Histograms of selected samples from Upper Saq Sandstone. 99

FIGURE 36 Histograms of selected samples from Upper Saq Sandstone. 100

FIGURE 37 Plot of standard deviation vs mean size. 101

FIGURE 38 Plot of standard deviation vs skewness. 102

FIGURE 39 Plot of standard deviation vs median of Stewart's diagram. 103

FIGURE 40 Rose diagram to represent palaeocurrent of lower part of Lower Saq Sandstone. 115

FIGURE 41 Rose diagram to represent palaeocurrent of upper part of Lower Saq Sandstone. 116

FIGURE 42 Distribution of dip angle of cross-stratification of Lower Saq Sandstone. 117

FIGURE 43 Log probability plot of cross-stratification thickness. 118

FIGURE 44 Rose diagram to represent palaeocurrent of basal unit of Lower Saq Sandstone. 119

		Page No.
FIGURE 45	Rose diagram to represent palaeocurrent of Upper Saq Sandstone	120
FIGURE 46	Distribution of dip angle of cross-stratification of Lower Saq Sandstone.	121
FIGURE 47	Rose diagram to represent palaeocurrent of Upper (a) and Lower (b) Saq Sandstone.	122
FIGURE 48	Structure of sedimentary bar from Lower Saq Sandstone (A) compared with a similar structure from fluvial bar (B) and marine bar (C).	123
FIGURE 49	Facies 2: on downstream part of bar with large-scaled foresets F2 with smaller F1.	124
FIGURE 50	Idealized reconstruction of shelf model of Saq Sandstone	138
FIGURE 51	Model illustrating major sedimentary facies of Saq Sandstone (B) compared with similar facies of Jura Quartzite (A). ...	139
FIGURE 52	Palaeogeographical map of late Cambrian to Early Ordovician	140
FIGURE 53	Palaeogeographical map of late Precambrian to early Early Cambrian	141
FIGURE 54	Palaeogeographical map of middle to late Early Cambrian	142
FIGURE 55	Palaeogeographical map of Middle Cambrian.	143
FIGURE 56	Palaeogeographical map of Late Cambrian.	144
FIGURE 57	Palaeogeographical map of Ordovician.	145

LIST OF TABLES

		Page No.
TABLE 1:	Mineralogy of Upper Saq Sandstone.	23
TABLE 2:	Mineralogy of Lower Saq Sandstone.	24
TABLE 3:	The average of mono & polycrystalline quartz in Upper and Lower Saq Sandstone.	25
TABLE 4:	Chemical analysis of Upper Saq Sandstone. (Major elements)	49
TABLE 5:	Chemical analysis of Lower Saq Sandstone. (Major elements)	53
TABLE 6:	Chemical analysis of Upper Saq Sandstone. (Trace elements)	57
TABLE 7:	Chemical analysis of Lower Saq Sandstone. (Trace elements)	61
TABLE 8:	Average major element composition in Upper and Lower Saq Sandstone.	65
TABLE 9:	The average of trace element for Upper and Lower Saq Sandstone.	66
TABLE 10:	Unstandardized discriminant function coefficient used to calculate discriminant scores for Saq Sandstone.	67
TABLE 11:	Discriminant scores of Upper Saq Sandstone.	68
TABLE 12:	Discriminant scores of Lower Saq Sandstone.	69
TABLE 13:	Average chemical composition of quartz-arenite of Upper Saq Sandstone and representative quartz arenite.	70

		Page No.
TABLE 14:	Summary of grain size analysis (Upper Saq Sandstone).	90
TABLE 15:	Summary of grain size analysis (Lower Saq Sandstone).	91
TABLE 16:	Vector mean, magnitude of vector mean (L), standard deviation (S) and variance (S^2) of Lower Saq Sandstone.	113
TABLE 17:	Vector mean, magnitude of vector mean (L), standard deviation (S) and variance (S^2) of Upper Saq Sandstone.	114
TABLE 18:	Heavy minerals and related source rock type.	126
TABLE 19:	Distribution of heavy minerals in Upper and Lower Saq Sandstone.	130

LIST OF PLATES

		Page no.
PLATE No. 1	Well rounded biomodal quartz grains (Upper Saq Sandstone).	33
PLATE No. 2	Undulatory polycrystalline quartz (Lower Saq Sandstone).	33
PLATE No. 3	Overgrowth in quartz grains (Upper Saq Sandstone).	34
PLATE No. 4	Overgrowth in quartz grains (Lower Saq Sandstone).	34
PLATE No. 5	Monocrystalline quartz with strong undulatory extinction (Upper Saq Sandston).	35
PLATE No. 6	Undulatory monocrystalline quartz breaking down to non-undulatory quartz and showing re-entrant filled with cement (Lower Saq Sandstone).	35
PLATE No. 7	Lamina of heavy minerals in beach deposits.	131
PLATE No. 8	Heavy minerals from Upper Saq Sandstone.	131
PLATE No. 9	Heavy minerals from Upper Saq Sandstone.	132
PLATE No.10	Heavy minerals from Lower Saq Sandstone.	132
PLATE No.11	Trace fossils (Cruziana) from Upper Saq Sandstone.	146
PLATE No.12	Trace fossils (Cruziana) from Lower Saq Sandstone.	146
PLATE No.13	Debris of brachiopod shell (Upper Saq Sandstone).	147
PLATE No.14	Beach deposits (Upper Saq Sandstone).	147

CHAPTER ONE

INTRODUCTION

The geology of Saudi Arabia can readily be generalized into two positive structural elements. On the west the Precambrian complex of igneous and metamorphic rocks that occupies roughly one-third of the Kingdom, and the central Palaeozoic, Mesozoic and Tertiary sedimentary rocks which crop out in a great curved belt, flanking the eastern margin of the Arabian Shield (Fig. 1).

Since the earliest Palaeozoic, the Arabian Shield has been amazingly stable, subject only to gentle, epeirogenic movement. It can be regarded as a continuation of the adjacent African Shield from which it is now separated by the comparatively young Red Sea rift. This Shield can be clearly dated as Precambrian, not only by its unconformable position beneath unaltered sediments which in Jordan have furnished Cambrian fossils, but by a series of radiometric age dates.

Age dating has shown the Arabian Shield to have suffered metamorphism from c.1770 - 586Ma (Stacey & Agar, 1985). Peneplanation of the Arabian Shield was accomplished mainly in the Lipalian interval and since that time the region has had a generally cratonic role.

On this Precambrian craton was deposited a thick cover of continental and shallow-water shelf sediments, dipping gently to northeast, east and southeast. The dip of these cover rocks changes from slightly more than $1^{\circ}00'$ in older units to less than $0^{\circ}30'$ in Upper Cretaceous and Eocene.

This dip of such remarkable constancy for rocks which range from

Cambrian, gives rise to the fundamental structural provenance of the Arabian Peninsula Interior Homocline bordering the Arabian Shield (Power et al., 1966). It is clear that no major orogenic event has affected these rocks since Cambrian time and that the whole area is typically cratonic.

The Palaeozoic stratigraphic sequence in Saudi Arabia (Fig. 2), totals approximately 3092m and consists of five formations, mainly of marine aspect. Individual formations of these Palaeozoic rocks are variable in thickness and composition. Although there are several major lithologic assemblages, the Cambrian-Ordovician Saq Sandstone, Tabuk Formation and Juaf Formation are all found as a great belt around the northern limb of the Arabian Shield. On the other hand, the Permian Wajid Formation and Khuff Formation gird the south of the Arabian Shield (Helal, 1965). The Lower Palaeozoic sequence is terminated at the top by a definite unconformity. Running south from An Nafud (Lat. 29^{o}N, Long. 42^{o}E) pre-Permian erosion progressively eliminates Devonian, Silurian, Ordovician and Cambrian beds, eventually bringing the Permian Wajid Formation into contact with the basement near the latitude of Ad Dawadimi (Lat.24^{o}29'N) From here the erosion surface can be traced south across the basement arch of central Saudi Arabia and again affects the southern wedge of Palaeozoic clastic rocks (Power et al., 1966).

The Saq Sandstone is the oldest known sedimentary rock in Saudi Arabia and begins the Phanerozoic cratonic sequence. Power et al. (1966) considered it to be Cambrian to Early Ordovician. It is exposed along a belt parallel to the Arabian Shield, from the southern Al-Qassim region to the Jordan border, with distance about 1200km and outcrop width of about 120km.

The Saq Sandstone was named by Burchfiel and Hoover in 1935 for Jabal Saq (Lat. $26^{o}16'02''$N, Long. $42^{o}18'37''$E)(Fig. 3). Bramkamp and Hasson (1956) studied the Saq Sandstone and details of the type section were published by Steink et al., (1958). The thickness of Saq Sandstone ranges from 600m in type section (area of study) to about 750m at Al-Quwayrah (Power et al. 1966). The age of Saq Sandstone is uncertain, as no fossil evidence has yet been found, but it has been referred to Cambrian - Ordovician age because it is overlain by the Llanvirnian, graptolite-bearing, Al-Hanadir shale member (Tabuk Formation) and underlain by Precambrian basement.

The study area forms a fairly flat surface where there are numerous exposures, but few deep sections. Only in a few instances do inselbergs rise up from the surrounding landscape to give good sections through part of the Formation.

The Saq Sandstone lies with marked unconformity on a planar erosion surface cut into Precambrian crystalline rocks. These rocks, comprising calc-alkaline granitoid suites, form at least 60% of basement outcrop in the Arabian Shield.

Recent isotopic studies (Duyverman et al., 1982; Stacey et al., 1984; Stacey & Agar, 1985) have confirmed that the Shield evolved through rapid and extensive subduction-related processes during Late Precambrian (850-550Ma), with no substantial reworking of older material although there is some evidence of isolated older source regions for intrusive rocks in south-eastern Shield (Stacey & Headge, 1984). Nd and Sr isotope determinations have been used on Precambrian to early Palaeozoic igneous and sedimentary rocks from different localities in the Arabian Shield (Fig. 4)(Dryverman et al., 1982) to investigate the proportion of reworked "Older" crust and the rate at which new crust was generated during the Pan-African event. The results yield ages in the range 770 - 590Ma, which data confirm that magmatism in this area was largely restricted to the period 850 - 550Ma.

The different igneous suites examined were:

1. Fatima granite (Locality A, Fig. 4) which is a part of a large syntectonic igneous body, which yields an age of 773 ± 16Ma.

2. Badr area which appears to be underlain by an older granitic basement. Five of the Hamra tonalites (an intrusion with weak amphibole lineation) situated within the basement (Locality B, Fig. 4) yielded an age of 641 ± 218Ma.

3. Nugrah area (Locality C, Fig. 4) contains a suite of post-tectonic and unmetamorphosed granitic and volcanic rocks. Four samples of Nugrah granite define indistinguishable isochron, corresponding to ages 635 ± 18Ma.

4. Midian granite (Locality D, Fig. 4) is a post-tectonic granitic complex composed of a granite rim and a biotite core, both of which yield an age of 586 ± 11Ma.

5. The remaining samples are all "basement" lithologies from the Quday'an (Locality H, 24°00'N, 45°12'E) and yield ages of 750 ± 100Ma.

Using Rb/Sr; K/Ar isotopic systems in localities E, F and G, Baubron et al. (1976) obtained ages of 577 ± 15, 571 ± 6 and 688 ± 35Ma, respectively.

Bokhari & Kramers (1981) used isotopic techniques to date the Surgah Formation (Locality K, Fig. 4) which yielded an age of 721 ± 55Ma.

Stacey & Agar (1985) used U-Pb zircon isotopic techniques to date the Kabid Formation in the Zalim region (Locality L, Fig. 4) which yielded an age of 1773 ± 32Ma.

Generally, the whole-rock ages of the Arabian Shield which have been dated by isotopic methods range from an oldest of 1773 ± 32Ma on the Kabid Formation in the Zalim region to the late peralkaline complex of Midian with an age of 586 ± 11Ma.

The initial Sr isotope ratios all cluster tightly around a value of 0.7026 , confirming that 800-600Ma was a time of considerable crustal growth in what is now the Arabian Shield (Duyverman et al., 1982). Early crustal growth began with the accumulation of calcic-Alkalic, basaltic to dacitic volcanic rocks, and immature sedimentary rocks that were subsequently moderately deformed, metamorphosed and intruded about 960Ma. Later crustal development occurred after the Bishah Orogeny, 570 ± 550Ma (Greenwood et al., 1976).

In the interval between the Bishah Orogeny and the overlying Saq Sandstone, the Saudi Arabian area became a stable cratonic shield. The Saq Sandstone is Cambro-Ordovician in age, and with the base of the Cambrian being c. 505Ma (Harland et al., 1982), the time available for the transformation of the Shield from a mobile belt to a craton is c. 50Ma.

The contact between Saq Sandstone and the Precambrian basement rocks is observed in numerous localities. It is marked by a planar surface overlain by basal Saq Sandstone which comprises a thin veneer of sandstone, conglomerate and breccia derived from underlying basement rocks. The upper contact coincides with a sharp lithological and topographical break between the Saq Sandstone and Al-Hanader shale (Tabuk Formation).

The Saq Sandstone dips gently northeastwards under this

Ordovician Tabuk Formation.

In the subcrop to the east the Saq Sandstone thickens to over 1000m. Whilst the nature of the thickness change is not known in the north, the sandstone thins towards the present outcrop. This outcrop is therefore the SW margin of a basin which thickens NE. A minor basin, the axis of which trends N-S, has developed in the S region (Fig. 5). Care has to be taken in the strict interpretation of isopachs since the Saq Sandstone may be diachronous, or may include facies variants of younger sediments. Neither is it possible at this stage to determine whether the W thinning is by differential subsidence, or by overstep and overlap.

The Saq Sandstone (Fig. 6) is often tanished to a brown colour, but when fresh is a gray and white quartz arenite. It is abundantly cross-stratified, moderately to well-sorted in its upper part and moderately to poorly-sorted in its lower part. It is composed of fine- to medium-grained sandstone in the upper and medium to coarse in the lower part, and has mainly monocrystalline grains which range from angular to sub-angular in the lower part and sub-rounded to rounded in the upper part.

A section through the type area of Jabal Saq (Fig. 7) shows its cross-stratified nature and upwards decrease in grain size. A tough quartz-arenite forms the local top to the sequence. The dominant cement is carbonate, which is locally replaced by ferruginous material which hardens the sandstone and gives it a reddish-brown colour. This ferruginous crust is related to present-day weathering.

The Saq Sandstone is a permanent aquifer in the north and central Saudi Arabia and this aquifer yields large quantities of generally good quality water used for drinking and irrigation purposes.

Sampling: Due to the nature of outcrop of the study area, generally three fresh samples or more were taken from each outcrop and more than one outcrop was sampled in each locality (Fig. 8).

Aim and Scope of study:

The object of this study is to examine in detail the sedimentary history of the Saq Sandstone. It includes:-

i. The establishment of the dispersal system using cross-stratal dip orientation.

ii. Examination of the grain composition in order to identify the nature of the provenance area. In this respect, particular attention has been given to the type of quartz (mono-polycrystalline), nature of the heavy mineral assemblages, and the chemistry of the sediments.

iii. The environment of deposition of Saq Sandstone has, up to now, been loosely defined. Examination of the lithological sequences, sedimentary structures and grain sizes will allow the establishment of facies, and the nature of the palaeoflow in relation to facies will help to recognise the various environments of deposition.

iv. In addition to these problems, the nature of the unconformity beneath the Cambrian is examined and its significance is assessed.

v. Within the known framework of changing source and environment within the Saq Sequence, a study of geochemistry of the sandstone has been undertaken. This has been done in order to relate chemistry to petrographic composition, and to aid in the identification of source.

vi. To examine the vertical changes in sedimentary parameters so that an assessment of the changing regime may be documented.

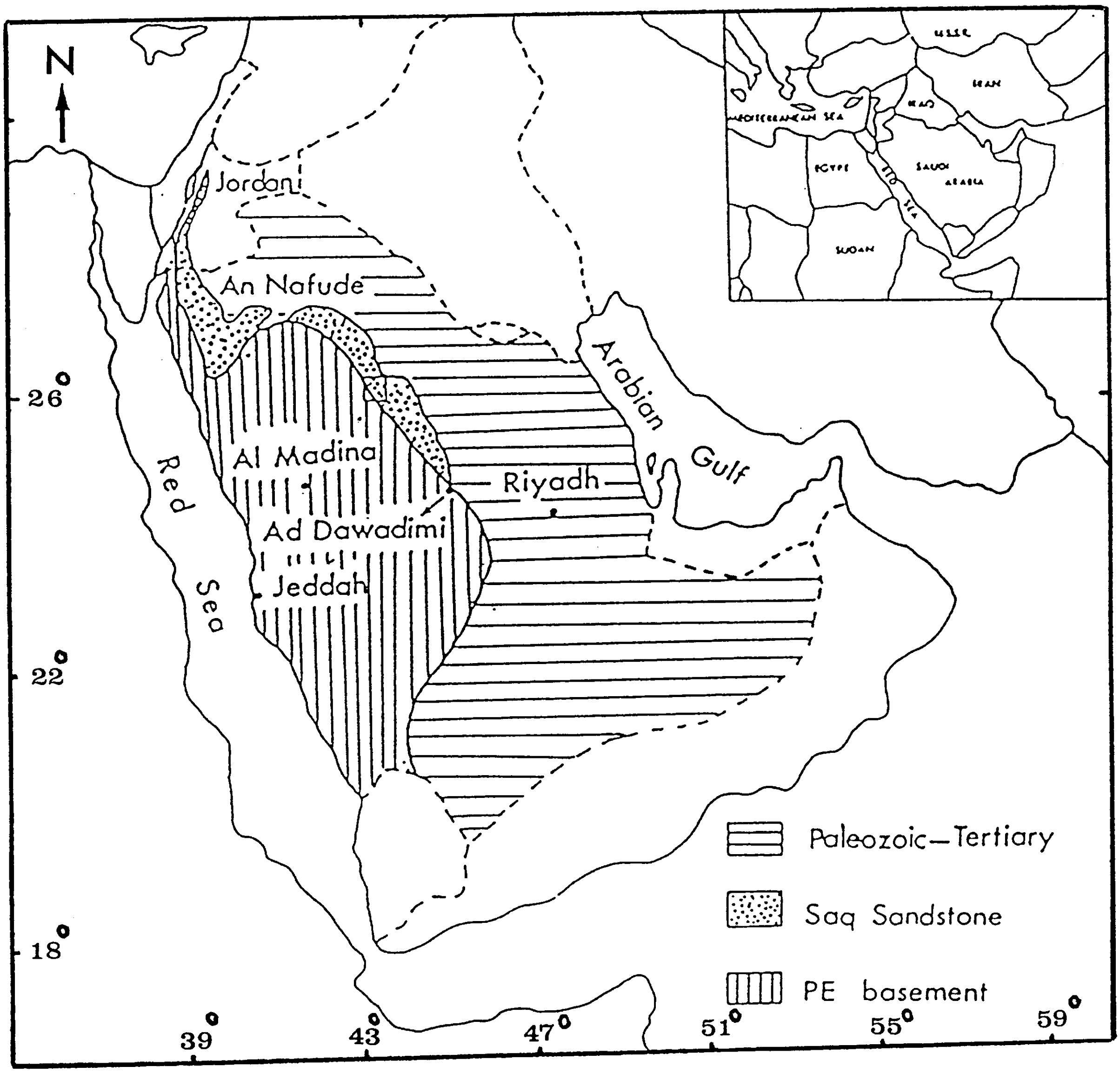


FIG. 1 Outcrops of Cambro-Ordovician Saq Sandstone in Saudi Arabia and adjacent countries.

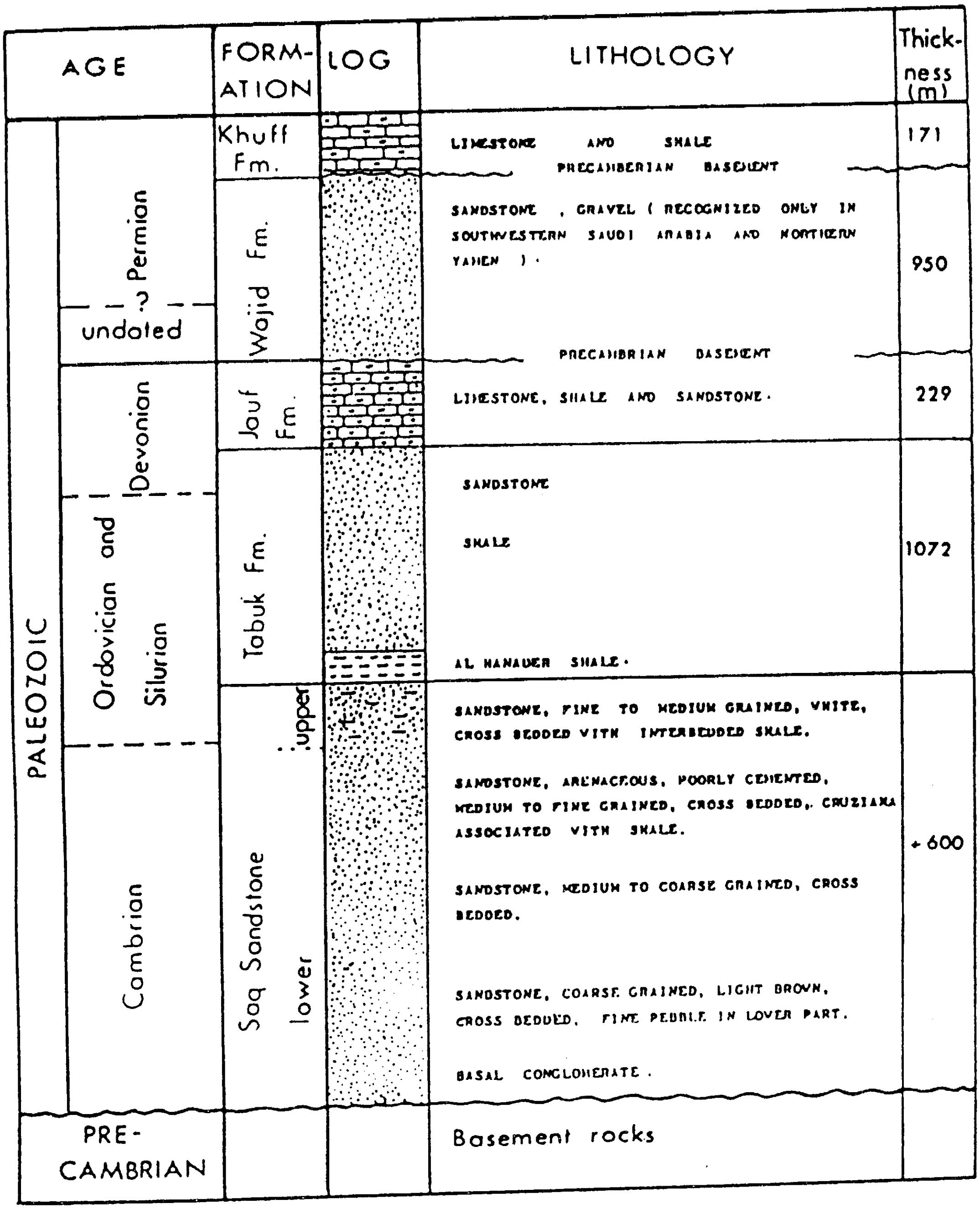


FIG. 2 Sedimentary geology of Palaeozoic Saudi Arabia (Powers *et al.*, 1966).

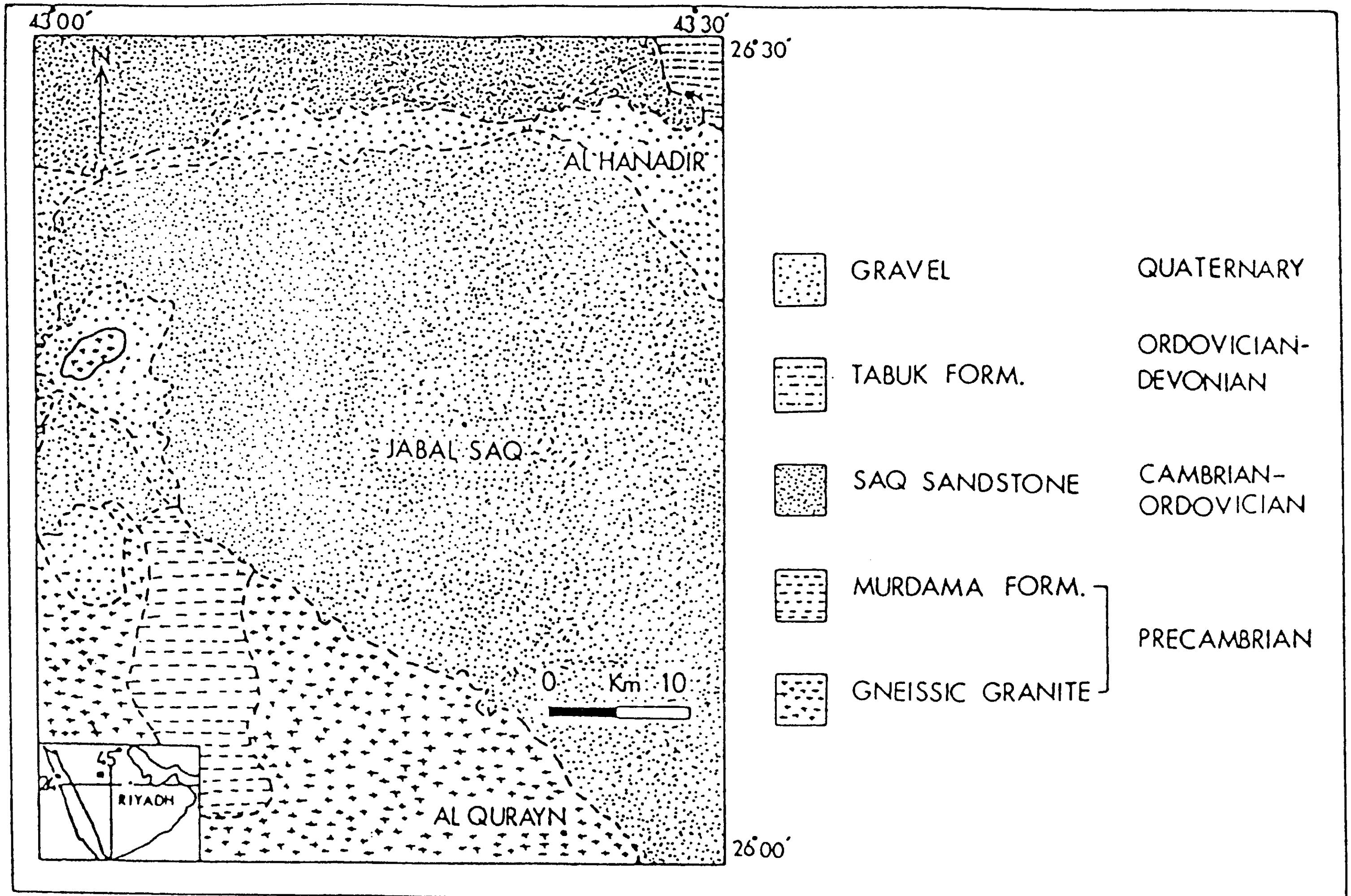


FIG. 3. Geological map of the area of study

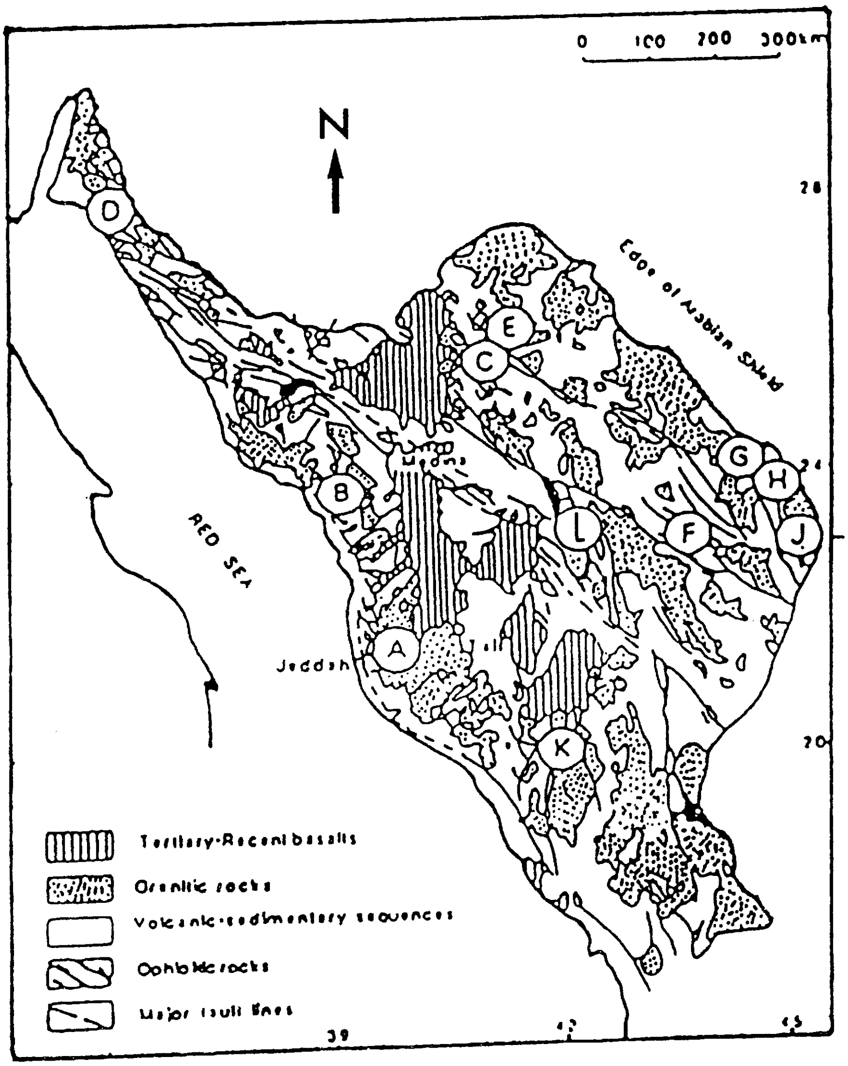


FIG. 4 Geological map of Arabian Shield, illustrating sample localities (after Duyverman et al., 1982).

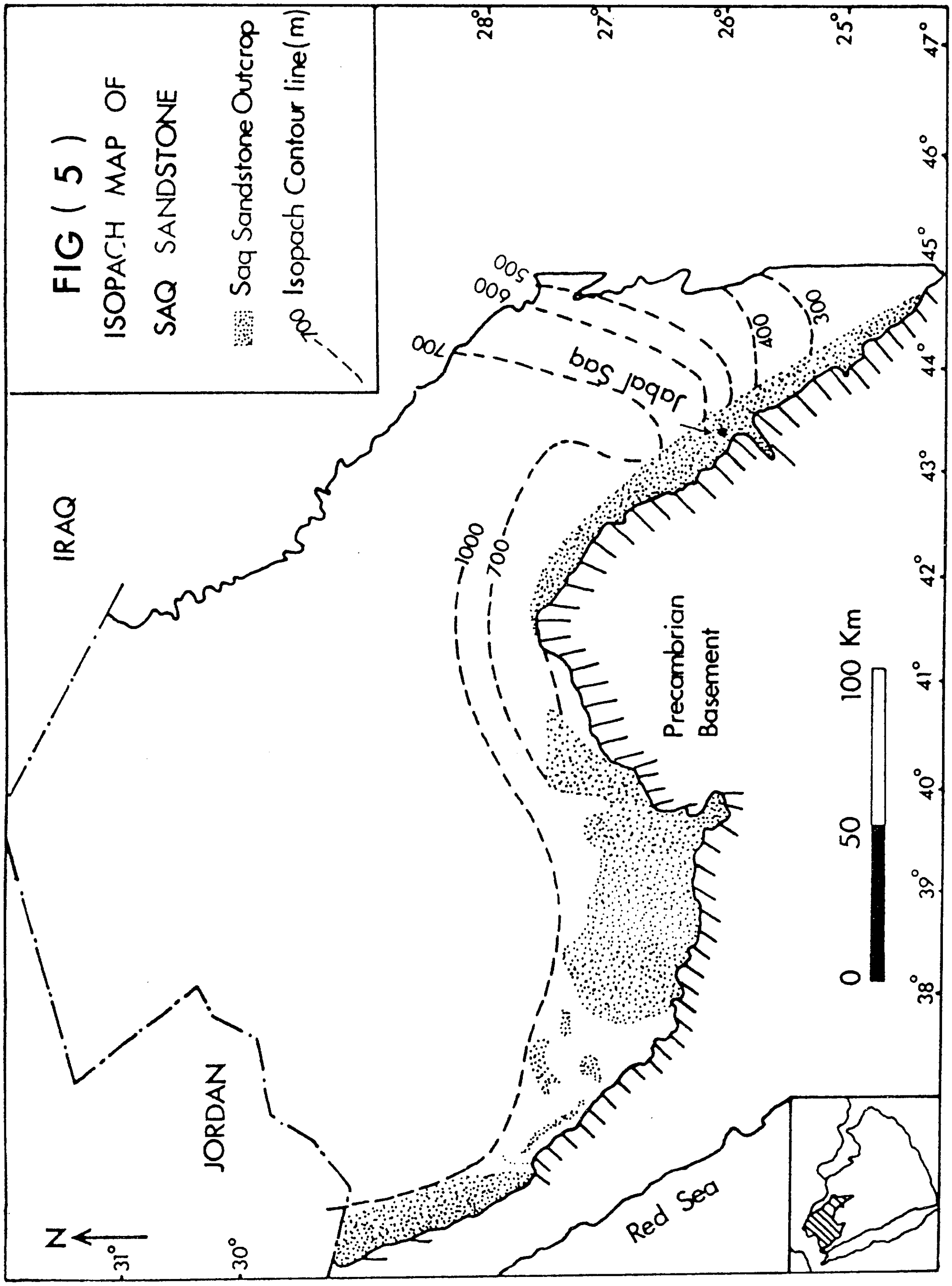
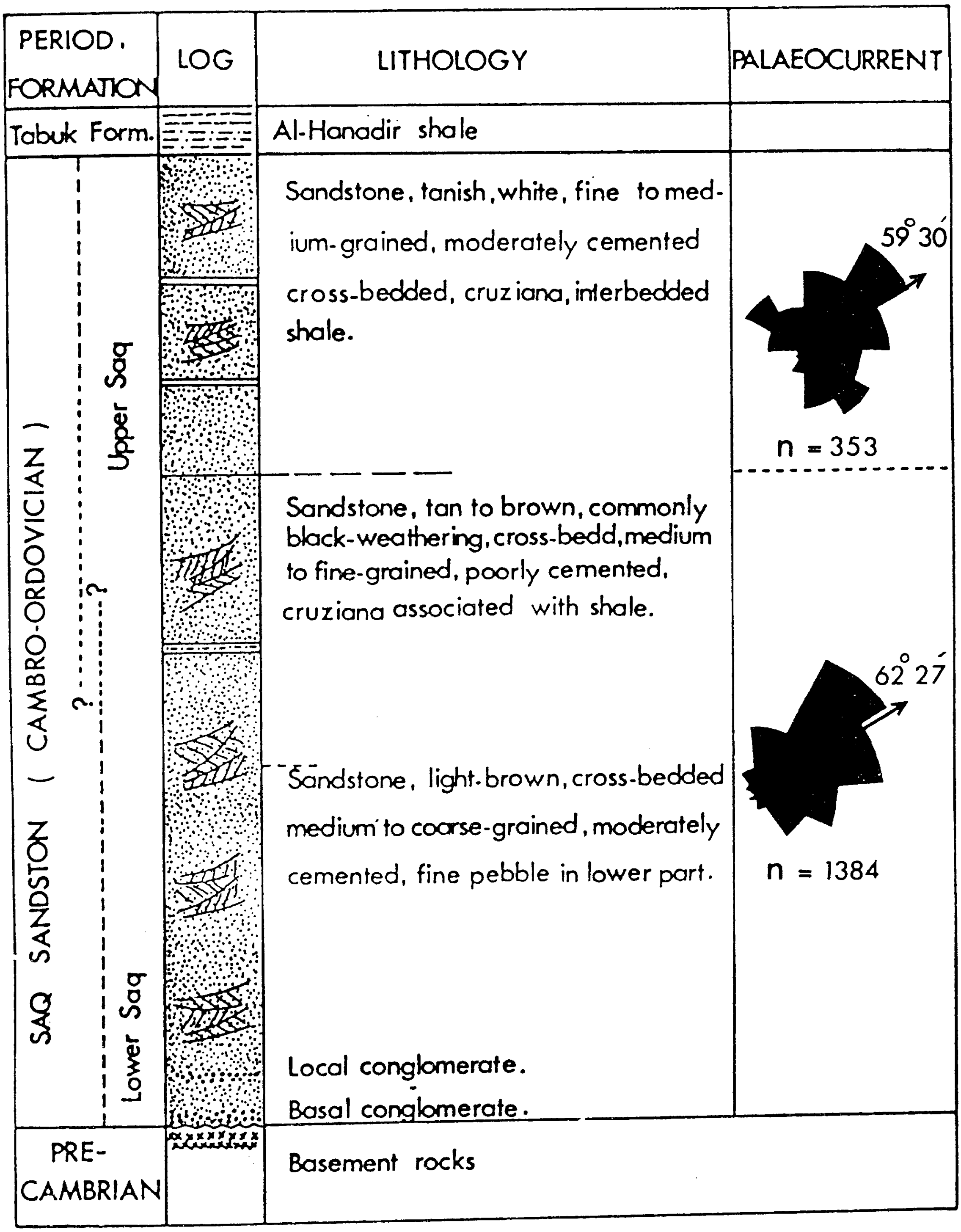


FIG (5)
ISOPACH MAP OF SAQ SANDSTONE

Source: Ministry of Agriculture and Water, Saudi Arabia.



Fig(6) Composite coulmnar section of Saq Sandstone.

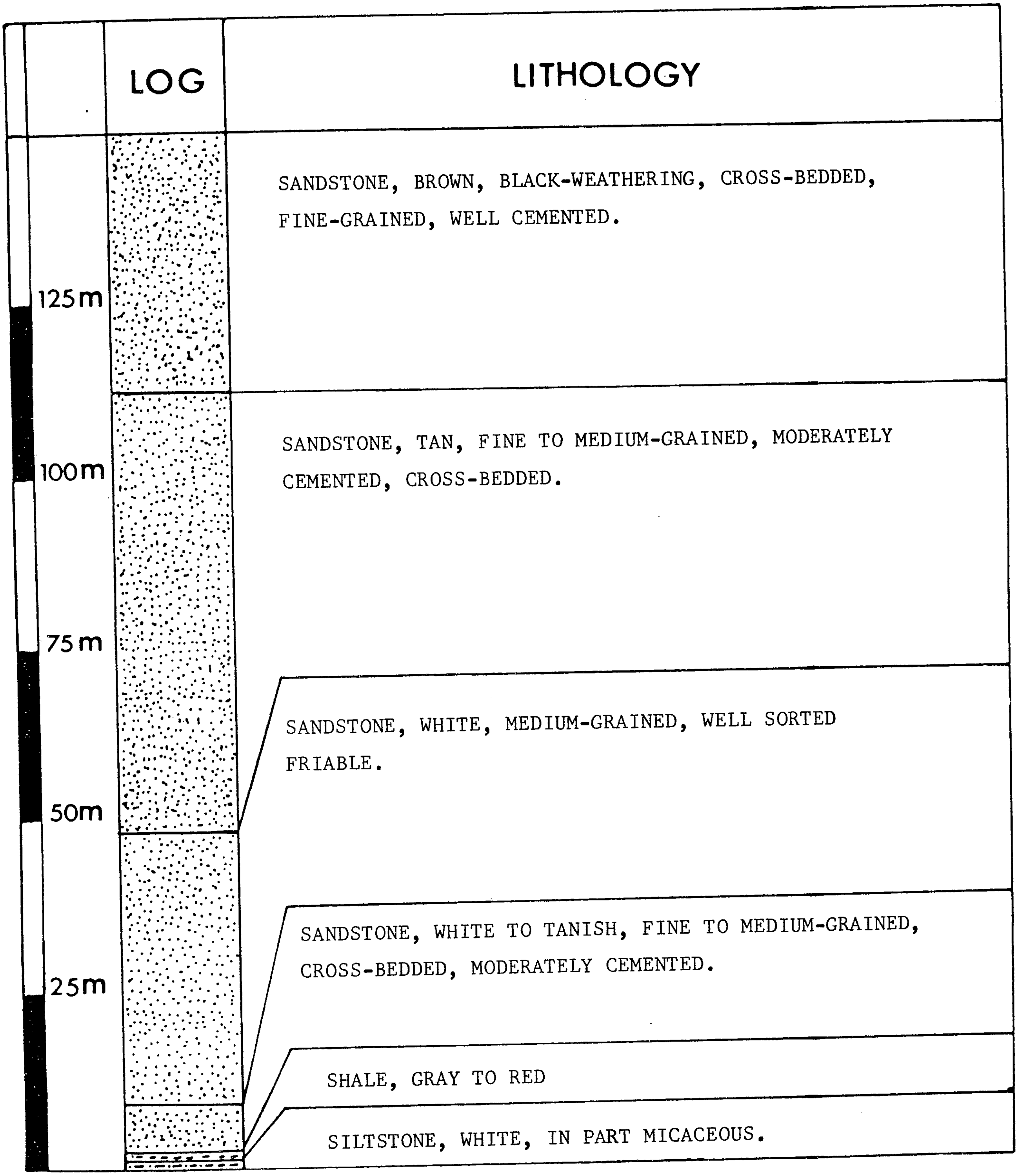


FIG. 7. Columnar section for Jabal Saq (Saq Sandstone).

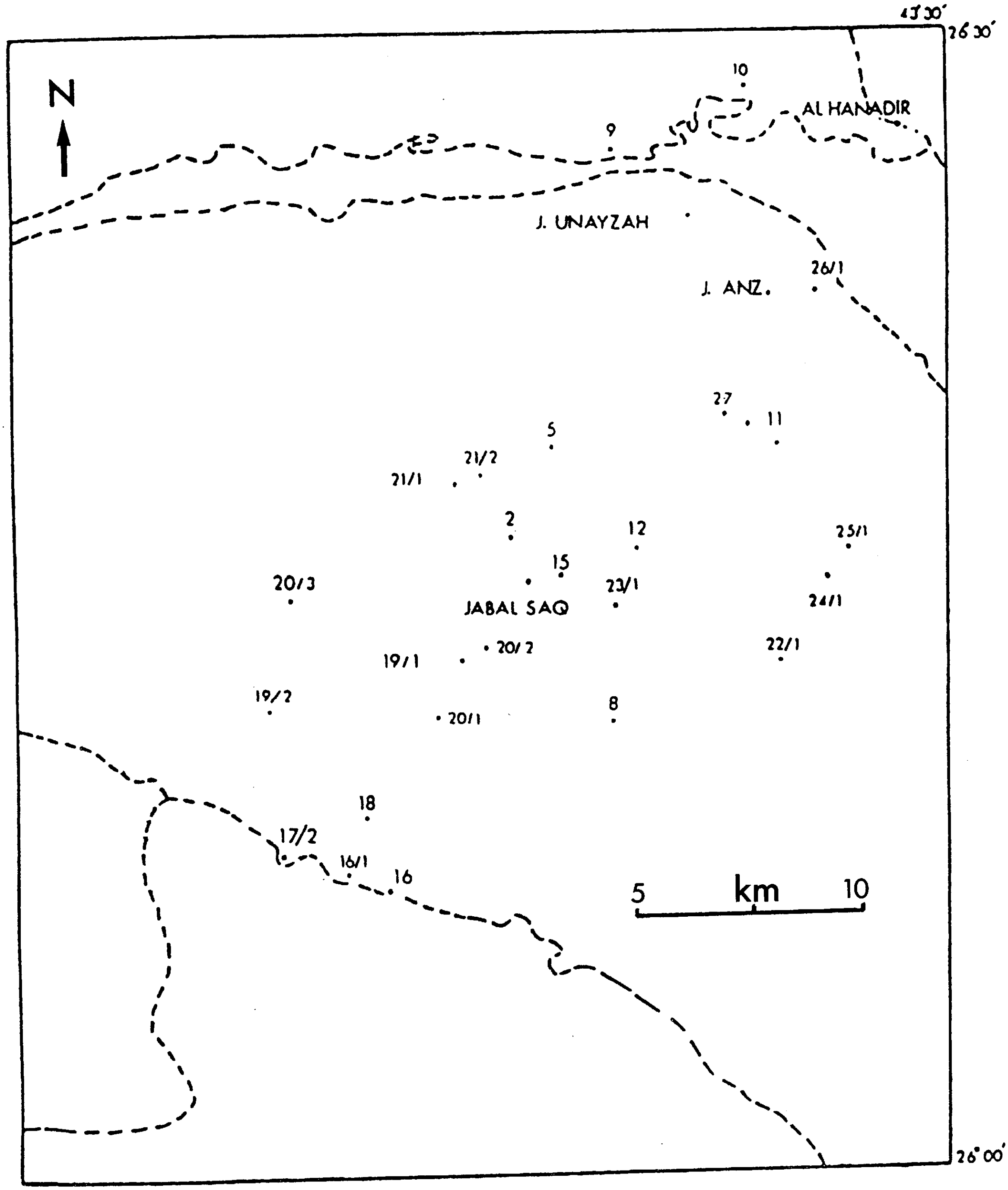


FIG. 8 Location map of Saq Sandstone showing sample locations.

CHAPTER TWO

SAQ SANDSTONE PETROGRAPHY AND PROVENANCE

The relationship between the framework mineralogy of sandstone and tectonic setting has been summarized and interpreted by many workers (Crook, 1974; Schwab, 1975; Dickinson and Suczek, 1979; Dickinson *et al*. 1983). The nature of source rock near to a sedimentary basin is considered a guide to general tectonic regime in which sediments accumulate. In addition framework mineralogy is an indicator of the subsidence history of a basin and uplift history of a source. Continual reworking eliminates unstable grains and concentrates the more stable, such as quartz.

A petrographic study of Saq Sandstone was carried out using the petrographic microscope fitted with a Swift automatic point counter. Fifty thin sections, with 400 grains counted from each slide provides the data-base upon which the following discussion is based (see also Tables 1, 2).

Quartz is the predominant mineral, making up some 95 per cent of all Saq Sandstone. The remaining minerals include feldspar, micas and some rock fragments.

Mineralogical classification of sandstone.

In order to classify the sandstone, three fractions, quartz, feldspar and lithic rock fragments were plotted in a triangular diagram (McBride, 1963).

All the samples from Upper and Lower Saq Sandstone fall in the quartz arenite field (Figs. 10,11).

Framework Mineralogy.

The most significant compositional variations among the terrigenous sandstones can be displayed as ternary plots on triangular diagrams.

The three apices or poles, represent the recalculated proportion of key categories of grain type determined by modal point count. Two alternate sets of poles (QFL and QmFLt) are useful (Graham et al., 1976).

A. For QFL diagrams, the poles are:

(1) Total quartzose grains (Q) including polycrystalline fragments such as chert and quartzite.

(2) Monocrystalline feldspar (F).

(3) Unstable polycrystalline lithic fragments (L) of either igneous or sedimentary parentage, including metamorphic varieties.

B. For QmFLt diagrams, the poles are:

(1) Quartz grains (Qm) that are exclusively monocrystalline.

(2) Feldspar grains (F).

(3) Total polycrystalline lithic fragments (Lt), including quartzose varieties.

Dickinson and Suczek (1979) showed that mean composition of sandstone suites from various plate tectonic settings tend to lie within discrete and separate fields on QFL and QmFLt diagrams (Fig. 9).

The three main categories of provenance terranes thus distinguished were those within continental blocks, magmatic arcs and recycled orogens. Variants of each can be related to specific plate settings.

The Saq Sandstone is a quartz arenite in composition in terms of the triangular QFL and lies in the craton interior according to the

QmFLt diagrams (Figs. 12 to 15).

All this evidence indicates that these quartz arenites were derived from a stable craton interior which had low relief (Dickinson et al., 1983).

Quartz Petrography.

Quartz is the most common detrital mineral *in sandstone*. It has a source in many igneous, metamorphic and pre-existing sedimentary rocks and many attempts have been made to use it for source rock determination. Sorby (1877, 1880), Mackie (1896), Gilligan (1919), Tyler (1936), Krynine (1940), Pettijohn 1949), Bokman (1952), Blatt and Christie (1963), Blatt (1967), Basu et al., (1975), and Young (1976) have all used various characteristics of quartz in order to determine its provenance.

However, it was the pioneering work of Blatt and Christie (1963) which demonstrated that the relative abundance of mono- and polycrystalline quartz was a key to determine both the provenance and the maturity of sandstone. Investigations by Basu et al. (1975) and other workers (Blatt and Christie, 1963; Blatt, 1967), have shown that sand derived from low-rank metamorphic rocks (e.g. chlorite-biotite zone) contains more polycrystalline quartz than sand from high-rank metamorphic (e.g. granite-sillimanite zone). Monocrystalline quartz is typical not only of high-grate metamorphic but also of plutonic rocks.

There are, however, a number of constraints on the use of the type of quartz as an indicator of provenance:

(i) The abundance of monocrystalline grain is partly related to grain size (Blatt and Christie 1963; Blatt et al., 1972;

Basu et al., 1975). As the grain size of the rock increases so the abundance of monocrystalline quartz decreases. The investigation of Blatt (1967) shows that the number of crystal components in polycrystalline grains increases with increasing size.

(ii) Polycrystalline quartz is less stable than monocrystalline and also the undulatory monocrystalline quartz is less stable than the non-undulatory variety (Blatt and Christie, 1963; Basu et al., 1975). So the relative proportion of each may be an indication of sediment maturity.

The types of quartz grains found in Saq Sandstone are non-undulatory, undulatory monocrystalline quartz and polycrystalline quartz. Averages of these various quartz types are given in Table 3.

Non-undulatory Monocrystalline Quartz.

Any grain composed of a single crystal and showing no visible evidence of strain is called non-undulatory monocrystalline (Blatt & Christie, 1963).

The average of non-undulatory quartz is 61.99% in Upper Saq and 56.92% of total quartz in Lower Saq Sandstone. Blatt and Christie (1963) have observed that quartz arenites have an average 43.1 per cent of non-undulatory quartz. Since most sandstone in the Saq Sandstone fall within the medium sandstone grain size, the effect of size on the relative abundance of quartz type is thought to be minimal. The high abundance of non-undulatory monocrystalline quartz is therefore thought to be the consequence of maturing, or of a source which had little low grade metamorphic rock. However the Upper Saq Sandstone contains slightly more monocrystalline quartz than the Lower Saq and since the abundance of monocrystalline quartz is a function of grain, the fact that the Lower Saq is coarser than the Upper may explain this slight difference.

Undulatory Monocrystalline Quartz.

Any grain of a single crystal and showing visible evidence of strain (Plate No.5), is referred to as an undulatory monocrystalline grain. Mackie (1896) and Basu et al., (1975) have shown empirically that undulatory extinction is most useful in distinguishing source rock type. Basu et al., (1975) observed that metamorphic quartz have a larger true angle of undulosity (mean 7.9°) than plutonic quartz (mean 3.5°).

The average number of undulatory quartz grains in the Upper Saq is 31.18 per cent and 34.30 in the Lower.

Blatt and Christie (1963) observed that polycrystalline undulose quartz is not stable when it is transported and soon breaks down to monocrystalline grains with undulatory extinction. These later ones will eventually break down to provide non-undulatory monocrystalline quartz (Plate 6). It is therefore possible that the lower proportion of undulatory quartz in Upper Saq is a result of maturing of the sediment through time.

Polycrystalline Quartz.

Polycrystalline grains are those containing two or more crystal units of different optical orientation.

Blatt et al., (1972) indicated that the average number of crystal units in sand-size grains of polycrystalline quartz varies depending on the source rock of the quartz. They noted that in general Plutonic polycrystalline quartz is more coarsely crystalline (2-5 crystal units per grain) and that gneissic polycrystalline quartz is more finely crystalline (> 5 crystal units per grain). Crystal units in polycrystalline quartz from schist have an intermediate number.

Polycrystalline grains average 8.87% in Lower Saq Sandstone and 6.83% in Upper Saq. Most polycrystalline grains in Saq Sandstone contain more than five crystals per grain and the boundaries between crystals vary from sutured to straight (Plate 2).

Breakdown of quartz grains, if it takes place along polycrystalline grain boundaries, will produce progressively finer-size grains with fewer crystal grains in each size. On the basis of the work of Blatt and Christie (1963) these polycrystalline grains would appear to have a source in a gneissic terrane.

There is only a slight vertical change in the percentage of polycrystalline quartz from Lower to Upper Saq Sandstone, suggesting that either there is a change in provenance upward or that there is a change in maturity.

An upward increase in maturity is also suggested by (1) increase of SiO_2 upward in the sequence, (2) and an increase of ultra-stable heavy minerals upward sequence.

The Saq Sandstone is typified by a low percentage of polycrystalline quartz (< 9%) and a correspondingly high percentage of monocrystalline quartz (> 90%). This high proportion of monocrystalline quartz could be due either to the nature of the provenance or to the maturity of sediment (Folk, 1960; Blatt and Christie, 1963;

Blatt, 1967; Mackel, 1967; Basu et al., 1975; Granmayeh, 1978).

The basement rocks in the region covered by this thesis comprises a variety of rock types, including a lithic graywacke which is weakly metamorphosed.

The graywacke is composed of 30% monocrystalline quartz, 20% plagioclase and 50% lithic fragment (du Bray, 1983). Quartz monzo-granite comprised the rest of the basement and all these rock types produce an abundance of monocrystalline quartz. These lithologies yield sediment to the rocks immediately above the unconformity and here the percentage of polycrystalline quartz is less than 5, while the monocrystalline quartz is always more than 80%.

The local provenance area did not, therefore, yield much polycrystalline quartz. However the presence of detrital chert grains and quartz overgrowth which have been abraded before becoming part of this sediment is interpreted as evidence for a provenance in pre-existing sandstone (Plates 1, 2, 3). Both these factors are thought to be responsible for concentrating the monocrystalline quartz, but it is not possible at this stage to assign any relative importance to either of these factors.

The other detrital components in Saq Sandstone are rock fragments, which is very rare, most of which are chert and metamorphic rock fragments. The average in Upper Saq and Lower are 0.31% and 1.01% respectively.

Micas in Saq Sandstone are averaged at 1.9% in Upper Saq and 2.74% in Lower Saq. Most of the micas are muscovite but some biotite were observed.

TABLE 1: MINERALOGY OF UPPER SAQ SANDSTONE.

Sample No.	Quartz mono.	Quartz poly.	Feldspar	Rock Fragment	Micas	Carbonate Cement
1-1-24	84.5	6.8	-	-	0.25	8.80
1-1-21	85.75	8.65	-	-	0.50	5.08
1-1-20	78.3	8.10	-	-	2.16	11.35
1-1-19	82.16	13.31	-	-	-	4.52
1-1-18	69.67	8.27	-	-	1.00	21.05
1-1-27	83.46	2.58	0.25	-	0.25	13.43
23-1-1	83.14	1.97	2.80	-	2.80	8.71
23-1-2	83.59	0.52	0.52	-	2.08	13.28
11-1-2	78.85	4.96	1.56	1.30	0.52	12.79
24-1-9	76.41	4.61	2.05	-	7.69	9.23
24-1-8	79.69	6.06	1.21	0.60	3.03	9.39
24-1-7	79.00	6.56	-	-	0.52	13.91
24-1-5	73.61	6.59	0.79	0.26	6.86	11.08
21-1-1	88.86	6.07	-	-	-	5.06
21-1-2	93.41	3.29	0.25	-	0.50	2.53
Uniz. 1	72.35	9.11	1.76	2.35	2.35	12.05
24-1-10	79.19	6.06	0.86	0.57	2.02	11.27
22-1-10	75.07	6.07	1.91	0.31	2.23	14.37
24-1-11	79.06	8.13	1.16	0.87	1.45	9.30
2-1-1	93.48	3.75	-	0.25	0.75	1.75
1-1-17	91.64	4.30	-	-	1.51	2.53
$\bar{x}$	81.49	5.99	0.72	0.31	1.9	9.59

TABLE 2: MINERALOGY OF LOWER SAQ SANDSTONE.

Sample No.	Quartz mono.	Quartz poly.	Feldspar	Rock Fragments	Micas	Carbonate Cement
17-1-2	79.83	3.64	1.96	1.68	2.80	10.08
17-2-1	83.76	4.63	0.77	0.51	-	10.30
18-1-1	71.91	9.71	1.05	1.83	2.36	13.12
19-1-3	78.34	8.28	1.06	1.60	2.94	7.75
20-2-1	79.00	8.48	0.87	1.16	1.45	9.03
20-2-2	86.03	2.79	1.67	2.5	0.55	6.42
21-2-9	73.95	6.77	0.26	0.52	2.60	15.88
21-2-14	75.58	9.01	2.03	4.36	1.45	7.55
21-2-16	73.28	7.14	1.58	2.38	4.76	10.84
21-2-17	75.97	10.33	2.51	3.07	1.95	5.30
21-2-18	79.25	5.50	0.75	1.5	7.75	5.25
21-2-5	86.32	6.58	0.50	-	0.75	5.82
21-1-4	75.92	5.51	0.25	0.25	0.50	17.54
21-1-6	84.8	6.02	0.52	-	0.52	8.11
1-1-7	90.76	6.66	-	-	0.76	1.79
21-1-8	70.55	9.39	0.50	0.25	1.26	18.02
21-2-10	66.66	10.59	1.55	2.32	2.58	16.27
21-2-1	71.53	7.17	1.02	1.53	3.58	15.12
21-2-6	66.57	12.27	1.30	2.08	4.96	12.53
21-1-7	84.45	5.36	0.80	-	1.60	7.77
1-1-12	77.06	4.89	-	-	-	10.04
1-1-14	78.11	6.87	-	-	-	15.01
1-1-13	90.90	2.77	-	-	1.26	5.05
1-1-15	63.49	18.76	-	-	2.57	15.16
18-1-2	85.63	4.10	0.24	-	1.17	8.79
18-1-3	81.44	4.71	0.62	0.31	1.88	11.00
19-2-2	74.75	12.13	0.98	0.65	2.29	9.18
2-2-1	71.59	11.53	0.88	0.29	5.32	9.46
21-1-3	91.26	1.97	0.84	0.56	-	5.35
$\bar{x}$	78.23	7.36	0.85	1.01	2.74	9.81

TABLE 3: The average of mono- and polycrystalline quartz in Upper and Lower Saq Sandstone (Recalculation to 100%).

Type of quartz / Formation	Monocrystalline quartz %		Polycrystalline quartz %
	Undulatory	Non-undulatory	
Upper Saq	31.18	61.99	6.83
Lower Saq	34.30	56.92	8.87

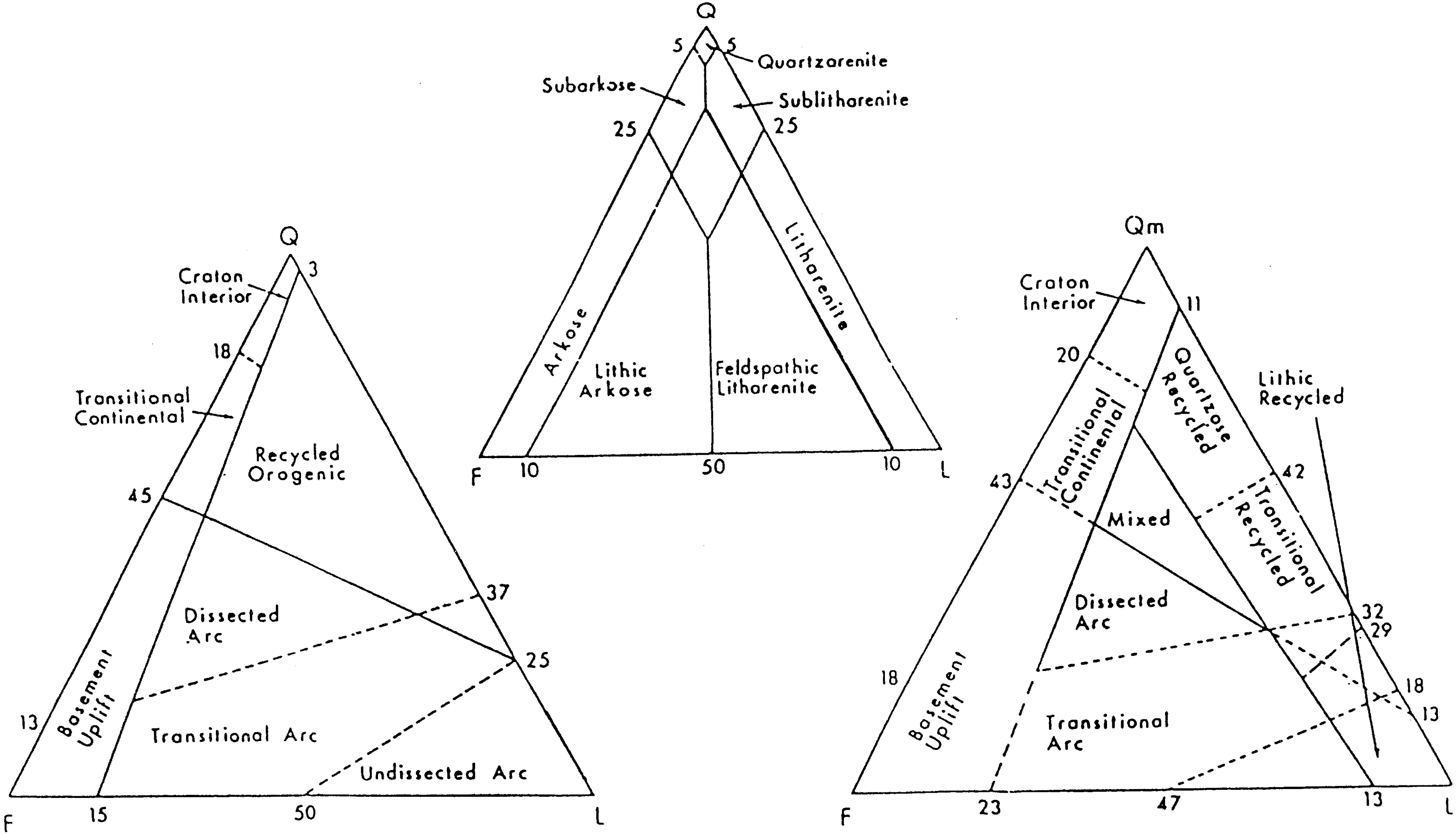


FIG. 9 Reference diagrams for petrographic data (1) QFL diagram (after McBride, 1963) for classification of sandstone; (2) QFL diagram; (3) QmFLt diagram (after Dickinson et al., 1983) to decipher the provenance.

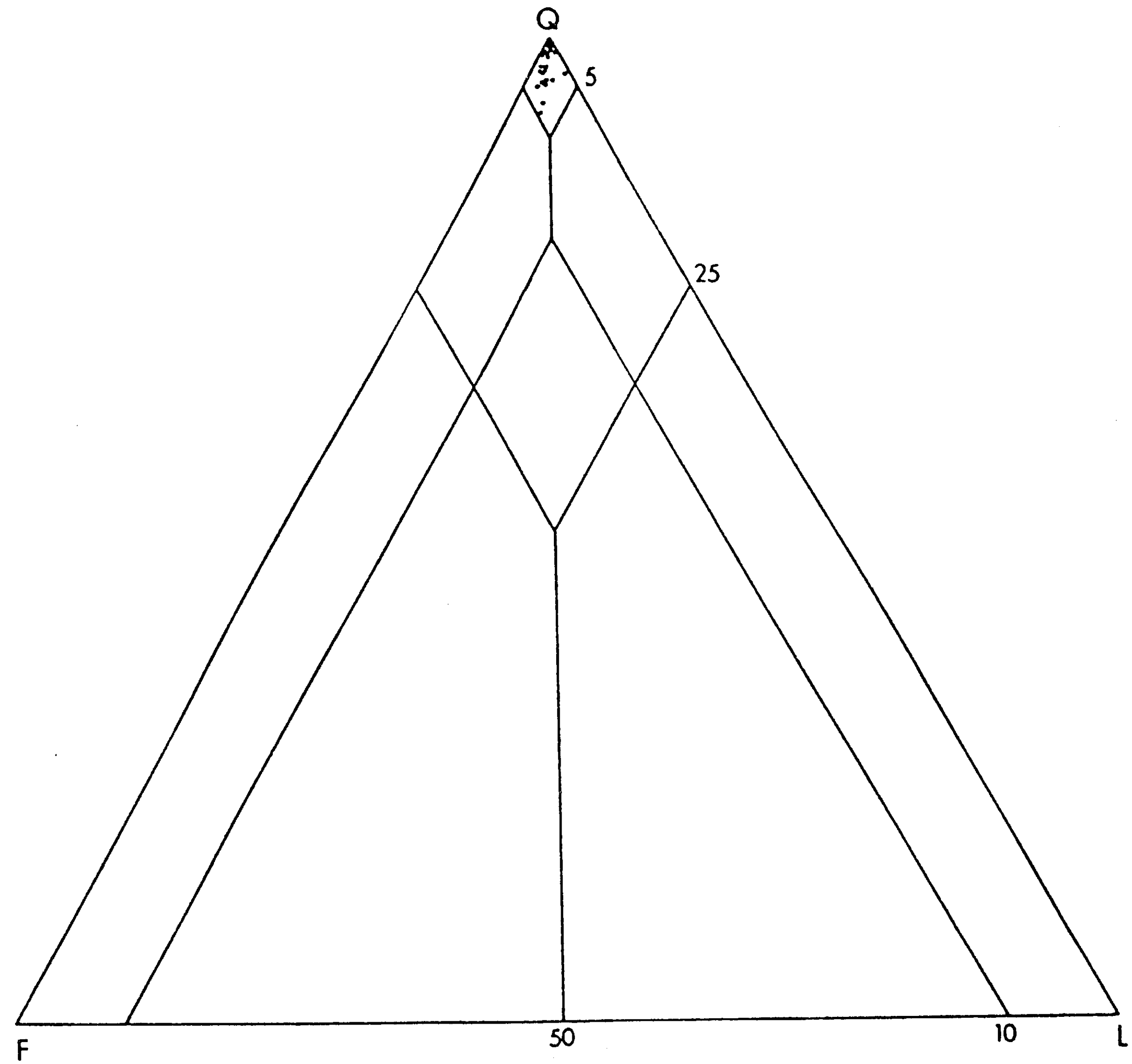


FIG.10 QFL diagram showing the composition of Lower Saq Sandstone.

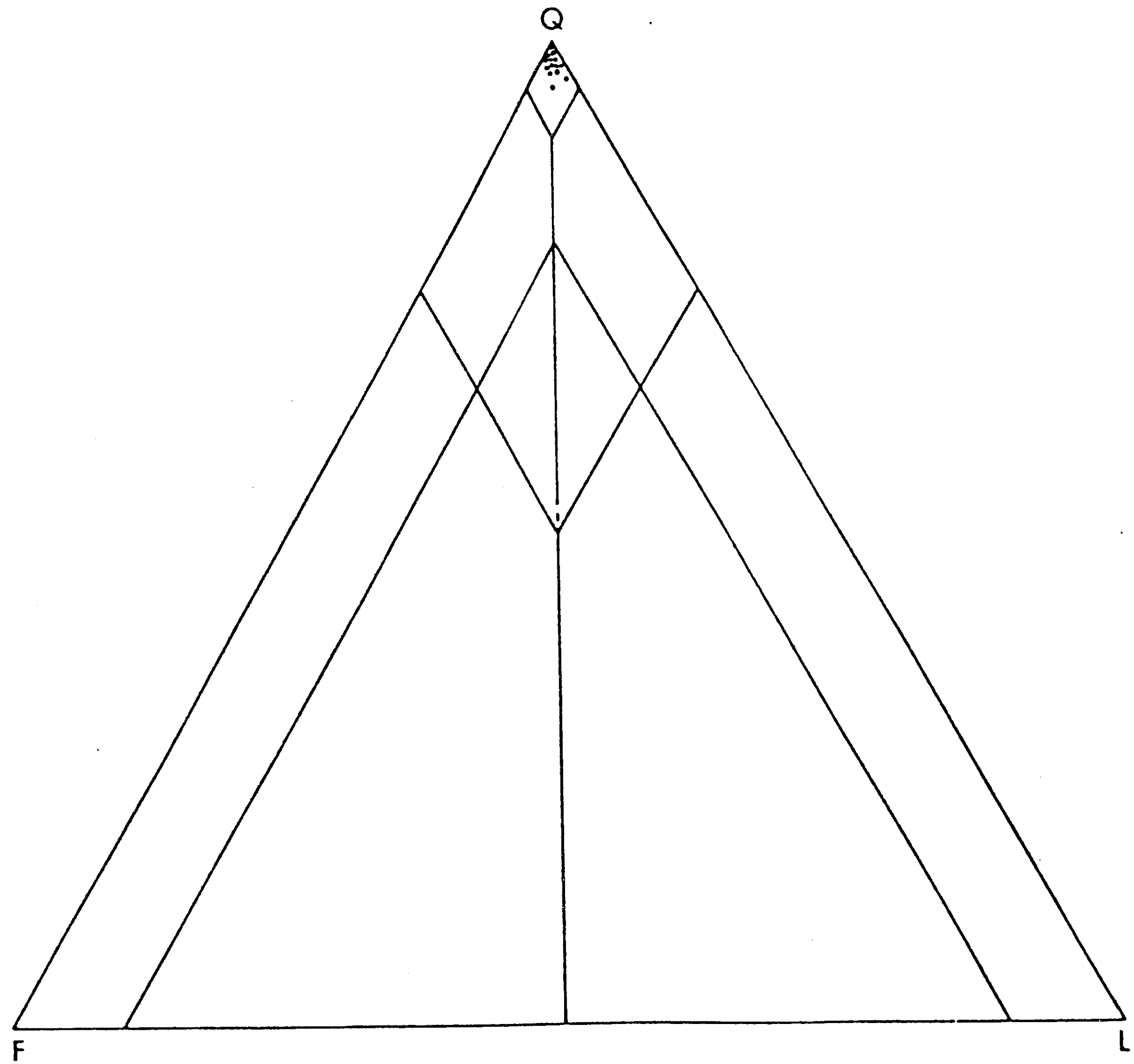


FIG. 11 QFL diagram showing the composition of Upper Saq Sandstone.

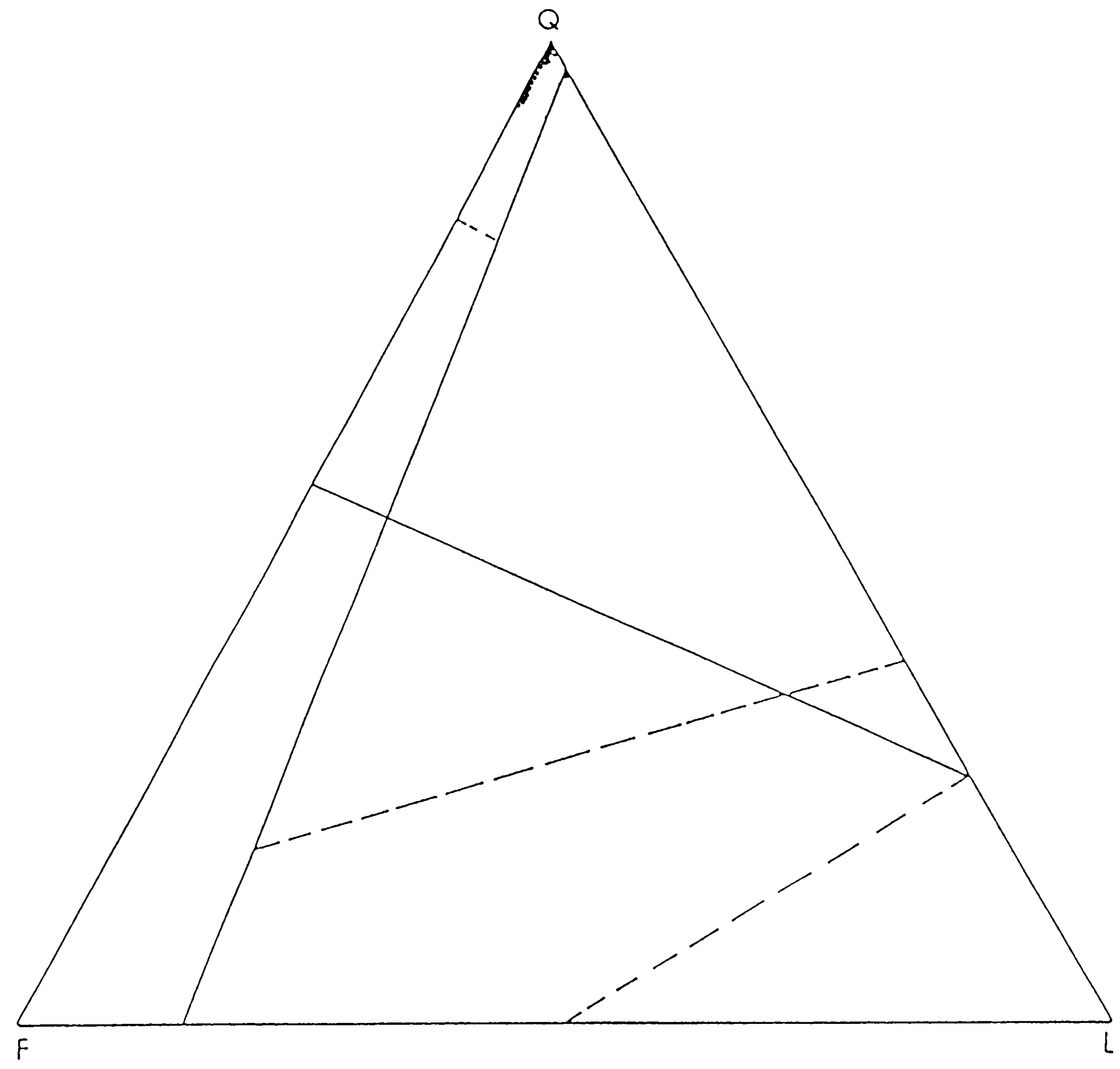


FIG. 12 QFL diagram to decipher the provenance of Lower Saq Sandstone.

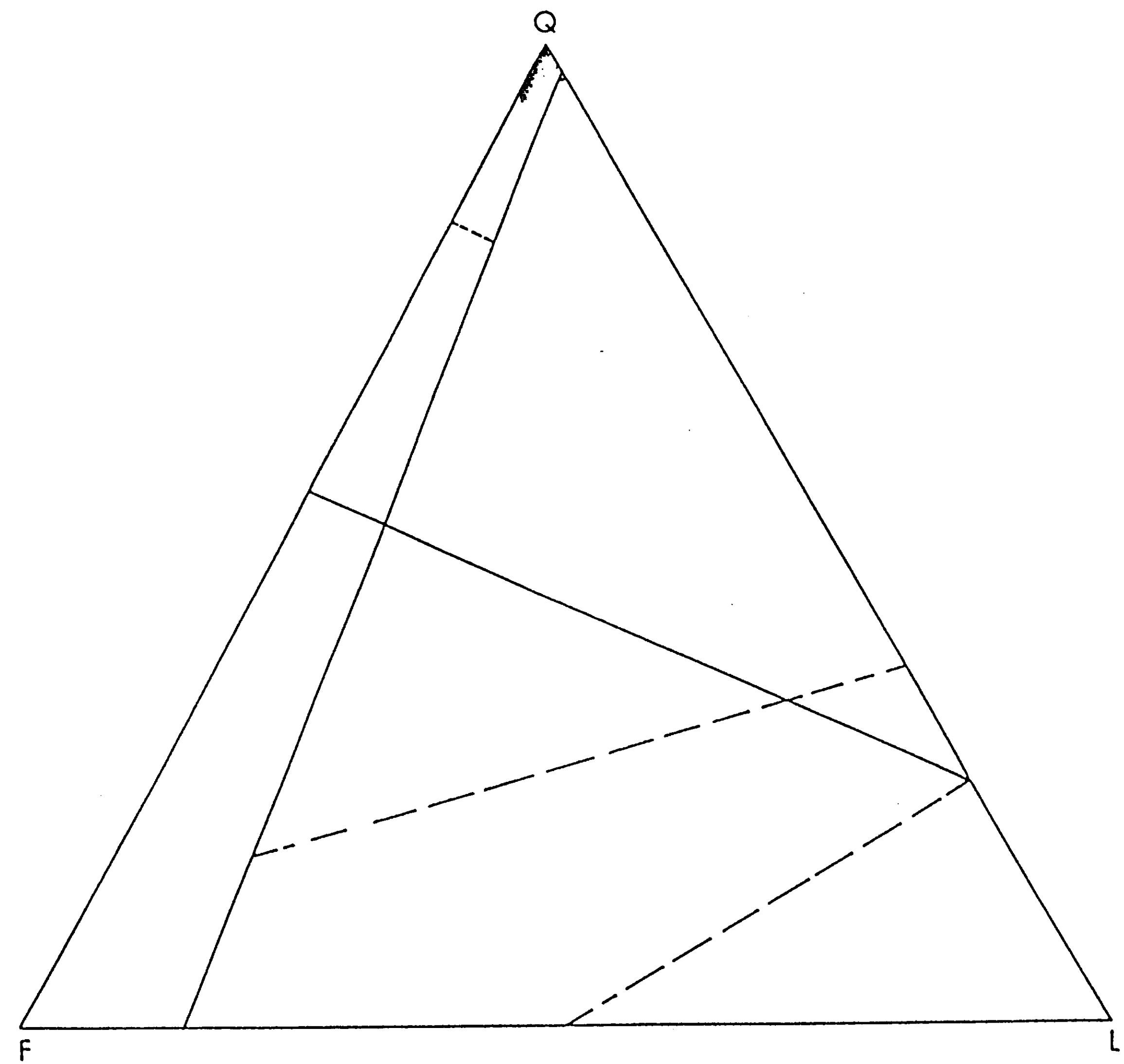


FIG. 13 QFL diagram to decipher the provenance of Upper Saq Sandstone.

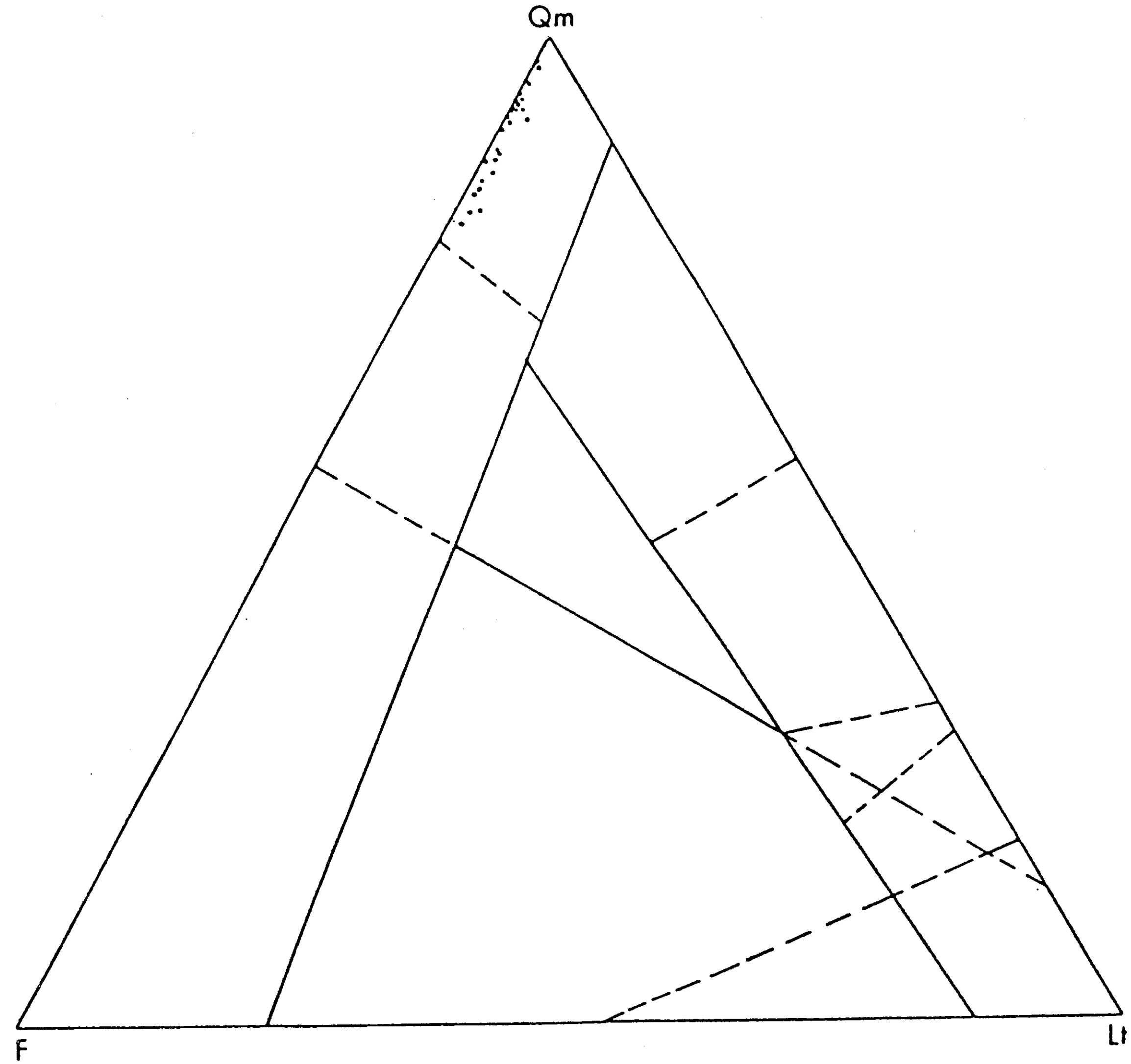


FIG.14 QmFLt diagram to decipher the provenance of Lower Saq Sandstone.

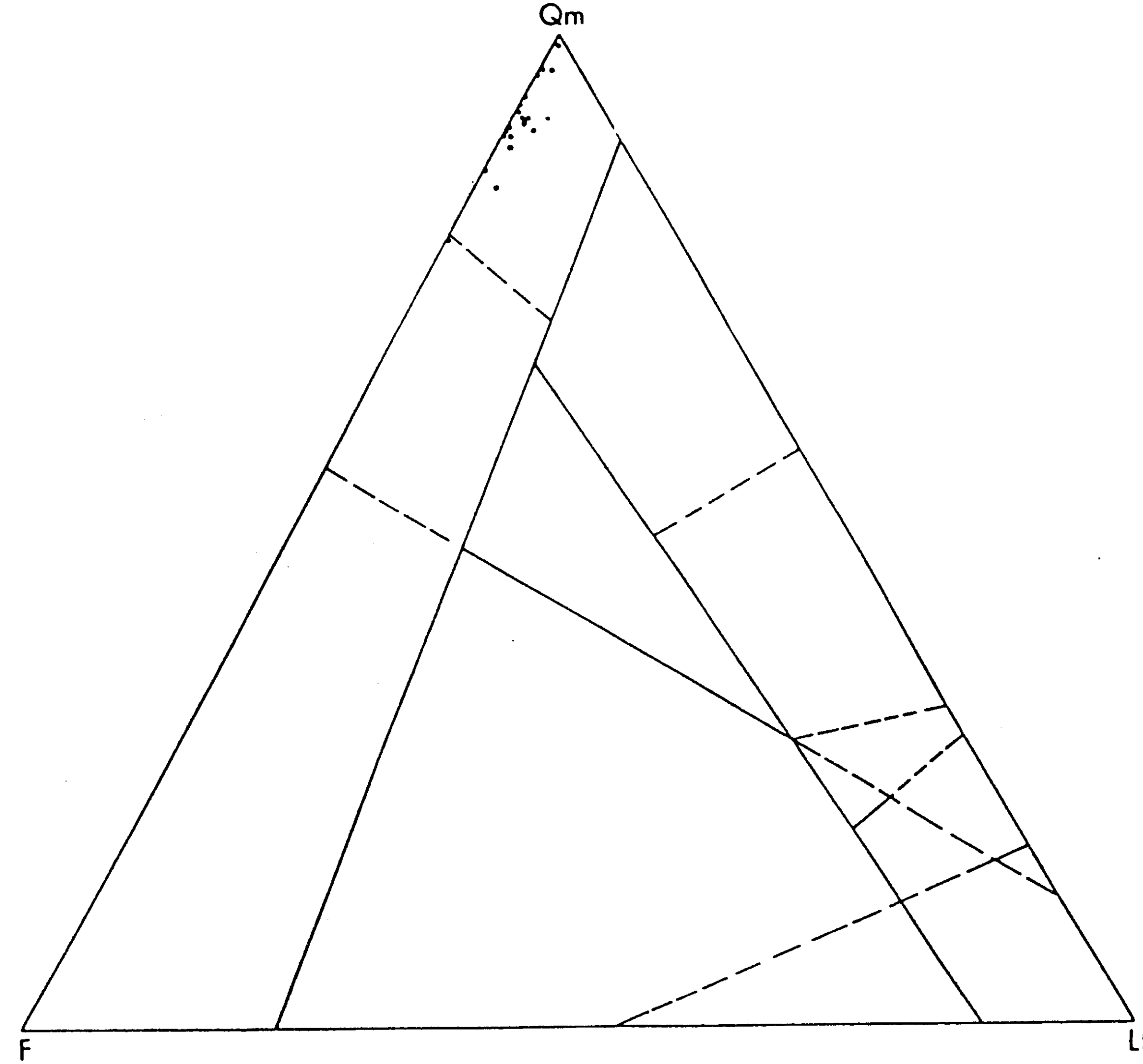


FIG. 15 QmFLt diagram to decipher the provenance of Upper Saq Sandstone.

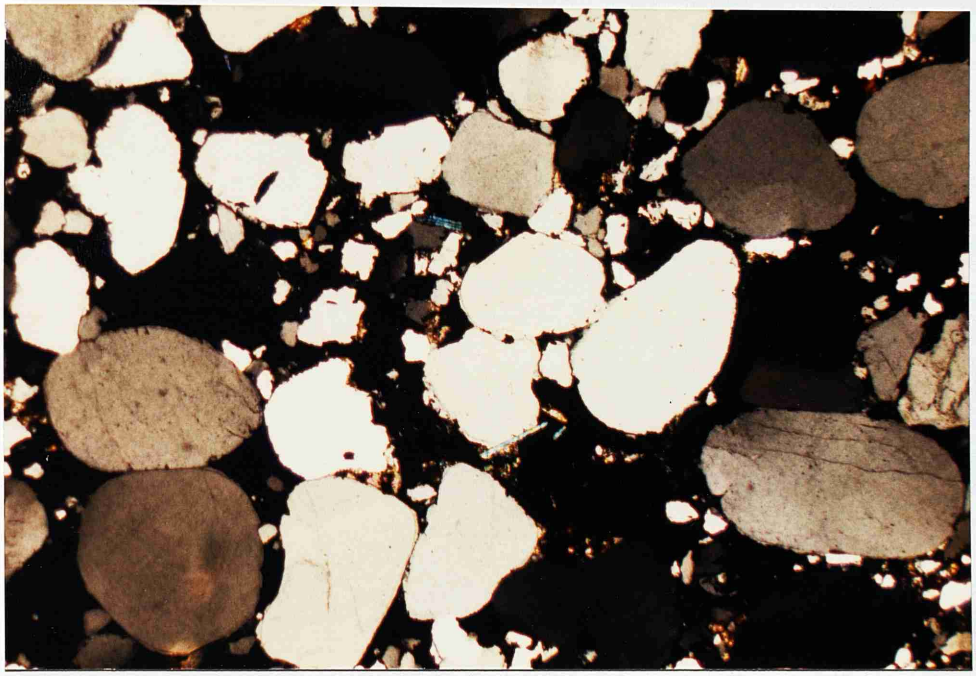


PLATE No. 1. Well rounded biomodal quartz grain sizes (Upper Saq Sandstone) x 10

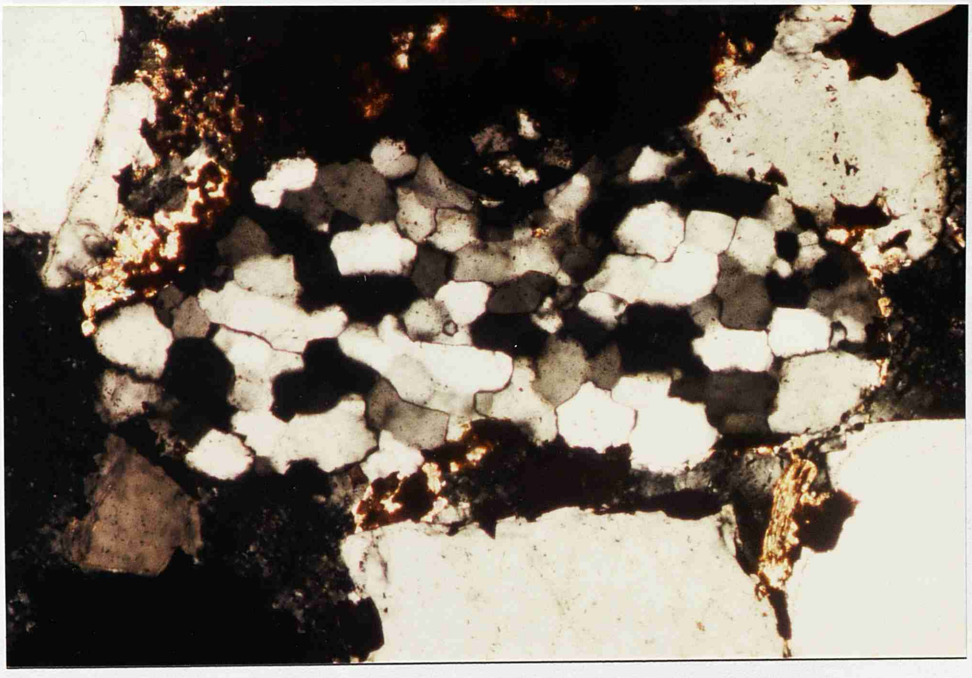


PLATE No. 2. Undulatory polycrystalline quartz (Lower Saq Sandstone) x 40

PLATE No. 3. Overgrowth in quartz grains preserving the rounded nature of the original grain (Upper Saq Sandstone) x 40

PLATE No. 4. Overgrowth in quartz grains (Lower Saq Sandstone) x 40

PLATE No. 5. Monocrystalline quartz with strong undulatory extinction (Upper Saq Sandstone) x 40

PLATE No. 6. Undulatory monocrystalline quartz breaking down to non-undulatory monocrystalline quartz and showing re-entrant angle filled with cement (Lower Saq) x 40

CHAPTER THREE

GEOCHEMISTRY OF SAQ SANDSTONE

The geochemistry of Saq Sandstone has been used in conjunction with the petrographic study in order to: (1) document the geochemical nature of quartz arenite; (2) investigate if there are any vertical changes in composition which were not recorded in the petrographic data.

Procedure.

A total of 42 samples from both the Upper and Lower Saq Sandstone were analysed for major and trace elements using an X-ray fluorescence spectrometer (XRF).

10 Major oxides were determined by using XRF (SiO_2, TiO_2, Al_2O_3, Total Fe, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5), and 16 trace elements (Ba, Ce, Co, Cr, Cu, Ga, La, Ni, Pb, Rb, Sr, Th, Y, Zn, Zr, U). The fused glass beads (Harvey et al., 1973) were used for major element analysis by fusing 0.375gms of 100 mesh rock powder and 2gms of flux (Lithiumlettaborate).

Trace element composition was determined on pressed pellets (Leake et al. 1969) comprising of 6.0gms of 250 mesh rock powder and 1.0gm of thermal binder (phenol formaldehyde).

All the major and trace element determinations were carried out using the Phillips PW 1450/20 Sequential Automatic X-Ray Spectrometer of the Department of Geology, University of Glasgow.

Wet Chemical Analysis

FeO, H_2O and CO_2 were determined by conventional chemical analysis, FeO was determined by titration of standard dichromate solution with rock solution made by dissolving a measured amount of whole rock powder in sulphuric and hydrofluoric acid. The FeO percentage, determined by titration, is used to calculate the amounts of Fe_2O_3 per cent using the following equation:

$$Fe_2O_3 = FeO(XRF\ value) - (1.112 \times (FeO\ (titration))).$$

H_2O and CO_2 were determined by using the Penfield method of combustion adsorption and gravimetry: all the analyses were carried out in duplicate.

The major and trace element compositions for the Upper and Lower Saq Sandstone are given in Tables 4 to 7 and the average major and trace element composition of the Saq Sandstone is given in Tables 8, 9.

Chemical composition of Upper and Lower Saq Sandstone.

Variation in the major element geochemistry of the Saq Sandstone are shown in diagrams (Figs 16 to 28). There are a variety of minor trends to be considered, but in general there is an upward increase of SiO_2. There is such an abundance of SiO_2 in these sequences that any differences between Upper and Lower Saq Sandstones may be very minor. However these differences are pointed out and simple explanations are offered for them.

SiO_2

Generally all samples from Upper Saq Sandstone appear to be enriched in SiO_2 (88 to 99 Wt.%, $\bar{x}$ = 93.45) compared with samples from Lower Saq Sandstone (66 to 93 Wt.%, $\bar{x}$ = 81.29). This indication that the Upper Saq Sandstone is more mature than the Lower agrees with petrographic studies: 88% quartz in Upper; 86% in Lower. But the amount of $CaCO_3$ plays an important role in the amount of % SiO_2 - the greater the $CaCO_3$ the lower the total % SiO_2.

Al_2O_3 vs SiO_2

The content of Al_2O_3 in Upper Saq Sandstone ranges from 0.06 to 6.37 Wt.% with an average of 1.91, and the Lower Saq Sandstone from 0.06 to 15.77 Wt.% with an average of 4.85. The Upper and Lower Saq both show an inverse correlation ($r = -0.5$, $p = 0.001$) between Al_2O_3 and SiO_2 (Fig. 16). Feldspar, micas and clay minerals are likely to contribute most Al_2O_3 to sedimentary rocks. From petrographic studies there is no large quantity of feldspar, thus the Al_2O_3 in Lower Saq could be directly due to the abundance of micas as seen in thin section. Micas form 1.9% of the Upper and 2.74% of the Lower Saq Sandstone.

The inverse relationship between SiO_2 and Al_2O_3 in this formation could either be an indication of the upward change in maturity of the Saq Sandstone, or due to the progressive sorting out of micas by current activity.

TiO_2 vs SiO_2

The content of TiO_2 in Upper Saq Sandstone ranges from 0.20 to 0.6 Wt.% with an average of 0.18 and the Lower Saq from 0.1 to 0.9 Wt.% with an average of 0.35.

The Upper and Lower Saq Sandstone show an inverse correlation ($r = -0.4$, $p = 0.01$) between TiO_2 and SiO_2 (Fig.17).

The main sources of TiO_2 in sediments are (1) residue of weathering in the form of chemically unaltered grains like rutile and ilmenite. (2) new products of weathering such as anatase and clay minerals and (3) diagenetic minerals (Wedepohl, 1978, 22-K-1).

Rutile is the fourth dominant heavy mineral in the Saq Sandstone, comprising 13% (Lower) and 10% (Upper) of the heavy mineral population. The inverse relationship between SiO_2 and TiO_2 could, therefore, be a consequence of there being less mica and rutile in more mature sandstones. The Upper Saq, being the more mature formation, has less rutile and mica (see above).

Na_2O vs SiO_2.

The content of Na_2O in Upper Saq Sandstone ranges from 0.04 to 0.7 Wt.% with an average of 0.27, and in Lower Saq from 0.01 to 0.90 Wt.% with an average of 0.31.

There are no clear trends between Na_2O and SiO_2 (Fig. 18). Na-feldspar and clay minerals are the main sources of Na in sandstone (Wedepohl, 11-K-2, 1978), and as the petrographic study of Upper and Lower Saq Sandstone does not show any Na-feldspar, the main source of Na could be clay minerals.

CaO vs SiO_2

The CaO content in Upper Saq Sandstone ranges from 0.01 to 5.27 Wt.% with an average of 1.09 and in Lower Saq from 0.02 to 14.44 Wt.%, averaging 5.72. There is an inverse relationship (r = -0.81) between CaO and SiO_2 in both Upper and Lower Saq (Fig. 19).

Carbonate cement is mainly responsible for the abundance of CaO and CO_2 in the Saq Sandstone. The petrographic study shows that the percentage of carbonate cement in Upper and Lower Saq Sandstone is 9.6 and 9.8 respectively.

The negative relationship between SiO_2 and CaO is clearly related to the fact that the greater abundance of cement the less quartz in the sample rock.

However, the reason for the higher percentage of carbonate in Saq Sandstone is difficult to establish. Carbonate may have replaced some of the clay, or even some micas, during diagenesis. It may also be due to an increase in the amount of carbonate available from pure fluids during diagenesis.

MnO vs SiO_2.

The content of MnO in Upper Saq Sandstone ranges from 0.01 to 0.34 Wt.%, with an average of 0.05 and the Lower Saq from 0.01 to 0.38 Wt.%, with an average of 0.06 (Fig. 20).

The high MnO content in Upper and Lower Saq Sandstone from the average MnO in sandstone (0.1 Wt.%) could be due to high amounts of CaO, because the size of Mn^{2+} fits into calcite crystal (Wedepohl, 1978, 25-K-1).

K_2O vs SiO_2.

The content of K_2O in Upper Saq Sandstone ranges from 0.02 to 1.72 Wt.%, average 0.22 and Lower Saq from 0.03 to 1.78 Wt.%, with an average of 0.19. The K-content in sandstone is primarily from K-feldspar and K-mica (Wedepohl, 19-K-1).

The weak inverse relationship ($r = -0.29$, $p = 0.05$) between K_2O and SiO_2 could be explained by the fact that the K-feldspar content decreases with increasing SiO_2 content.

The segregation between Upper and Lower Saq could be interpreted as an indication of change of the degree of maturity (Fig. 21).

$Fe_2O_3 + FeO$ vs SiO_2.

The content of $Fe_2O_3 + FeO$ in Upper Saq Sandstone ranges from 0.02 to 5.57 Wt.%, average 0.36, and in Lower Saq from 0.09 to 0.78 Wt.% with an average of 0.7. The $Fe_2O_3 + FeO$ content of Upper and Lower Saq Sandstone shows an inverse relationship ($r = -0.33$, $p = 0.02$) and shows a segregation between Upper and Lower Saq (Fig. 22).

The high content of $Fe_2O_3 + FeO$ in Upper Saq Sandstone could be interpreted as a presence of ferriginous cement, as seen in thin section.

Al_2O_3 vs K_2O.

The content of K_2O in Upper Saq Sandstone ranges from 0.02 to 1.72 Wt.%, with an average of 0.22 and Lower Saq from 0.03 to 1.78 Wt.% averaging 0.19. Both Upper and Lower Saq show a positive relationship ($r = 0.3$, $p = 0.02$) and show a good segregation between Upper and Lower Saq, and could be interpreted as an indication of the change in the degree of maturity of Upper and Lower Saq Sandstone (Fig. 23), with both mica and feldspar being eliminated during the maturing of the sandstones.

Al_2O_3/SiO_2 vs $Fe_2O_3 + FeO + MgO$.

The Upper and Lower Saq Sandstone show positive relationship ($r = 0.21$, $p = 0.10$) between Al_2O_3/SiO_2 and $Fe_2O_3 + FeO + MgO$. Bhatia (1983) used this relationship for sandstone to discriminate samples from different provenances. He used the ratio Al_2O_3/SiO_2 because it gives an indication of the quartz enrichment in sandstones and $Fe_2O_3 + FeO$ because of their low mobility and low residence times in sea-water (Holland, 1978), to classify the plate tectonic setting

Oceanic Island Arc, Active Continental Margins and Passive Margins. According to Bhatia the Upper and Lower Saq Sandstones fall into passive margin areas characterized by low Al_2O_3/SiO_2 and Fe_2O_3 + FeO+ MgO (Fig. 24).

P_2O_5.

The content of P_2O_5 in Lower Saq Sandstone ranges from 0.03 to 0.5 Wt.%, with an average 0.10, and in Upper Saq from 0.02 to 0.62 with an average 0.15. Apatite is the main phosphorous mineral in sediment (Wedepohl, 1978, 15-K-1). The heavy mineral study shows more apatite in Upper Saq Sandstone than in the Lower Saq and this could explain the differences in P_2O_5 in the two units.

Discrimenent function analysis and tectonic setting.

Middleton (1962) used discrimination function analysis for sandstone geochemistry and several workers such as Davis (1973); Klovan and Billings (1967); Davies and Ethridge (1975); Le Maitre (1982) used these techniques in solving geological probelms.

Bhatia (1983) used discrimination function analysis to classify individual sandstone samples into predefined groups on the basis of multiple variables, for identifying the tectonic setting of provenance, and he used 11 major element oxides as variables and five sandstone suites of Eastern Australia as predefined groups.

The unstandardized discriminant function coefficients used by Bhatia (1983) are used in this study to calculate discriminant scores for Upper and Lower Saq Sandstown, shown in Table 10.

The results are shown in Tables 11,12, and plotted in Fig. 25. There is no distinct segregation between Upper and Lower Saq

Sandstone, but all samples (except two) fall into passive margin areas which are characterized by sediments which are generally highly mature, and derived from recycling of older sedimentary and metamorphic rocks.

Trace Element Geochemistry.

Trace element geochemistry contributes significantly in deciphering the physical and chemical processes (e.g. partial fractionation, mixing and contamination) in the evolution of magmatic rocks. Understanding the chemical variability of these rocks has also led to the identification of a chemical signature which is characteristic of sandstone from various plate tectonic settings (Bhatia et al., 1986).

16 Trace elements were analysed and their average concentration is given in Table 9.

La vs Th.

The concentration of La in Lower Saq Sandstone ranges from 6 to 49ppm (average 16.9ppm) and in Upper from 3 to 29ppm (average 7.8 ppm) and the concentration of Th in Lower and Upper Saq Sandstone ranges from 1 to 17ppm with an average of 3.4 and 4.4ppm respectively.

The significant positive correlation (r = 0.799) between La and Th in quartz arenite of Saq Sandstone suggests that these elements behave concordantly during sedimentary processes (Fig. 26).

Th vs Zr.

The concentration of Zr in Lower Saq Sandstone ranges from 46 to 522ppm with an average of 159.70ppm and in Upper Saq from 50 to

520ppm, average 184.4ppm.

A significant, positive correlation (r = 0.934) between Th and Zr in Upper and Lower Saq Sandstone (Fig. 27). The average of Th and Zr in sandstone is 1.7 and 220ppm respectively (Turekian and Wedepohl, 1961). Zircon grains, which are the most heavy mineral abundant in sandstone and hence considered to be the major source of Zr in Saq Sandstone.

Usually zircon and monazite have high concentrations of both Th and U, a Florida beach sand, for example, has 160ppm Th and 75ppm U (Pettijohn, 1963)

La + Y + Ce vs Ni + Cr vs Sr.

Using these elements, there is no segregation between Upper and Lower Saq Sandstone (Fig. 28). However, Hickman and Wright (1983) used this relationship to decipher the provenance for the Appin Group Slates. They suggest the Ni + Cr end is to represent provenance composed of basic rock and La + Y + Ce to represent provenance composed of granites and Sr end to represent the provenance containing the highest amount of sedimentary rocks. However the pattern shown by most of the samples of Upper and Lower Saq Sandstone falls in the Sr end and suggests that most of the Saq Sandstones are derived from pre-existing sandstones.

Rankama and Sahama (1950) reported that the average of Y, La, and Ce in sandstone are 1.6ppm, 17ppm and 24ppm respectively, while the average in Saq Sandstone is 13ppm, 12ppm and 25ppm respectively.

Ba, Co, Cu, Zn.

Ba: The concentration of Ba in Lower Saq Sandstone ranges from 27 to 940ppm with an average of 141ppm and in the Upper Saq ranges from

43 to 527ppm with average 139ppm.

Wedepohl (1978, 56-K-1) reported that generally Ba substitutes for K^+ and Ca^{2+} in plagioclase, micas, clay and carbonate.

In general, pure quartz sandstone is very low in Ba, but the presence of considerable amounts of carbonate fractions and mica present in these rocks could increase the amount of Ba.

Co: Wedepohl (1978, 27-K-2) reported that pure quartz sandstones have low concentrations of Co. The concentration of Co in Lower Saq Sandstone ranges from 1 to 71ppm with average 7ppm and in Upper Saq ranges from 0 to 36ppm with an average of 5ppm.

The Co distribution in sedimentary rocks must closely follow that of iron content (Wedepohl, 1978, 27-K-2), the higher than average percentage of Fe_2O_3 could result in a higher than average Co abundance in these rocks.

Cu and Zn: The concentration of Cu in Lower Saq Sandstone ranges from 4 to 57ppm and averages 14ppm, and in Upper Saq ranges from 0 to 64ppm and an average of 17ppm. The average of Cu in sandstone ranges between 10 and 20 (Pettijohn, 1963).

The concentration of Zn in Lower Saq Sandstone ranges from 2 to 254ppm and averages 40ppm, and in Upper Saq ranges from 7 to 136ppm with an average of 23ppm. The average of Zn in sandstone is 16ppm (Wedepohl, 1953).

Wedepohl (1978, 30-K-1) reported that because of low solubility of Zn in natural water, its major transport and accumulation in sedimentary environment is to be expected in detrital material. Detrital minerals of major importance, such as quartz, muscovite and feldspars, are low in structural zinc. Zn replaces Fe^{2+} and Mg and as a result chlorite and magnetite are better Zn carriers (Das, 1985).

Ga, Pb, U.

Ga: The concentration of Ga in Lower Saq Sandstone ranges from 1 to 10ppm and averages 5ppm, in Upper Saq it ranges from 1 to 22ppm and averages 8ppm. The average of Ga in sandstone is 6ppm (Wedepohl, 1978, 31-K-1).

Burton et al. (1959) reported that the gallium content is higher in the more aluminous sandstone, such as the graywackes.

Pb: The Pb content in pasammitic rocks usually increases with decreasing quartz content (Moore, 1963).

The concentration of Pb in Lower Saq Sandstone ranges from 1 to 26ppm with an average of 11ppm and in Upper Saq from 4 to 29ppm with an average of 9ppm. The lead content in sandstone from German sandstone ranges from 7-8ppm (Wedepohl, 1956).

U: Uranium is present in very small quantities in sands and sandstones. The average of U in sandstone ranges from 1 to 2ppm (Murray and Adams, 1958; Wedepohl, 1978, 90-A-1).

The concentration of U in Lower Saq Sandstone ranges from 1 to 4ppm, with an average of 2.7ppm and in Upper Saq from 1 to 7ppm averaging 2.6ppm.

Discussion.

Quartz arenites are the most mature of the sandstones and is characterized by a high amount of SiO_2 ($>$ 95%): the average SiO_2 for the Saq Sandstone is 87.4%. This difference is due to the presence of considerable amounts of CaO and CO_2 as carbonate cement in the Saq Sandstone.

Pettijohn (1963) analysed representative quartz arenites which compare closely with the average chemical analysis of quartz arenite of Upper and Lower Saq Sandstone given in Table 13. As can be seen from Table 13 , all oxides other than silica (A, C) may make up as little as 3% of the rock, except for those with carbonate cement (B, Upper Saq, Lower Saq).

The chemical composition of Upper and Lower Saq Sandstone agrees very well with the petrographic study. The SiO_2 increases with increase of detrital quartz content as determined from the microscope.

All major oxides, except SiO_2 in the Saq Sandstone show an upward decrease through the sequence, this could be interpreted as the elimination of all unstable minerals which results in an upward increase of maturity for the Saq Sandstone sequences.

It follows from these observations :

1. Quartz-rich sandstones which acquire a cement before they are involved in pressure solution (e.g. 18-1-1, 21-2-16 in Table 5), will have lower silica percentages than those which have undergone early pressure solution and loss of pure space. In the latter instance cement will not be able to enter the sandstone.

2. The degree to which diagenesis has removed feldspar grains and transformed them into clay is not known.

Bhatia (1983) and Bhatia et al. (1986) used different relationships between major and trace elements of sandstone to discriminate them into different groups derived from different tectonic environments. The most discriminating parameters are Fe_2O_3 + FeO + MgO%, TiO_2%, Al_2O_3/SiO_2, K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$. In general there are four types of tectonic setting recognized: (1) Oceanic island arc characterized by higher Fe_2O_3 + FeO + MgO and low K_2O/Na_2O; (2) Continental island arc which has higher Fe_2O_3 + FeO + MgO, higher TiO_2, higher Al_2O_3/SiO_2 and lower K_2O/Na_2O; and (3) Active continental margin: sandstone of this type can be discriminated from those of the continental island arc by their lower Fe_2O_3 + FeO + MgO, lower TiO_2, lower Al_2O_3/SiO_2 and higher K_2O/Na_2O; (4) Passive margin characterized by low Fe_2O_3 + FeO + MgO, Al_2O_3/SiO_2 and high K_2O/Na_2O.

In this study I used Al_2O_3/SiO_2 vs Fe_2O_3 + FeO + MgO, La vs Th and Th vs Zi relationships which all show positive relationships agreeing with Bhatia (1983) and Bhatia et al. (1986). None of the relationships produced any meaningful result.

The interpretation of Bhatia (1983) and Bhatia et al. (1986) of fields representing provenances from the diverse tectonic environments leads to meaningless conclusions. In the bivariant relationships the Saq Sandstone plots on all four fields. Any conclusions based upon such an observation would mean that the Saq Sandstones were derived from all four tectonic environments - which is unrealistic, but the framework mineralogy suggests that the Saq Sandstones were derived from a stable craton of continental block.

TABLE 4: Chemical analysis of Upper Saq Sandstone. (Major elements).

	21-1-1	1-1-27	2-1-1	1-1-18	1-1-19	1-1-20
SiO_2	97.84	96.66	97.3	94.24	95.83	96.52
TiO_2	0.07	0.02	0.06	0.16	0.13	0.12
Al_2O_3	0.16	0.46	0.27	0.34	0.22	0.87
Fe_2O_3	0.046	0.769	0.03	0.114	0.156	0.086
FeO	0.13	0.10	0.06	0.05	0.04	0.04
MnO	0.005	0.05	0.02	0.01	0.01	0.01
MgO	0.0	0.12	0.0	0.0	0.0	0.0
CaO	0.475	0.60	0.62	1.7	1.62	0.72
Na_2O	0.21	0.25	0.72	0.55	0.32	0.50
K_2O	0.015	0.02	0.07	0.06	0.03	0.04
P_2O_5	0.37	0.04	0.62	0.03	0.03	0.03
H_2O	1.15	0.45	1.07	1.32	0.80	1.13
CO_2	0.17	0.81	0.36	1.43	1.50	0.64
TOTAL	100.65	100.36	101.18	100.01	100.69	100.71

(all values in weight per cent).

Cont. TABLE 4 (Major elements)

	21-1-2	22-1-3	1-1-24	Uniz.1	24-1-8	22-1-1
SiO_2	95.62	95.49	97.37	88.82	89.125	94.315
TiO_2	0.11	0.07	0.05	0.42	0.285	0.125
Al_2O_3	0.50	2.14	0.22	4.635	5.405	1.835
Fe_2O_3	0.23	1.75	0.0	0.59	1.075	0.619
FeO	0.07	0.059	0.0	0.398	0.0	0.59
MnO	0.03	0.01	0.01	0.02	0.34	0.02
MgO	0.01	0.0	0.0	0.05	0.0	0.23
CaO	1.47	0.32	1.05	2.04	0.19	0.445
Na_2O	0.25	0.44	0.21	0.075	0.205	0.26
K_2O	0.03	0.06	0.04	0.05	0.155	0.24
P_2O_5	0.39	0.02	0.06	0.11	0.065	0.04
H_2O	0.86	0.07	0.987	2.186	2.78	1.18
CO_2	0.32	0.21	0.869	0.01	0.339	0.36
TOTAL	99.9	100.58	100.86	99.46	99.77	99.731

Cont. TABLE 4 (Major elements).

	22-1-10	22-1-2	24-1-7	2-1-3	2-1-7	10-1-1
SiO_2	85.63	99.235	90.59	91.2	92.66	81.28
TiO_2	0.26	0.075	0.56	0.0	0.265	0.465
Al_2O_3	2.99	0.23	6.37	0.05	2.54	6.23
Fe_2O_3	0.11	0.01	0.01	0.057	1.12	4.98
FeO	0.06	0.01	0.12	0.106	0.039	0.0
MnO	0.02	0.01	0.06	0.02	0.01	0.2
MgO	0.01	0.0	0.025	0.32	0.055	0.185
CaO	5.265	0.0	0.015	1.72	0.01	1.58
Na_2O	0.225	0.145	0.43	0.09	0.145	0.04
K_2O	0.03	0.04	0.13	0.05	1.43	1.72
P_2O_5	0.035	0.04	0.03	0.54	0.10	0.145
H_2O	0.219	0.195	2.09	2.3	0.98	1.79
CO_2	5.789	0.07	0.24	3.55	0.19	1.02
TOTAL	100.64	100.45	100.76	100.01	99.59	99.63

Cont. TABLE 4 (Major elements)

	1-1-21
SiO_2	95.86
TiO_2	0.08
Al_2O_3	0.82
Fe_2O_3	0.12
FeO	0.08
MnO	0.01
MgO	0.02
CaO	0.81
Na_2O	0.05
K_2O	0.05
P_2O_5	0.07
H_2O	1.49
CO_2	0.92
TOTAL	99.23

TABLE 5: Chemical analysis of Lower Saq Sandstone. (Major elements)

	21-1-6	19-1-3	17-1-1	20-2-1	21-2-9	21-2-1
SiO_2	88.92	90.26	83.25	71.03	72.17	81.77
TiO_2	0.11	0.26	0.25	0.06	0.27	0.57
Al_2O_3	0.82	6.24	8.88	0.82	6.42	6.62
Fe_2O_3	0.06	0.15	0.27	0.34	0.37	5.53
FeO	0.05	0.08	0.26	0.04	0.10	0.0
MnO	0.02	0.01	0.05	0.05	0.04	0.15
MgO	0.44	0.02	0.26	0.33	0.12	0.21
CaO	4.46	0.0	5.42	14.44	9.23	1.0
Na_2O	0.20	0.0	0.40	0.12	0.90	0.62
K_2O	0.03	0.14	0.08	0.0	0.10	0.13
P_2O_5	2.24	3.51	0.2	1.06	2.27	2.69
H_2O	3.38	0.27	0.65	11.38	7.82	0.80
TOTAL	100.79	100.97	100.04	99.70	100.02	100.17

(all values in weight per cent).

Cont. TABLE 5 (Major elements).

	18-1-1	18-1-2	19-2-4	19-2-2	17-1-2	21-2-16
SiO_2	74.73	76.99	80.24	74.05	78.85	80.55
TiO_2	0.24	0.15	0.90	0.44	0.10	0.46
Al_2O_3	2.40	2.34	15.77	5.29	3.40	6.16
Fe_2O_3	2.58	1.60	0.08	1.02	3.80	4.76
FeO	0.0	0.09	0.08	0.40	0.08	0.08
MnO	0.15	0.03	0.01	0.38	0.04	0.20
MgO	0.20	0.04	0.03	0.01	0.01	0.0
CaO	9.36	9.76	0.20	7.52	6.13	1.56
Na_2O	0.01	0.32	0.28	0.28	0.25	0.38
K_2O	0.0	0.04	0.52	0.14	0.04	1.78
P_2O_5	0.07	0.09	0.08	0.12	0.17	0.15
H_2O	1.99	1.83	1.68	2.14	2.12	2.12
CO_2	8.25	7.50	0.35	7.70	5.42	2.15
TOTAL	99.98	100.78	100.22	99.49	100.41	100.73

Cont. TABLE 5 (Major elements).

	21-1-7	21-2-15	17-2-1	20-2-2	21-1-3	21-2-5
SiO_2	84.08	86.52	81.59	73.82	89.49	93.87
TiO_2	0.49	0.71	0.90	0.31	0.11	0.06
Al_2O_3	3.02	7.86	4.14	4.24	2.06	0.60
Fe_2O_3	5.69	0.33	0.28	0.20	0.09	0.17
FeO	0.04	0.06	0.07	0.09	0.07	0.03
MnO	0.03	0.02	0.02	0.01	0.03	0.01
MgO	0.0	0.0	0.0	0.06	0.0	0.04
CaO	2.18	0.81	6.23	11.27	3.25	2.50
Na_2O	0.40	0.06	0.18	0.61	0.70	0.87
K_2O	0.07	0.09	0.05	0.09	0.06	0.07
P_2O_5	0.16	0.04	0.06	0.04	0.04	0.06
H_2O	1.90	3.91	0.43	1.12	2.01	0.71
CO_2	2.95	0.98	5.97	8.57	2.56	1.19
TOTAL	101.01	101.39	99.92	100.43	100.47	100.18

Cont. TABLE 5 (Major elements).

	21-2-14	21-1-8	21-2-18	21-2-10	21-1-4
SiO_2	90.14	66.92	89.37	78.07	74.9
TiO_2	0.44	0.44	0.44	0.05	0.18
Al_2O_3	1.77	6.16	7.93	3.35	5.21
Fe_2O_3	0.53	0.86	0.20	0.40	0.71
FeO	0.04	0.16	0.04	0.04	0.12
MnO	0.03	0.04	0.01	0.03	0.04
MgO	0.0	0.12	0.02	0.0	0.0
CaO	4.81	12.86	0.02	9.9	8.63
Na_2O	0.04	0.08	0.09	0.05	0.19
K_2O	0.04	0.04	0.20	0.60	0.04
P_2O_5	0.05	0.09	0.04	0.50	0.07
H_2O	0.61	1.52	2.59	1.48	1.71
CO_2	2.19	10.46	0.17	7.23	7.62
TOTAL	100.69	99.75	101.12	101.7	99.42

TABLE 6: Chemical analysis of Upper Saq Sandstone (Trace elements).

	21-1-1	1-1-27	2-1-1	1-1-18	1-1-19	1-1-20
Ba	50	94	82	54	53	47
Ce	21	19	23	16	17	17
Co	ND	2	ND	ND	ND	ND
Cr	2	1	0	1	0	1
Cu	7	7	7	5	6	9
Ga	1	1	1	1	2	1
La	8	8	11	6	9	9
Ni	ND	9	ND	ND	0	0
Pb	4	7	7	6	4	6
Rb	1	1	1	1	1	0
Sr	48	36	105	46	44	43
Th	3	0	0	2	0	0
Y	10	6	12	7	8	8
Zn	9	32	9	7	7	9
Zr	98	50	60	112	126	95
U	2	2	1	2	2	2

ND: Not detected

Cont. TABLE 6 (Trace elements).

	21-1-2	22-1-3	1-1-24	Uniz.1	24.1.8	22-1-1
Ba	195	234	82	357	398	93
Ce	23	80	17	47	40	30
Co	ND	0	ND	6	36	4
Cr	1	70	4	71	13	27
Cu	8	32	2	23	22	27
Ga	2	22	2	4	6	4
La	10	29	3	18	18	13
Ni	ND	14	2	13	17	13
Pb	7	19	4	16	15	8
Rb	1	18	0	1	4	8
Sr	82	117	40	83	45	42
Th	0	17	ND	6	2	2
Y	11	42	6	10	18	8
Zn	9	24	8	29	38	16
Zr	142	510	46	382	150	68
U	2	4	1	3	3	3

Cont. TABLE 6 (Trace elements).

	22-1-10	22-1-2	24-1-7	2-1-3	2-1-7	10-1-1
Ba	527	51	96	56	43	78
Ce	47	28	47	20	42	55
Co	23	ND	ND	ND	28	1
Cr	51	10	24	ND	28	23
Cu	21	64	20	7	40	11
Ga	5	0	6	1	5	9
La	19	9	18	8	16	20
Ni	19	ND	ND	ND	75	14
Pb	12	7	11	5	8	29
Rb	4	2	4	0	2	2
Sr	124	38	39	92	70	241
Th	8	1	7	0	10	7
Y	19	6	16	10	18	23
Zn	46	12	8	12	136	23
Zr	357	57	360	51	520	264
U	4	3	3	2	7	3

Cont. TABLE 6 (Trace elements).

Ba	69
Ce	22
Co	ND
Cr	40
Cu	6
Ga	2
La	9
Ni	4
Ph	9
Rb	1
Sr	42
Th	0
Y	11
Zn	11
Zr	56
U	2

TABLE 7: Chemical analysis of Lower Saq Sandstone (Trace elements).

	21-1-6	19-1-3	17-1-1	20-2-1	21-2-9	21-2-1
Ba	46	69	111	27	170	134
Ce	25	37	52	22	37	61
Co	ND	5	ND	ND	1	12
Cr	2	61	6	4	14	18
Cu	11	15	9	10	10	16
Ga	2	2	7	2	7	7
La	9	17	26	7	14	30
Ni	2	7	1	1	11	20
Pb	4	17	14	6	11	15
Rb	0	2	3	0	1	6
Sr	58	76	71	112	114	62
Th	3	6	4	1	4	14
Y	9	18	12	8	27	23
Zn	5	13	19	15	14	144
Zr	169	241	147	109	233	159
U	2	3	2	1	3	4

ND: Not detected

Cont. TABLE 7 (Trace elements).

	18-1-1	18-1-2	19-2-4	19-2-2	17-1-2	21-2-16
Ba	159	191	33	103	70	123
Ce	32	24	21	34	11	25
Co	9	7	ND	ND	11	44
Cr	ND	22	13	10	40	26
Cu	11	15	25	16	26	57
Ga	3	4	2	4	6	10
La	14	6	8	16	13	13
Ni	12	13	0	1	29	112
Pb	10	1	8	11	2	13
Rb	1	1	1	2	1	3
Sr	59	132	35	119	84	84
Th	2	0	1	4	ND	2
Y	8	7	5	14	9	9
Zn	58	48	19	8	60	254
Zr	123	70	64	164	70	97
U	4	4	3	1	4	4

Cont. TABLE 7 (Trace elements).

	21-1-7	21-2-15	17-2-1	20-2-2	21-1-3	21-2-5
Ba	381	102	35	55	114	41
Ce	34	70	115	31	30	22
Co	2	3	ND	ND	ND	ND
Cr	16	31	28	19	13	8
Cu	13	15	12	10	7	3
Ga	3	8	4	6	5	1
La	14	30	49	10	13	9
Ni	6	5	2	3	ND	ND
Pb	17	26	7	9	14	6
Rb	31	3	1	2	2	0
Sr	93	69	110	119	104	59
Th	3	12	12	4	2	0
Y	8	22	27	13	13	6
Zn	15	17	22	9	7	13
Zr	234	522	283	210	95	57
U	2	3	3	3	2	1

Cont. TABLE 7 (Trace elements).

	21-2-14	21-1-8	21-2-18	21-2-10	21-1-4
Ba	74	940	85	82	113
Ce	41	65	58	10	33
Co	ND	71	ND	ND	5
Cr	9	23	32	20	10
Cu	10	18	4	9	10
Ga	9	6	10	3	6
La	21	26	21	9	15
Ni	1	49	4	4	11
Pb	25	21	6	6	3
Rb	3	74	7	2	2
Sr	64	133	60	131	75
Th	3	17	6	1	1
Y	14	21	16	6	8
Zn	7	133	8	19	27
Zr	113	216	240	46	92
U	2	5	2	1	3

TABLE 8 : Average Major Element Composition in Upper and Lower Saq Sandstone (all values in weight per cent).

Major Elements	Lower Saq	Upper Saq	Dharaymeeah syenogranite* 26°03'49"/43°13'02"
SiO_2	81.29	93.45	71.1
TiO_2	0.35	0.18	0.22
Al_2O_3	4.85	1.91	14.2
Fe_2O_3	1.31	0.62	1.09
FeO	0.09	0.10	1.58
MnO	0.06	0.05	0.13
MgO	0.08	0.05	0.10
CaO	5.72	1.09	1.25
Na_2O	0.31	0.27	4.00
K_2O	0.19	0.22	5.40
P_2O_5	0.10	0.15	0.10
H_2O	1.82	1.21	0.76
CO_2	4.59	0.99	-
TOTAL	100.76	100.29	99.9

* Edward A. du Bray (1983)

TABLE 9 : The Average of Trace Elements for Upper and Lower Saq Sandstone.

Element	Lower	Upper
Ba	141.652	139.947
Ce	38.695	32.157
Co	7.391	5.263
Cr	18.478	19.315
Cu	14.434	17.052
Ga	5.086	8.210
La	16.956	7.789
Ni	12.782	9.473
Pb	10.956	9.684
Rb	6.434	2.736
Sr	87.956	72.210
Th	4.434	3.421
Y	13.173	13.105
Zn	40.608	23.421
Zr	159.70	184.421
U	2.695	2.631

TABLE 10 : Unstandardized Discriminant Function Coefficient used to Calculate Discriminant Scores for Saq Sandstone.

Elements	Discriminant Function I	Discriminant Function II
SiO_2	-0.0447	-0.421
TiO_2	-0.972	1.988
Al_2O_3	0.008	-0.526
Fe_2O_3	-0.267	-0.551
FeO	0.208	-1.610
MnO	-3.082	2.720
MgO	0.140	0.881
CaO	0.195	-0.907
Na_2O	0.719	-0.177
K_2O	-0.032	-1.840
P_2O_5	7.510	7.244
Constant	0.303	43.57

TABLE 11 : Discriminant scores of Upper Saq Sandstone.

Sample	Discriminant Function I	Discriminant Function II
21-1-1	-1.12	4.4
1-1-27	-3.47	1.99
2-1	+1.14	6.29
1-1-18	-3.17	2.38
1-1-19	-3.4	1.88
1-1-20	-3.45	2.03
21-1-2	-3.75	4.51
22-1-3	-3.97	1.0
1-1-24	-3.3	1.95
Uniz. 1	-2.9	2.52
24-1-8	-4.58	4.1
22-1-1	-3.6	2.36
22-1-7	-2.37	1.76
22-1-2	-3.8	1.4
24-1-7	-3.8	3.00
2-1-3	0.67	7.28
2-1-7	-3.58	1.2
10-1-1	-4.56	1.41
1-1-16	-3.4	2.5
ALL	-1.83	2.91

TABLE 12 : Discriminant scores of Lower Saq Sandstone.

Samples	Discriminant Function I	Discriminant Function II
21-1-6	-2.32	2.54
19-1-3	-3.20	2.6
17-1-1	-1.90	-0.49
20-2-1	0.11	0.63
21-29	0.67	2.95
21-2-1	-4.5	3.67
18-1-1	-2.0	2.5
18-1-2	-0.86	0.72
19-2-4	-3.25	2.34
19-2-6	-2.22	4.04
19-2-7	-0.89	1.91
21-2-16	-3.94	1.41
21-1-7	-3.6	3.65
21-2-15	-3.83	3.8
17-2-1	-2.520	3.27
20-2-2	-2.59	0.49
21-1-3	-2.46	2.05
21-1-5	-2.45	1.66
8-1-1	-1.2	1.8
8-1-2	-3.84	1.2
17-2-2	-o.13	1.46
21-2-18	-3.8	2.4
21-2-4	2.3	2.4
ALL	-2.06	2.62

TABLE 13 : Average chemical composition of quartz arenite of Upper and Lower Saq Sandstone and representative quartz arenite (Pettijohn, 1963, Table 2).

Major Elements	Lower Saq (Average)	Upper Saq (Average)	A	B	C
SiO_2	81.29	93.45	93.45	83.79	99.54
TiO_2	0.35	0.18	0.05	-	0.03
Al_2O_3	4.85	1.91	0.73	0.48	0.35
Fe_2O_3	1.31	0.62	0.63	0.063	0.09
FeO	0.09	0.10	0.14	-	-
MnO	0.06	0.05	0.01	-	-
MgO	0.08	0.05	0.01	0.05	0.06
CaO	5.72	1.09	0.04	8.81	0.19
Na_2O	0.31	0.27	0.08	-	-
K_2O	0.19	0.22	0.19	-	-
P_2O_5	0.10	0.15	0.02	-	-
H_2O	1.82	1.21	0.68	-	0.25
CO_2	4.59	0.99	-	6.93	-
TOTAL	100.76	100.29	99.94	100.13	100.51

A: Lauhauuori Sandstone (Cambrian) Finland

B: Simpson Sandstone (Ordovician) Cool Creek, Oklahoma

C: Tuscarora Quartzite (Silurian)

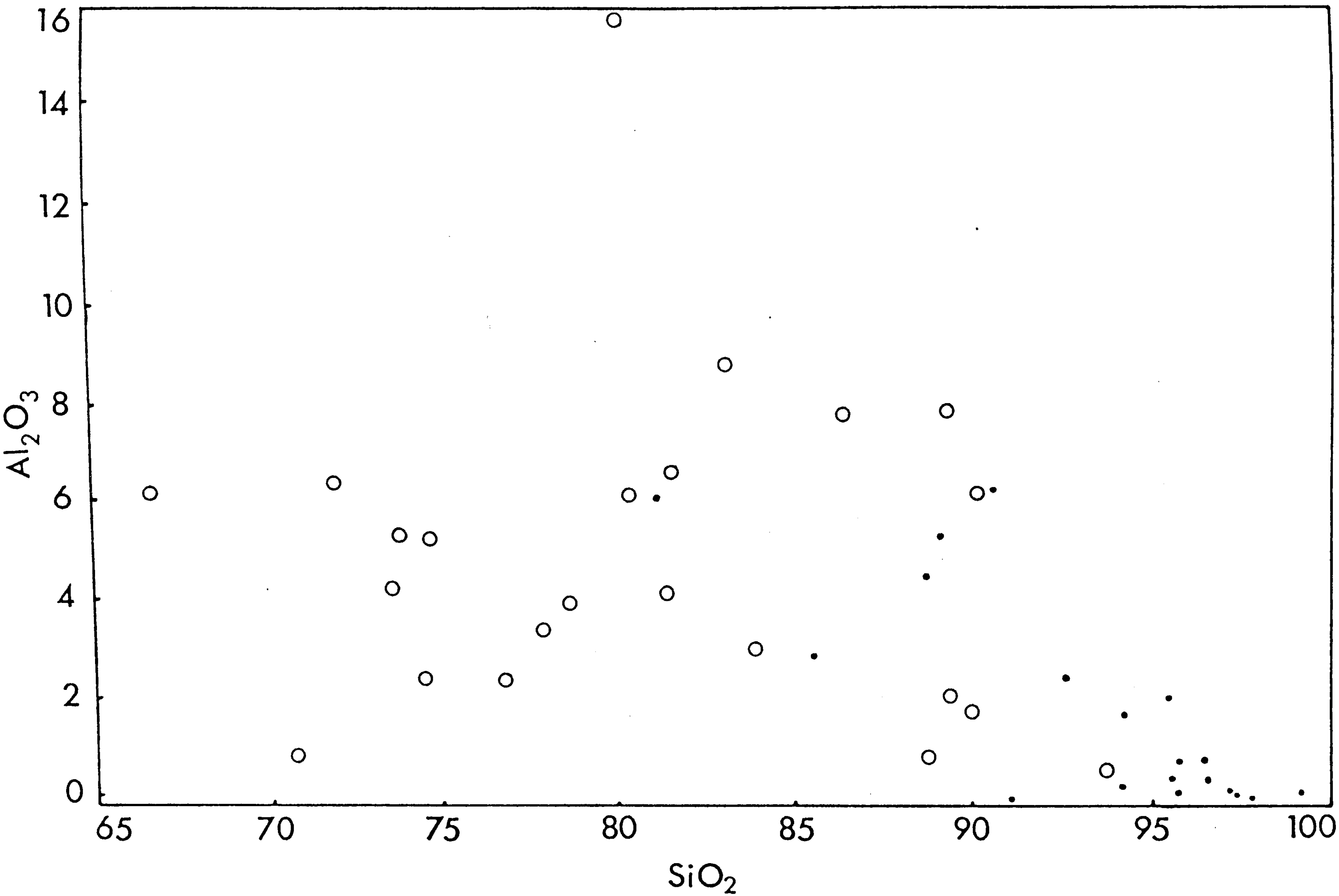


FIGURE 16 SiO_2 vs Al_2O_3 (circle: Lower; dot: Upper).

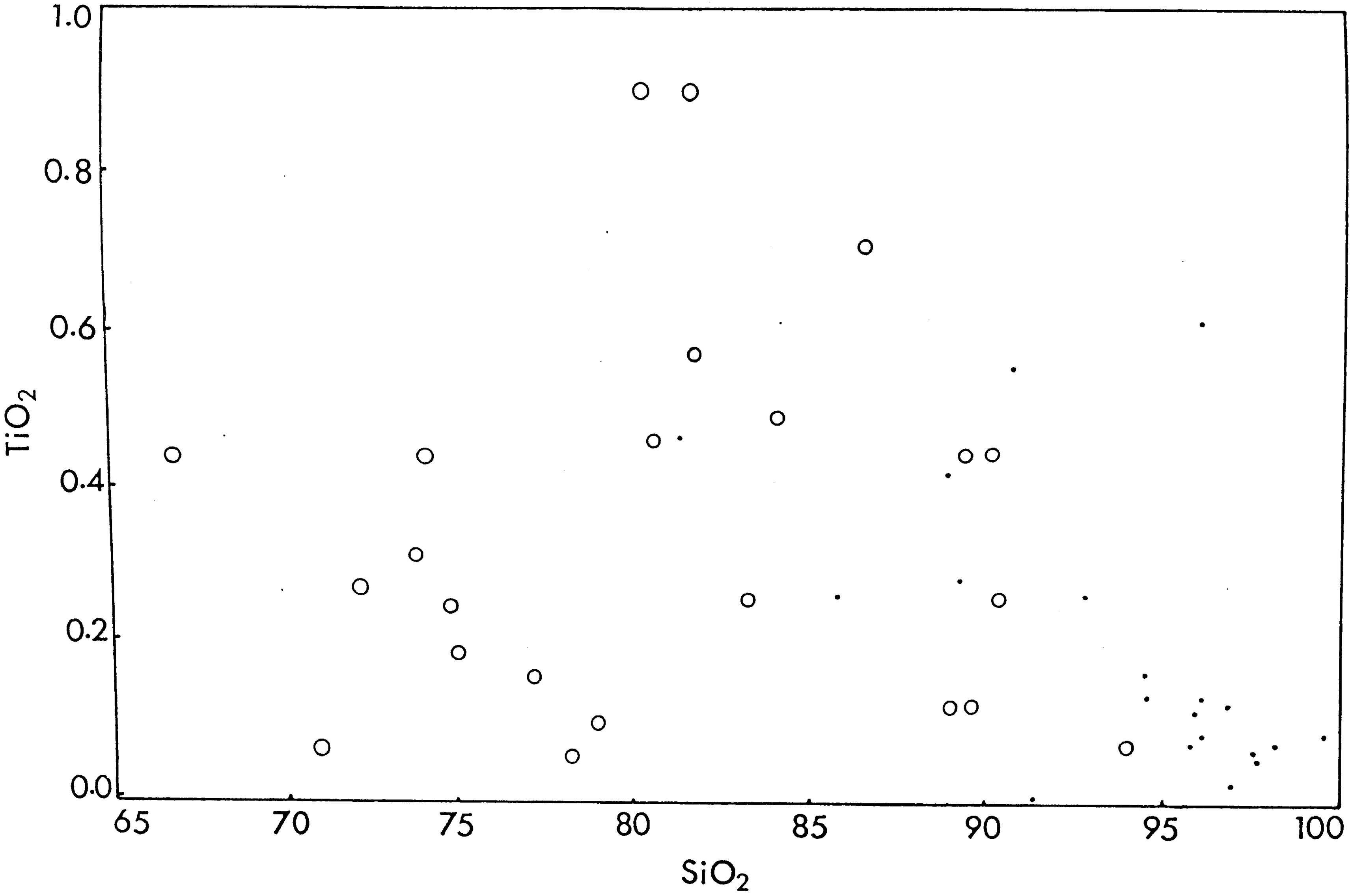


FIG. 17 SiO_2 vs TiO_2 (circle: Lower; dot: Upper).

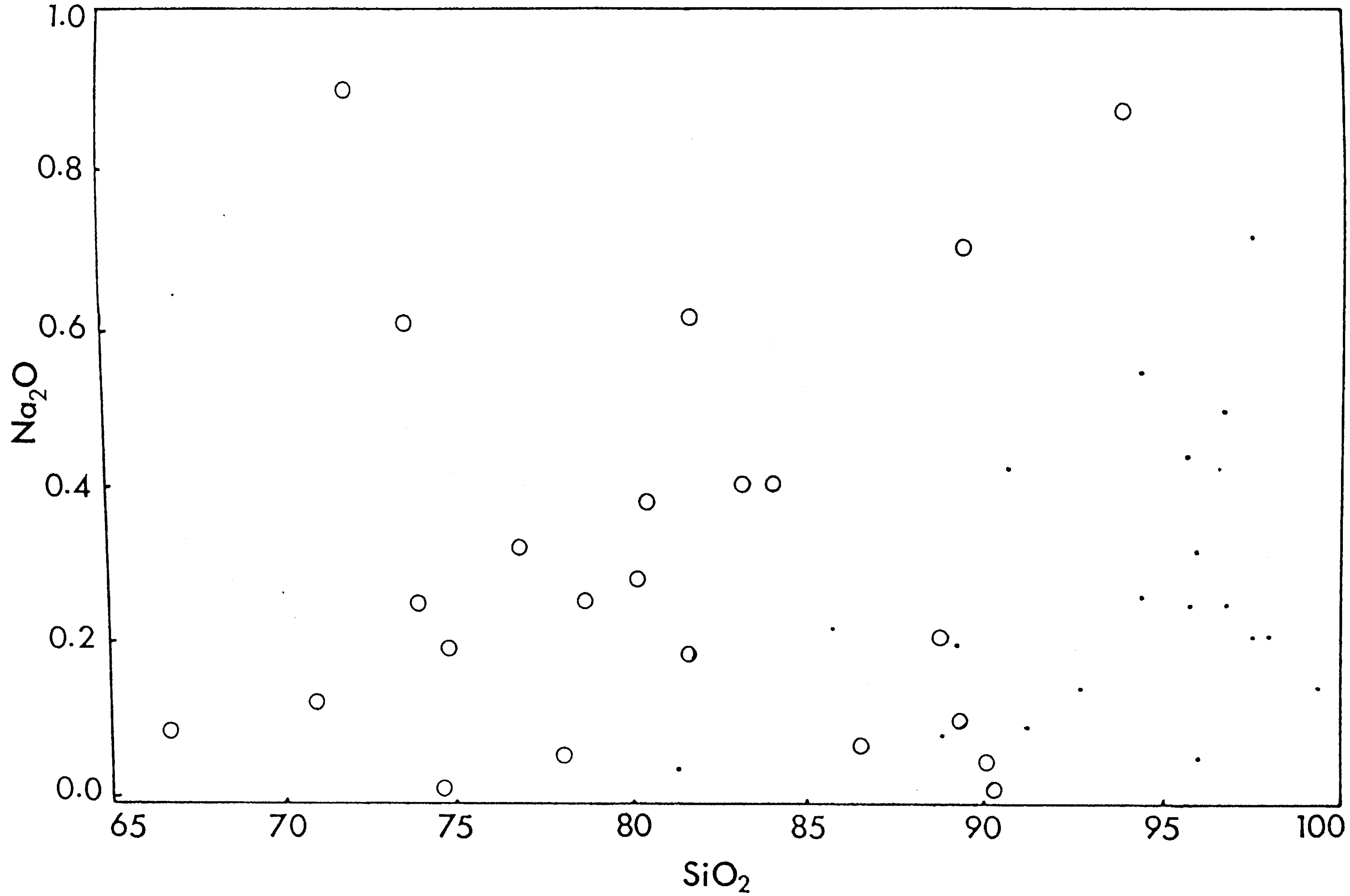


FIG. 18 SiO_2 vs Na_2O (circle: Lower; dot: Upper).

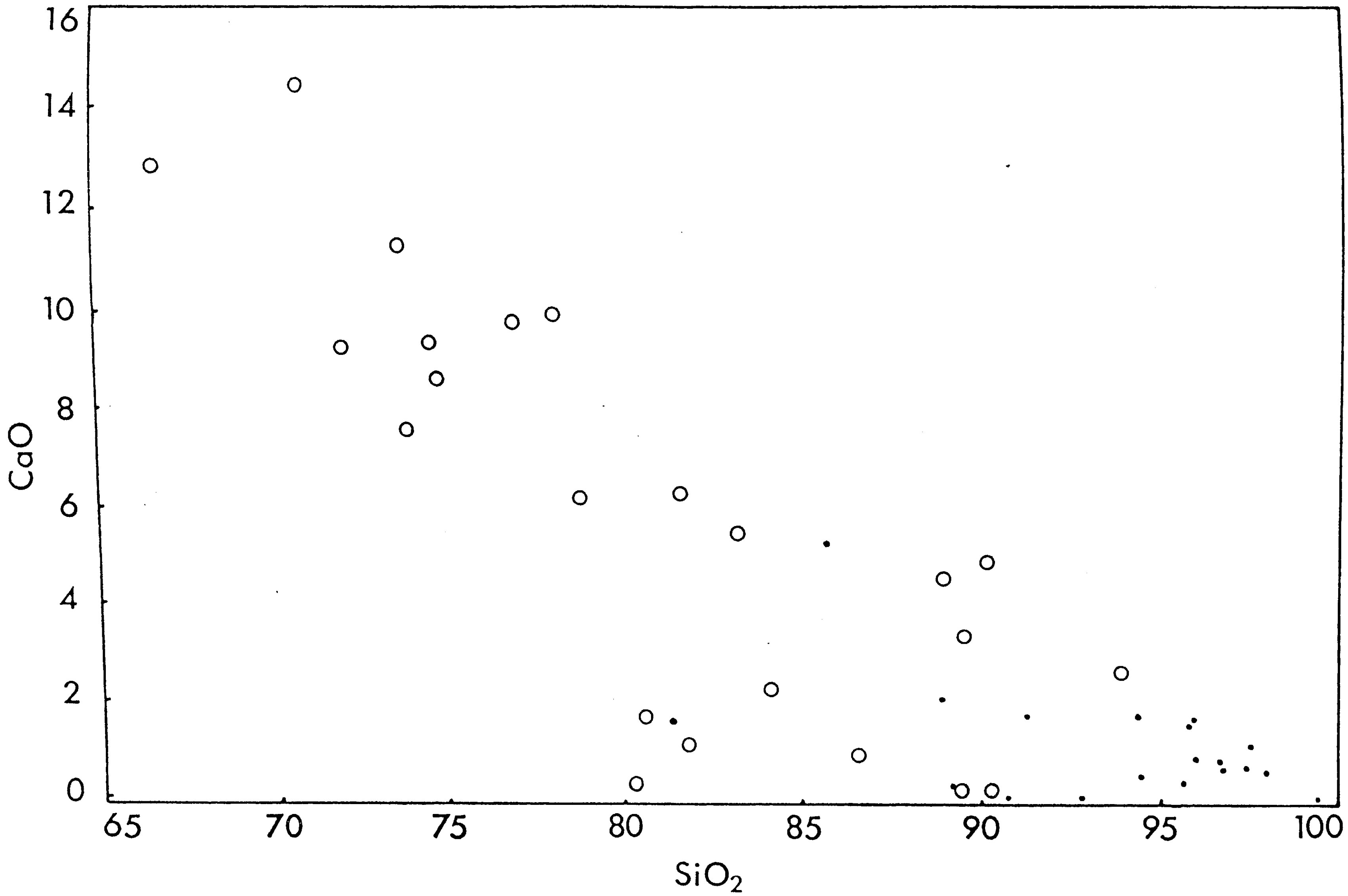


FIG. 19 SiO_2 vs CaO (circle: Lower; dot: Upper).

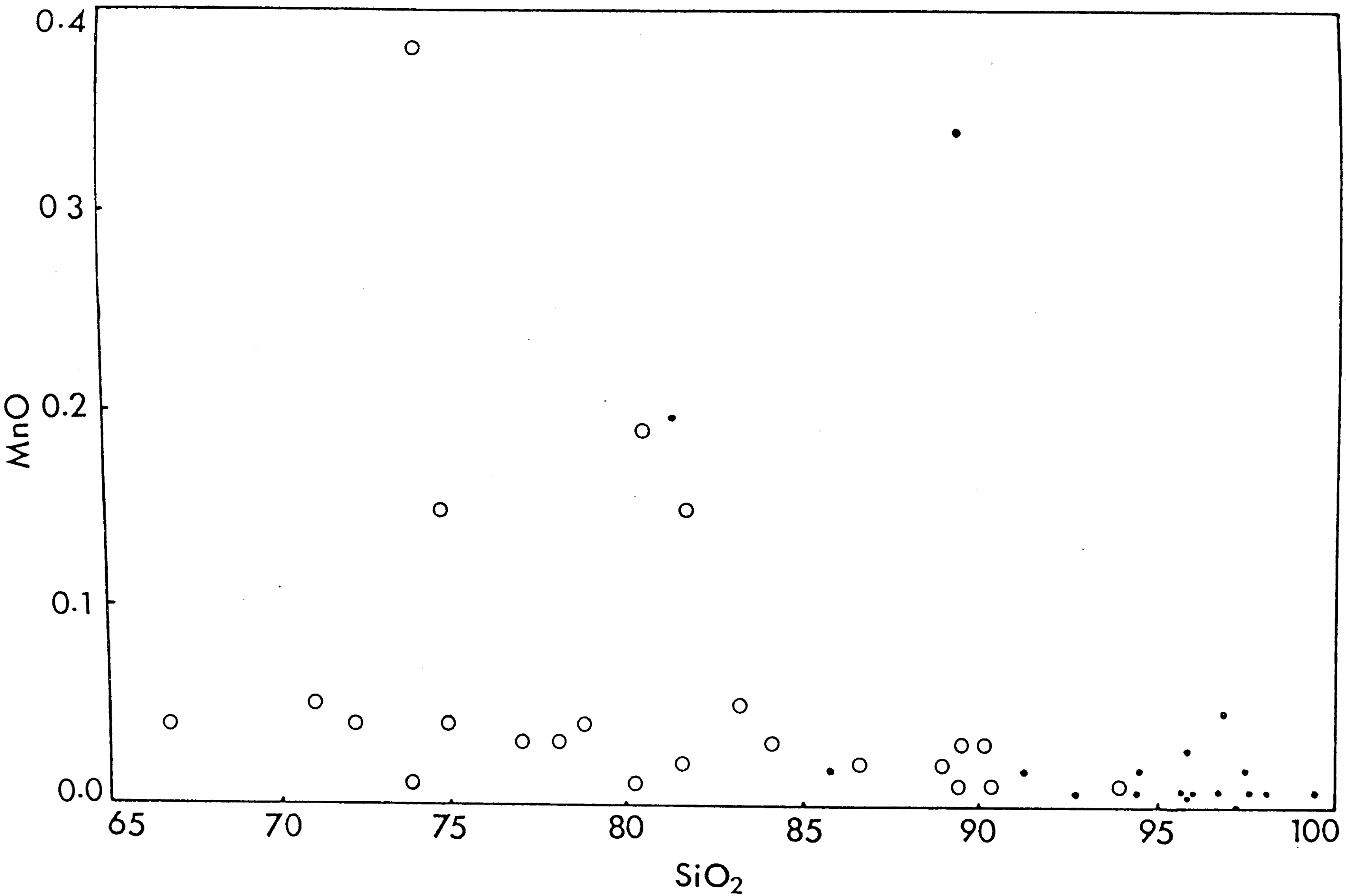


FIG. 20 SiO_2 vs MnO (circle: Lower; dot: Upper).

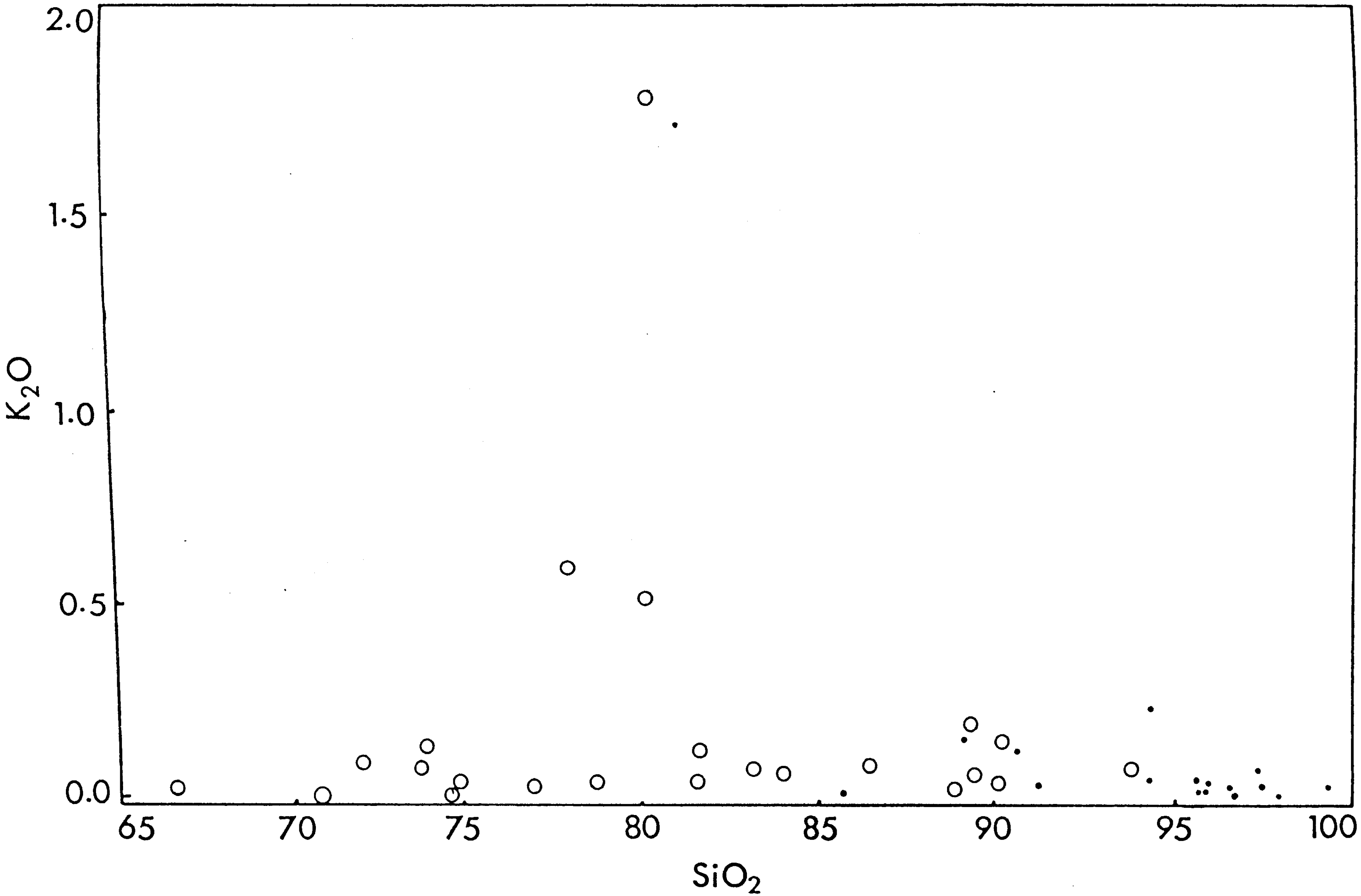


FIG. 21 SiO_2 vs K_2O (circle: Lower; dot: Upper).

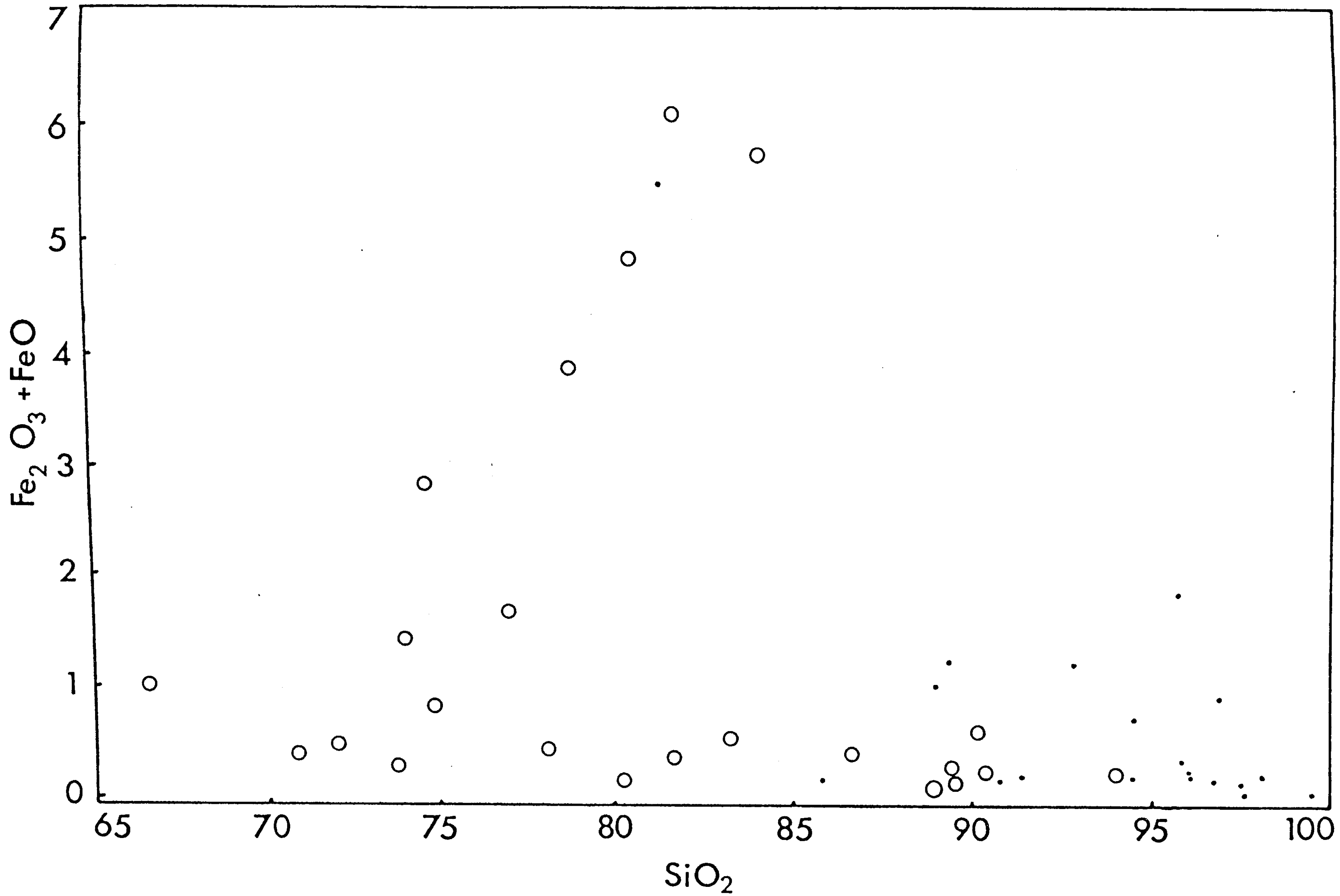


FIG. 22 SiO_2 vs Fe_2O_3 + FeO (circle: Lower; dot: Upper).

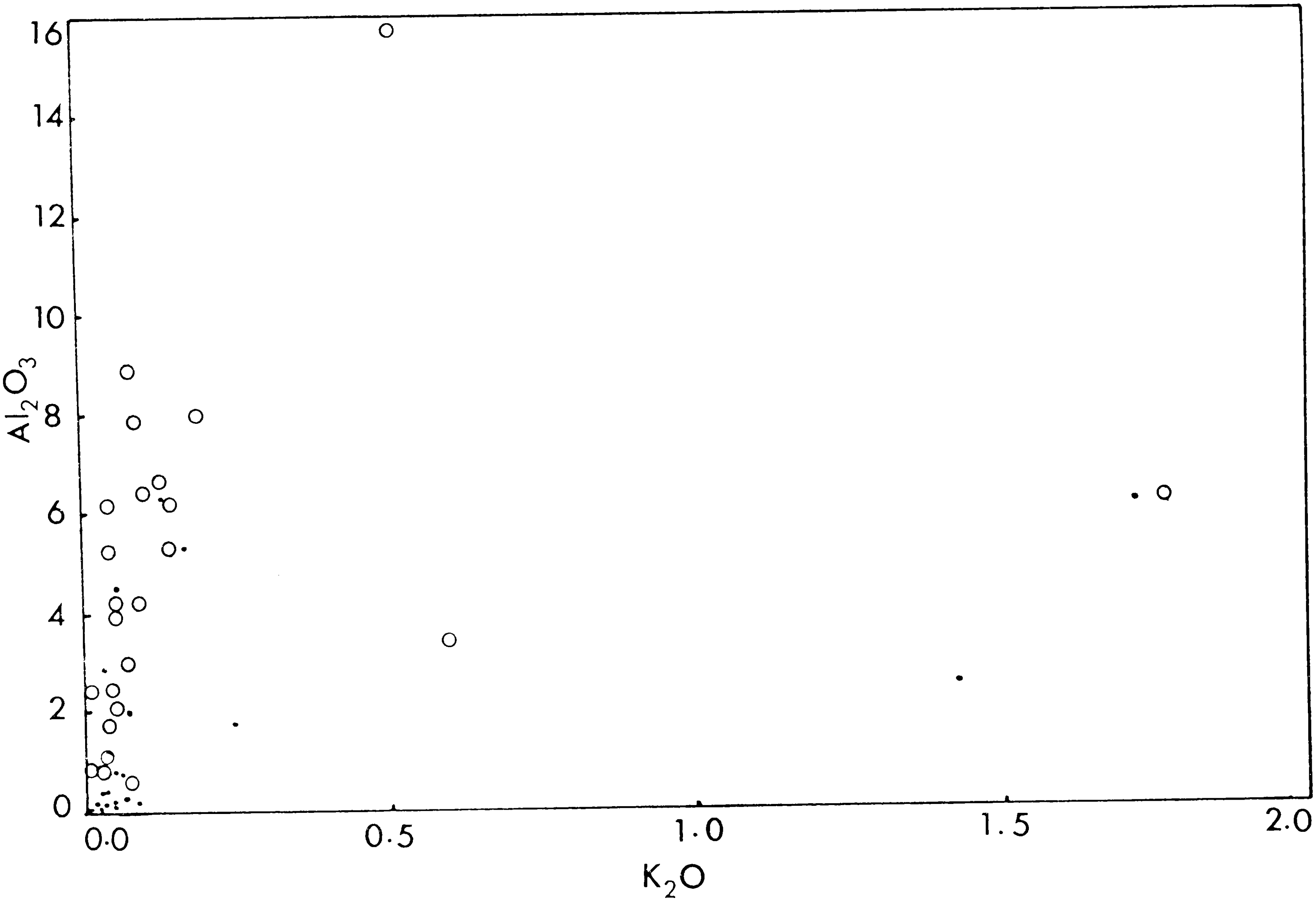


FIG. 23 K_2O vs Al_2O_3 (Circle: Lower; dot: Upper).

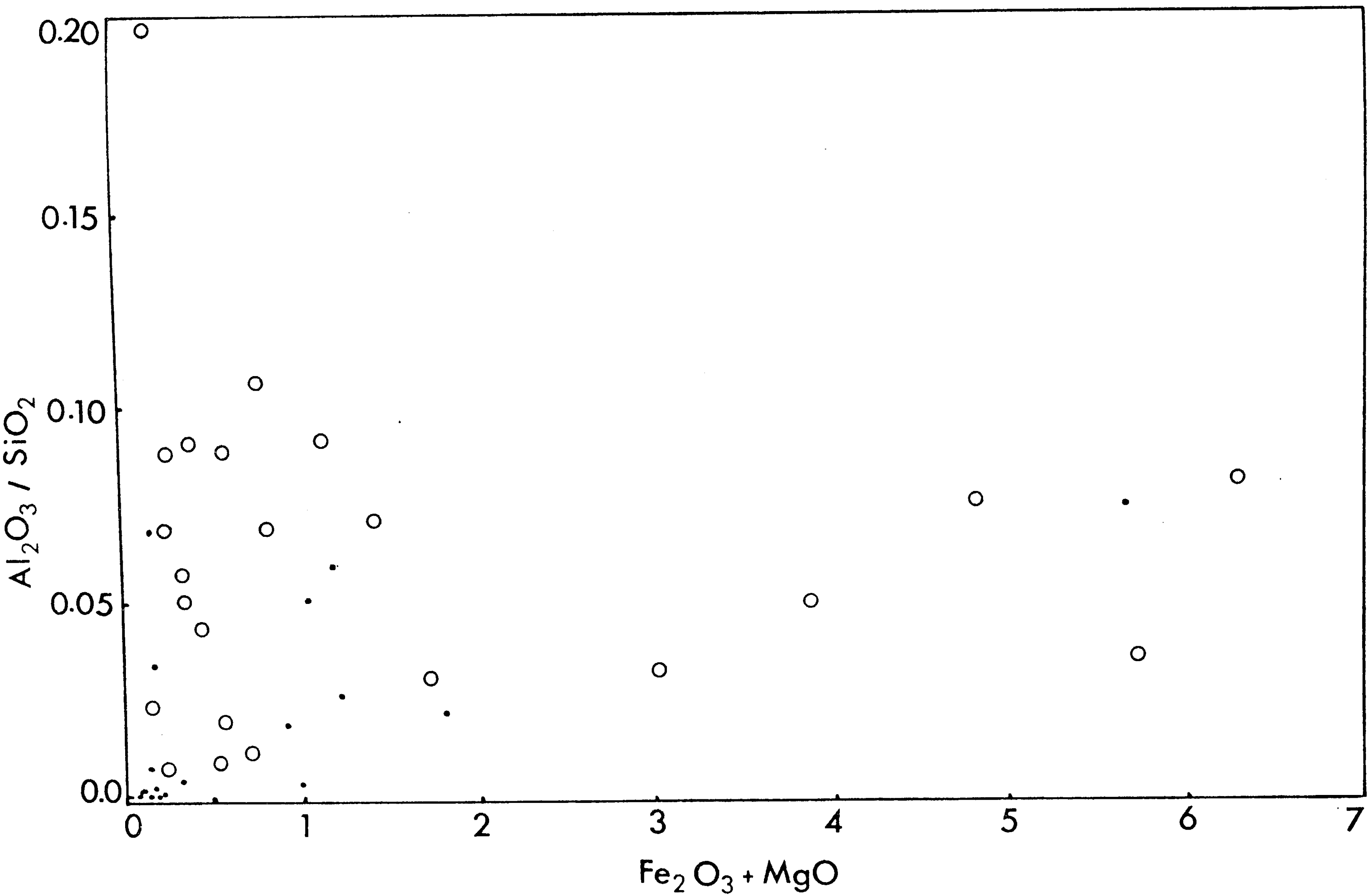


FIG. 24 $Fe_2{*}O_3$ + MgO vs Al_2O_3/SiO_2 (Circle: Lower; dot: Upper).

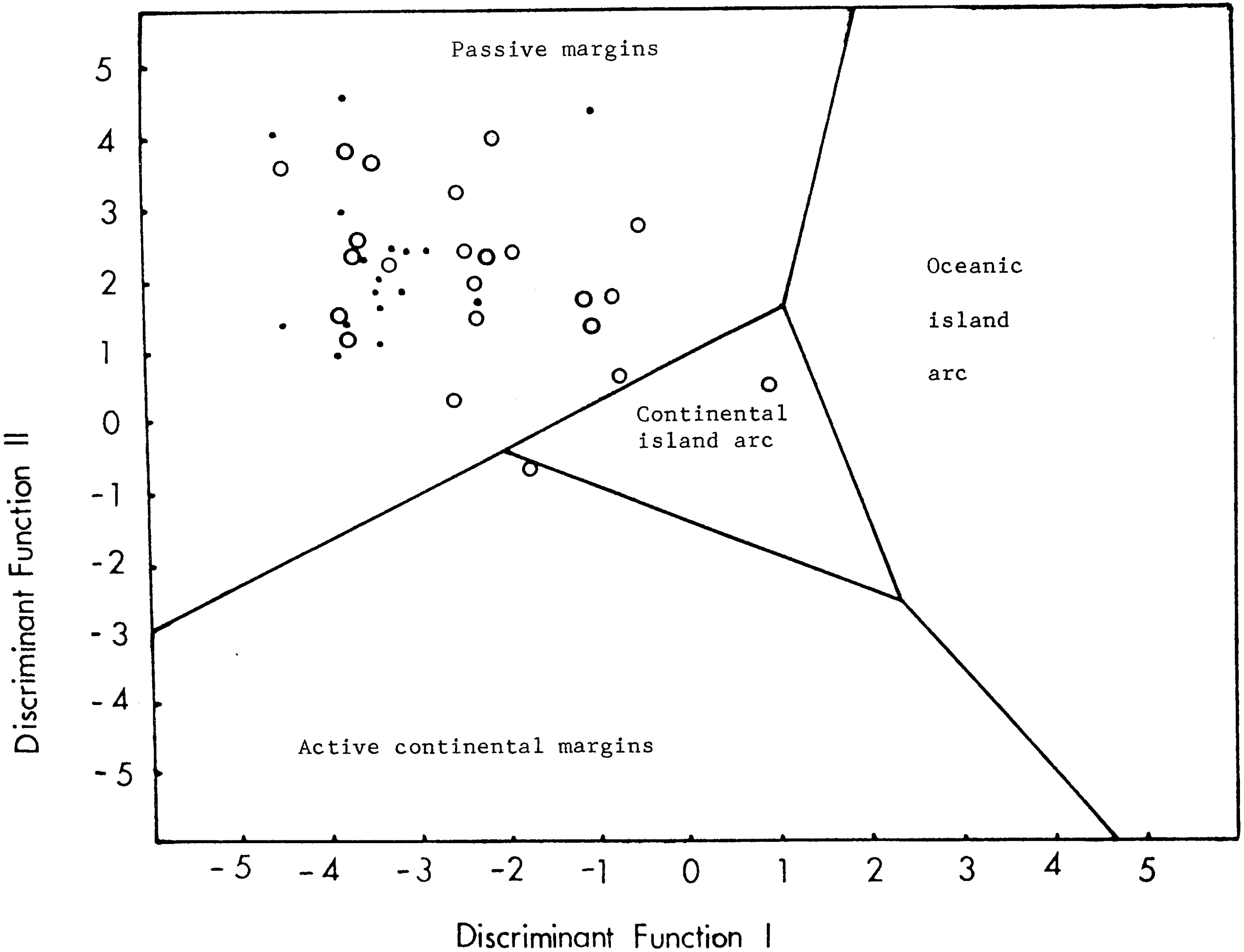


FIG. 25 Plot of discriminant scores along Function I vs Function II for Upper and Lower Saq Sandstone.

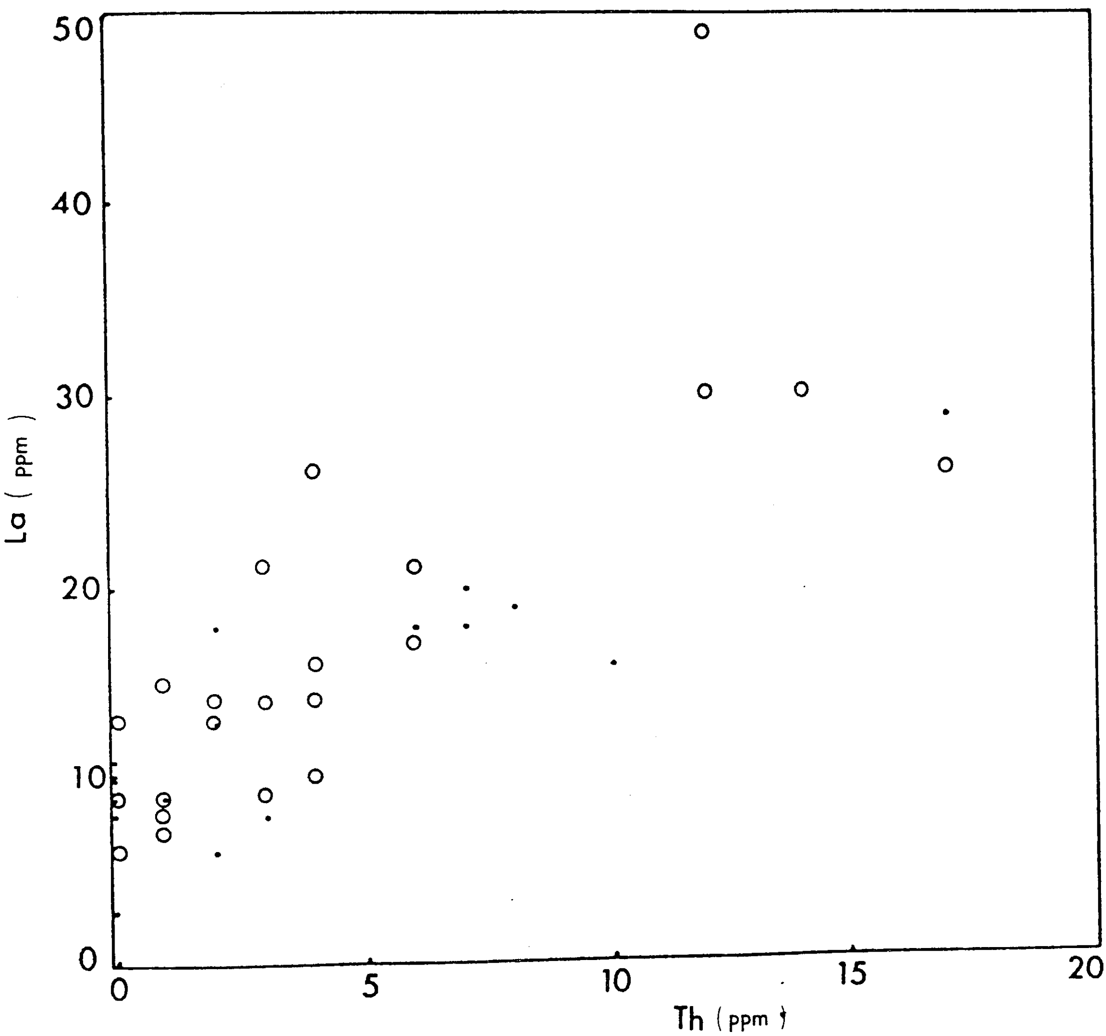


FIG. 26 Th vs La (Circle: Lower; dot: Upper).

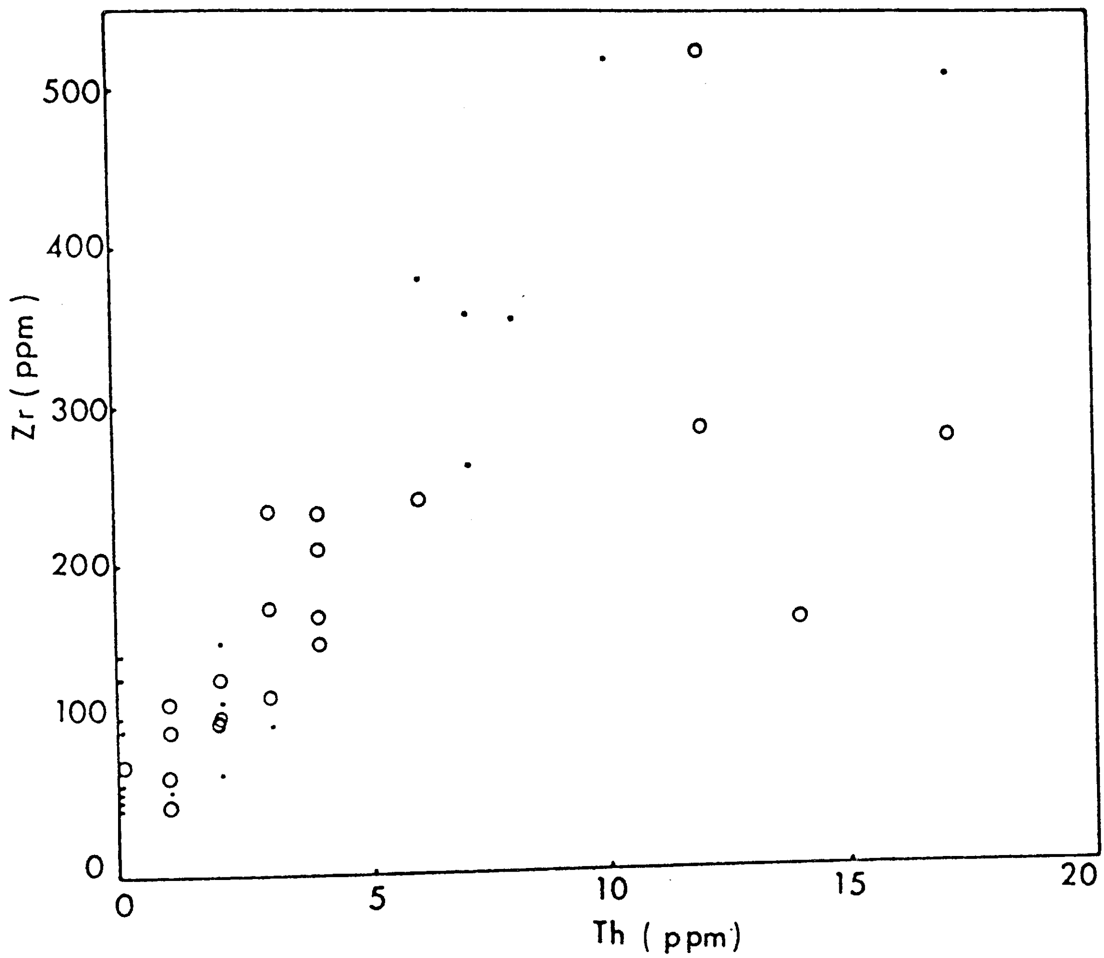


FIG. 27 Th vs Zr (Circle: Lower; dot: Upper).

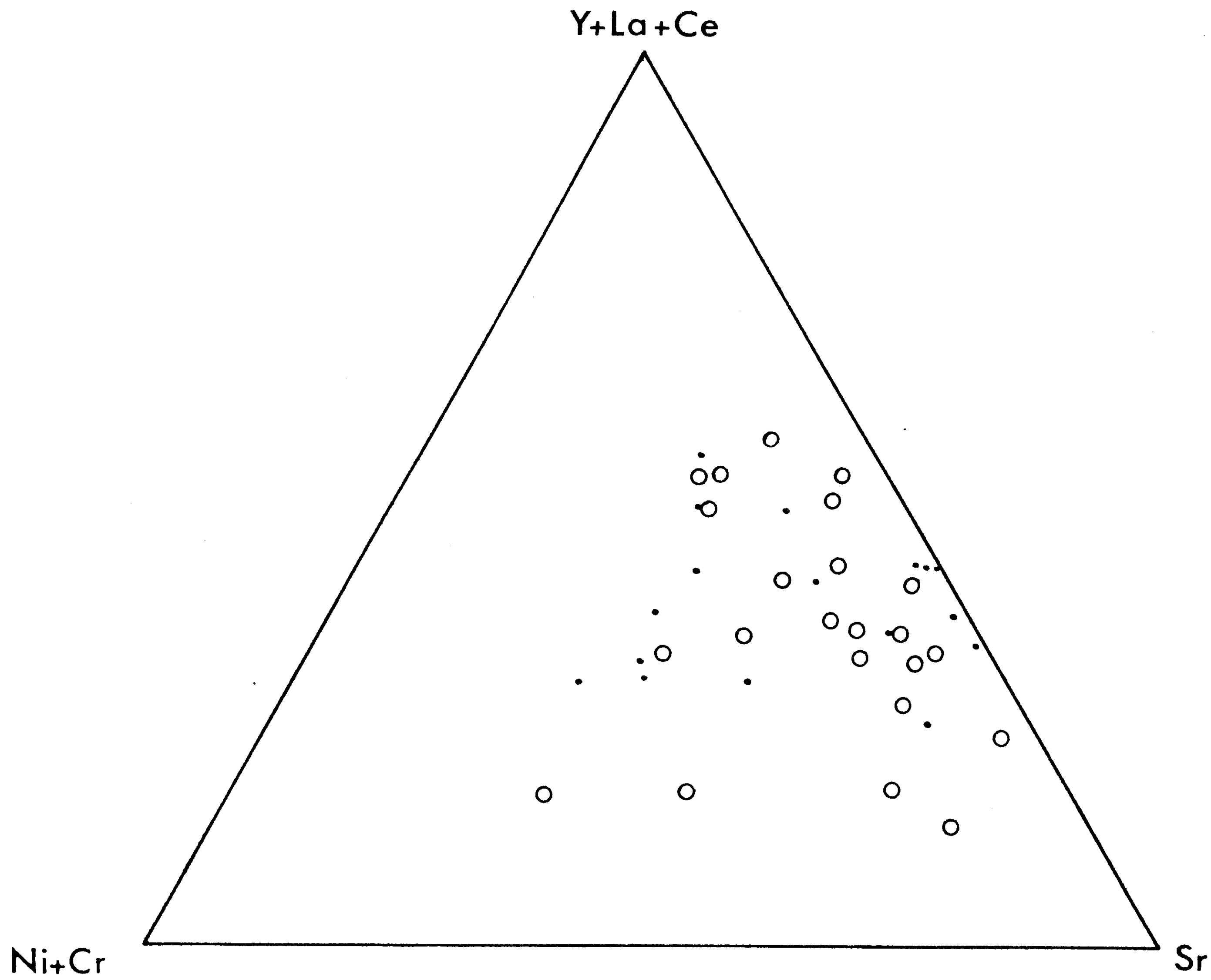


FIG. 28 Ni + Cr vs Y + La + Ce vs Sr (Circle: Lower; dot: Upper).

CHAPTER FOUR

GRAIN SIZE ANALYSIS

The distribution of sedimentary particles with intermediate diameters ranging from 0.0625mm-16mm (sand and fine conglomerate) is most commonly determined by sieving. The method used here is outlined by Folk (1974). 25 samples of the friable sandstones were collected and gently broken down to their constituent grains.

Logarithmic probability paper was used to obtain grain size parameters, which were used in turn as criteria for recognizing the environment of deposition, and to recognize the mechanisms of sediment transport and deposition.

The parameters used in this investigation have been summarized by Folk as follows:

(1) Median (Md).

The median corresponding to the grain size of the amounted 50% of the reading. Therefore 50% of the population is coarse and 50% is finer than this size grade.

(2) Graphic Mean (Mz).

The best graphic measure for determining average size is the graphic mean, which is given by the formula:

$$Mz = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

According to Folk (1974), the verbal limits of mean suggest the following interpretation:-

Mz from	-1.0	to	0.0	ϕ	Very coarse sand
	0.0	to	1.0	ϕ	Coarse sand
	1.0	to	2.0	ϕ	Medium sand
	2.0	to	3.0	ϕ	Fine sand
	3.0	to	4.0	ϕ	Very fine sand
	4.0	to	5.0	ϕ	Coarse silt

(3) Inclusive Graphic Standard Deviation (σ_I).

The inclusive graphic standard deviation is good for measuring sorting of the particles, and is given by the formula:

$$= \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

This formula includes 90% of the distribution and is the best overall measure of sorting. Measurement of sorting values has been suggested by Folk (1974). The following is a verbal classification scale for sorting:-

under	0.35			ϕ	Very well sorted
	0.35	to	0.5	ϕ	Well sorted
	0.5	to	0.71	ϕ	Moderately well sorted
	0.71	to	1.0	ϕ	= sorted
	1.0	to	2.0	ϕ	Poorly sorted
	2.0	to	4.0	ϕ	Very poorly sorted
	4.0 upward			ϕ	Extremely poorly sorted

(4) Inclusive Graphic Skewness (Sk_I).

The inclusive graphic skewness, measures the degree of symmetry as well as + ve, - ve. If the curve has a symmetrical tail on the left side then it is negative skewness, and if the curve has a symmetrical tail on the right side, it is positive skewness.

Inclusive graphic skewness is given by the formula:-

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

This formula determines the skewness of the tail, where the most critical differences occur between samples. Skewness values should be recorded with a positive or negative sign to avoid possible confusion. The verbal limits on skewness are suggested by Folk (1974) as follows:-

Sk_I	from	+ 1.0 to + 0.30	Strongly fine skewed
		+ 0.3 to + 0.10	Fine skewed
		+ 0.10 to - 0.10	Near symmetrical
		- 0.10 to - 0.30	Coarse skewed
		- 0.30 to - 1.0	Strongly coarse skewed

(5) Kurtosis (Sk_G).

Kurtosis is used to describe the departure from normality and is measured by the formula:-

$$Sk_G = \frac{\phi 95 - \phi 5}{2.44 (\phi 75 - \phi 25)}$$

Folk (1974) suggested the following verbal limits for Kurtosis:

Sk_G	under	0.67	Very platykurtic
		0.67 to 0.90	Platykurtic
		0.90 to 1.11	Mesokurtic
		1.11 to 1.5	Leptokurtic
		1.5 to 3.0	Very leptokurtic
	over	3.0	Extremely leptokurtic

When cumulative-frequency distributions of particle size of sediments are plotted on probability graphs, one of the most striking observations is that most of these distributions do not come out as one continuous straight line. In fact, commonly two or more straight-line segments are present, each having a different slope and often separated by a sharp break.

The interpretation of the shapes of cumulative grain size distributions (plotted on logarithmic probability paper) in terms of sediments any response to hydraulic conditions, attracted the attention of numerous geologists (Visher, 1969; Visher and Haward, 1974; Freeman and Visher, 1975; Sagoe and Visher, 1977). Visher and his co-workers propose that each cumulative curve comprises a number of straight-line segments and divide it into three populations (Fig. 29) associated with bedload "surface creep" (coarsest sub-population, saltation (intermediate) and suspension (finest)).

There are, however, a number of problems associated with this simple interpretation of these probability graphs:

(1) The fine segment is often seen to contain most of the heavy mineral population. With many of these minerals having a density greater than the density of sand (2.71), they would almost certainly be part of traction load. The size of 50 grains of zircon from each Upper (A) and Lower (B) Saq Sandstone has been measured and the mean size is 0.08mm and 0.16mm respectively. Both were plotted in a cumulative graph (Figs 30,31) and fall in suspension load according to Visher diagram. With zircon having a density of 4.7, it would almost certainly have been part of the traction load.

(2) When a sample of sand is taken it may contain many laminae,

each of which is characterized by its particle grain size. Laminae may be produced by different tractive events: some events being stronger, faster flow than others. On this diagram all laminae are plotted as one sample.

(3) The individual grains of given size may well travel in more than one transport mode depending upon weather (storm or not), Bridge, (1981).

(4) Grain modification after burial, either by development of overgrowths (Plate 3) or by size-reduction by pressure solutioning.

The results of twenty-five analysed samples taken are shown in Tables 14 and 15.

Interpreted in the views of Visher (1969) and others, the segments in Figure 30 represented unimodal sediments that have been transported by saltation and suspension currents, while the corresponding curves of Lower Saq Sandstone (Figs 31,32) represent bimodal sediment transported by saltation and traction currents.

Twelve samples were selected and recorded as histograms. Figures 33 to 36 show unimodal assymetrical distribution in Upper and Lower Saq Sandstone.

Bivariate Discriminat Plots

Discrimination of sedimentary environments using bivariate plots of statistical grain-size parameters (Median, mean diameter, standard deviation, skewness) has been employed on recent and ancient environment (Friedman, 1961, 1967; Stewart, 1958; Folk and Ward, 1957; Passega, 1957, 1964; Glaister and Nelson, 1974; Holmes and Oliver, 1973; Ameral and Pryor, 1977; Moshrif, 1980).

In view of the criticisms levelled at grain size analysis at the beginning of this chapter, it is difficult to put much faith in any of the methods used. Moreover in the discriminate plots (Figs 37 to 39) the Saq Sandstone falls into a number of environments. However, with respect to the Upper Saq, over 85% of the samples fall within the beach environment and there is conclusive evidence from some outcrops for beach deposits. Amongst these beach deposits are also cross-stratified sandstones which may also be beach lower foreshore, (see Clifton _et al_., 1971) but could also be sub-tidal shelf deposits.

TABLE 14: Summary of grain size analysis (Upper Saq).

Sample No.	Median (Md)	Mean (M_z)	Inclusive standard deviation (σ_I)	Skewness Sk_I	Kurtosis Sk_G
24-1-1	2.47	2.47 Fine sand	0.52 Moderately well sorted	0.05 Coarse skewed	1.10 Mesokurtic
26-1-1	3.12	3.14 Very fine sand	0.46 Well sorted	0.04 Near symmetrical	1.34 Leptokurtic
24-1-3	2.17	2.23 Fine sand	0.54 Moderately well sorted	0.07 Near symmetrical	1.12 Leptokurtic
1-1-26	1.77	1.77 Medium sand	0.34 Very well sorted	0.08 Near symmetrical	1.21 Leptokurtic
L.9.1	3.46	3.5 Very fine sand	0.26 Very well sorted	0.18 Fine skewed	1.24 Leptokurtic
26-1-2	2.97	2.99 Fine sand	0.44 Well sorted	0.11 Fine skewed	0.92 Mesokurtic
24-1-10	2.84	2.85 Fine sand	0.42 Well sorted	0.12 Fine skewed	1.18 Leptokurtic
24-1-4	2.42	2.44 Fine sand	0.24 Very well sorted	0.21 Fine skewed	1.12 Leptokurtic
24-1-2	2.32	2.37 Fine sand	0.28 Well sorted	0.38 Strongly fine skewed	1.26 Leptokurtic

TABLE 15: Summary of grain size analysis (Lower Saq).

Sample No.	Median (Md)	Mean (M_z)	Inclusive standard deviation (σ_I)	Skewness Sk_I	Kurtosis Sk_G
1-1-6	1.97	2.07 Fine sand	0.51 Moderately well sorted	0.19 Fine skewed	1.13 Leptokurtic
19-2-3	1.45	1.51 Medium sand	0.81 Moderately sorted	0.15 Fine skewed	1.11 Leptokurtic
21-1-7	1.67	1.68 Medium sand	0.37 Well sorted	0.15 Fine skewed	1.44 Leptokurtic
19-2-1	2.67	2.65 Fine sand	0.66 Moderately well sorted	0.19 Fine skewed	2.09 Leptokurtic
1-1-5	1.57	1.7 Medium sand	0.77 Moderately sorted	0.23 Fine skewed	1.03 Mesokurtic
19.2.4	2.13	2.01 Fine sand	0.88 Moderately sorted	-0.21 Coarse skewed	1.12 Leptokurtic
1-1-9	2.5	2.31 Fine sand	0.76 Moderately sorted	-0.32 strongly coarse skewed	0.74 Platykurtic
19-2-7	1.77	1.8 Medium sand	0.50 Moderately well sorted	0.19 Fine skewed	1.28 Leptokurtic
1-1-8	1.79	1.8 Medium sand	0.51 Moderately well sorted	0.05 Near symmetrical	1.01 Mesokurtic

Cont. TABLE 15

Sample No.	Median (Md)	Mean (M_z)	Inclusive standard deviation (σ_I)	Skewness Sk_I	Kurtosis Sk_G
19-2-6	2.0	2.04 Fine sand	0.59 Moderately well sorted	0.18 Fine skewed	1.21 Leptokurtic
21-2-3	2.07	2.23 Fine sand	0.66 Moderately well sorted	0.45 Strongly fine skewed	1.18 Leptokurtic
19-2-2	2.05	2.09 Fine sand	0.52 Moderately well sorted	0.13 Fine skewed	0.91 Mesokurtic
21-2-8	2.46	2.35 Fine sand	0.70 Moderately well sorted	-0.19 Coarse skewed	0.94 Leptokurtic
21-1-9	1.11	1.18 Medium sand	0.76 Moderately sorted	0.14 Fine skewed	1.28 Leptokurtic
21-2-4	0.70	0.72 Coarse sand	1.72 Poorly sorted	0.04 Near symmetrical	0.92 Mesokurtic
1-1-7	0.70	1.04 Medium sand	1.33 Poorly sorted	0.31 Fine skewed	0.94 Mesokurtic

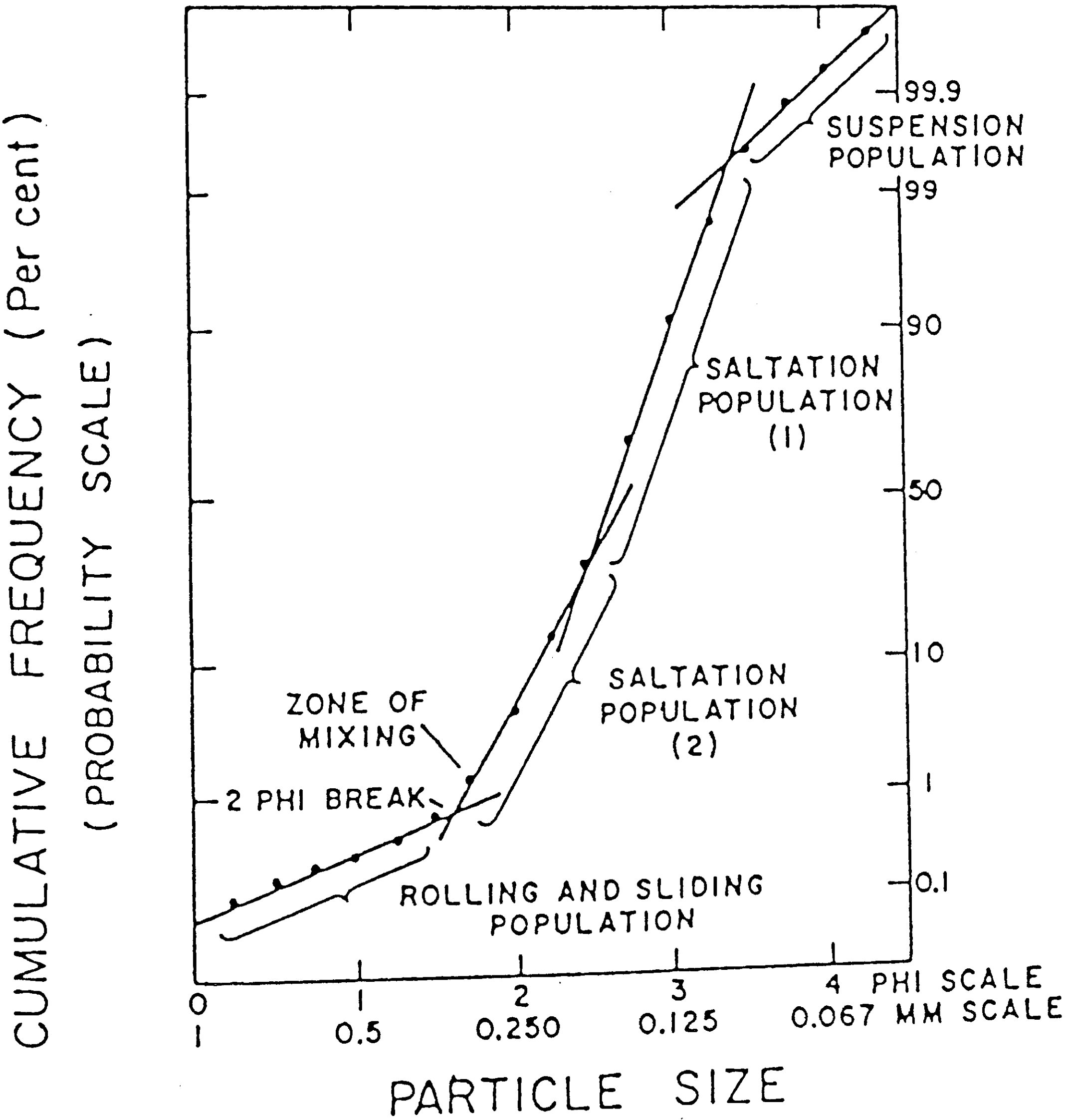


FIG. 29 Cumulative-frequency curve of beach sand, drawn on probability paper (Visher, 1969).

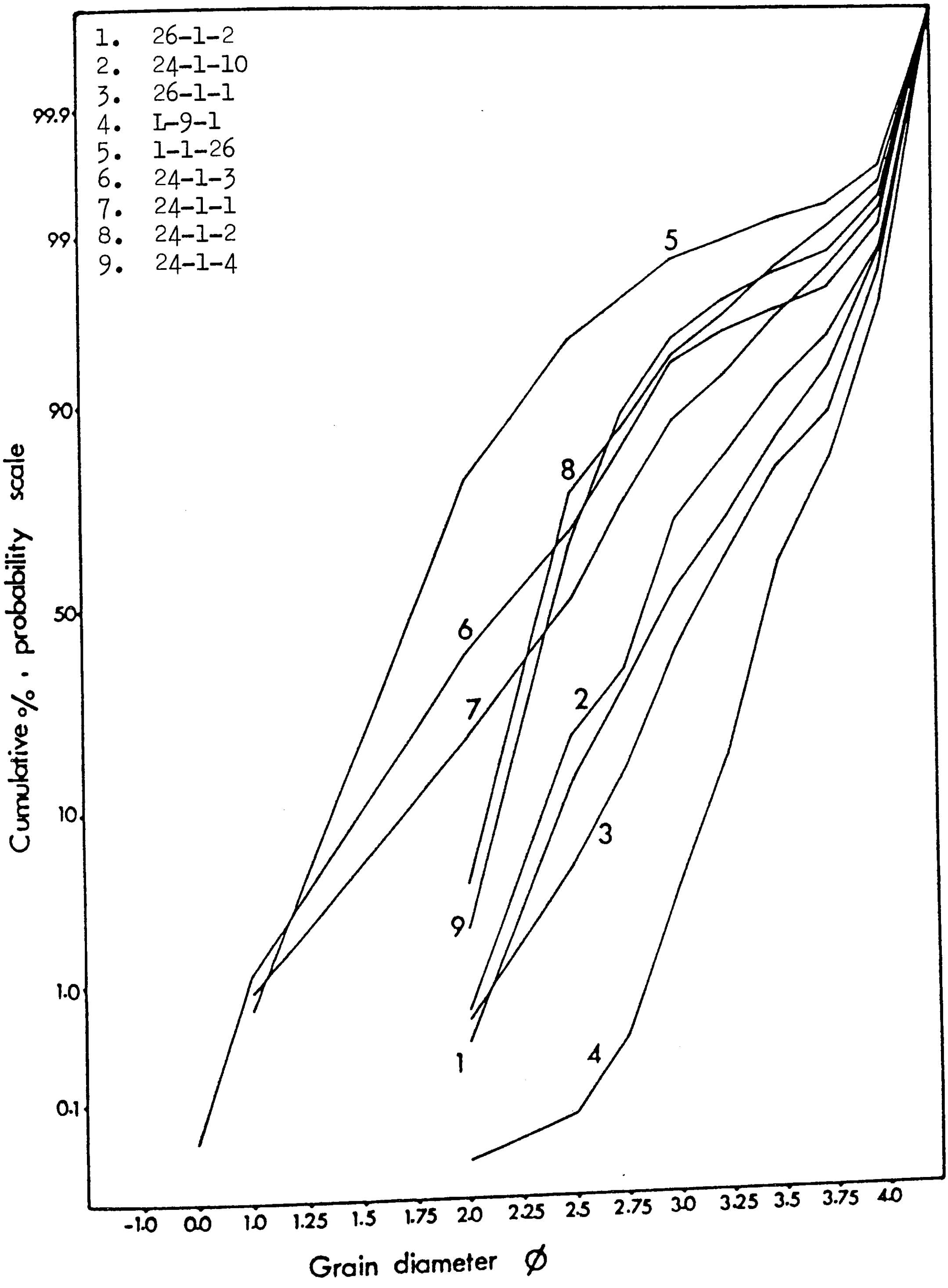


FIG. 30 Cumulative curves of Upper Saq Sandstone.

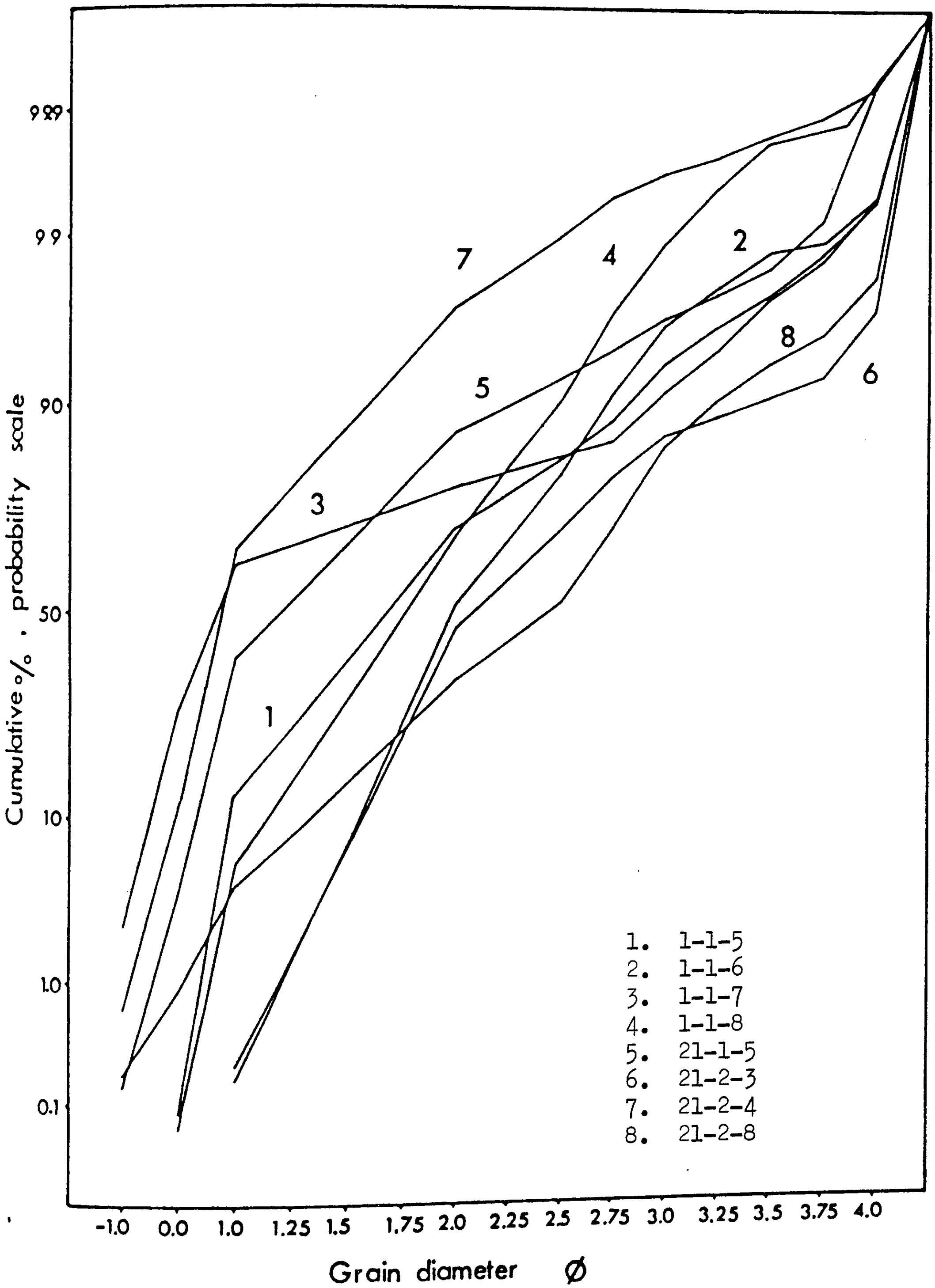


FIG. 31 Cumulative curves of Lower Saq Sandstone.

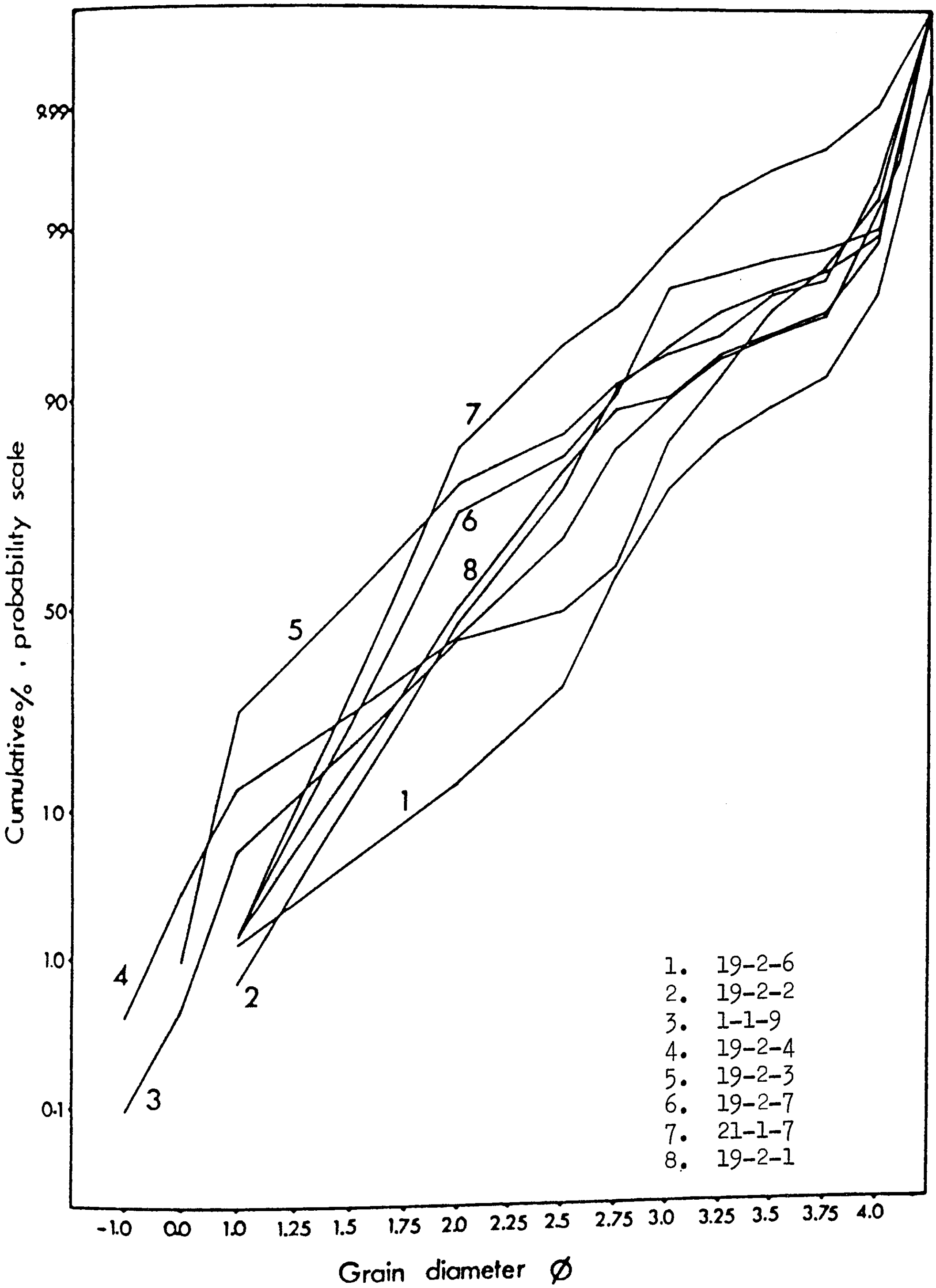


FIG. 32 Cumulative curves of Lower Saq Sandstone.

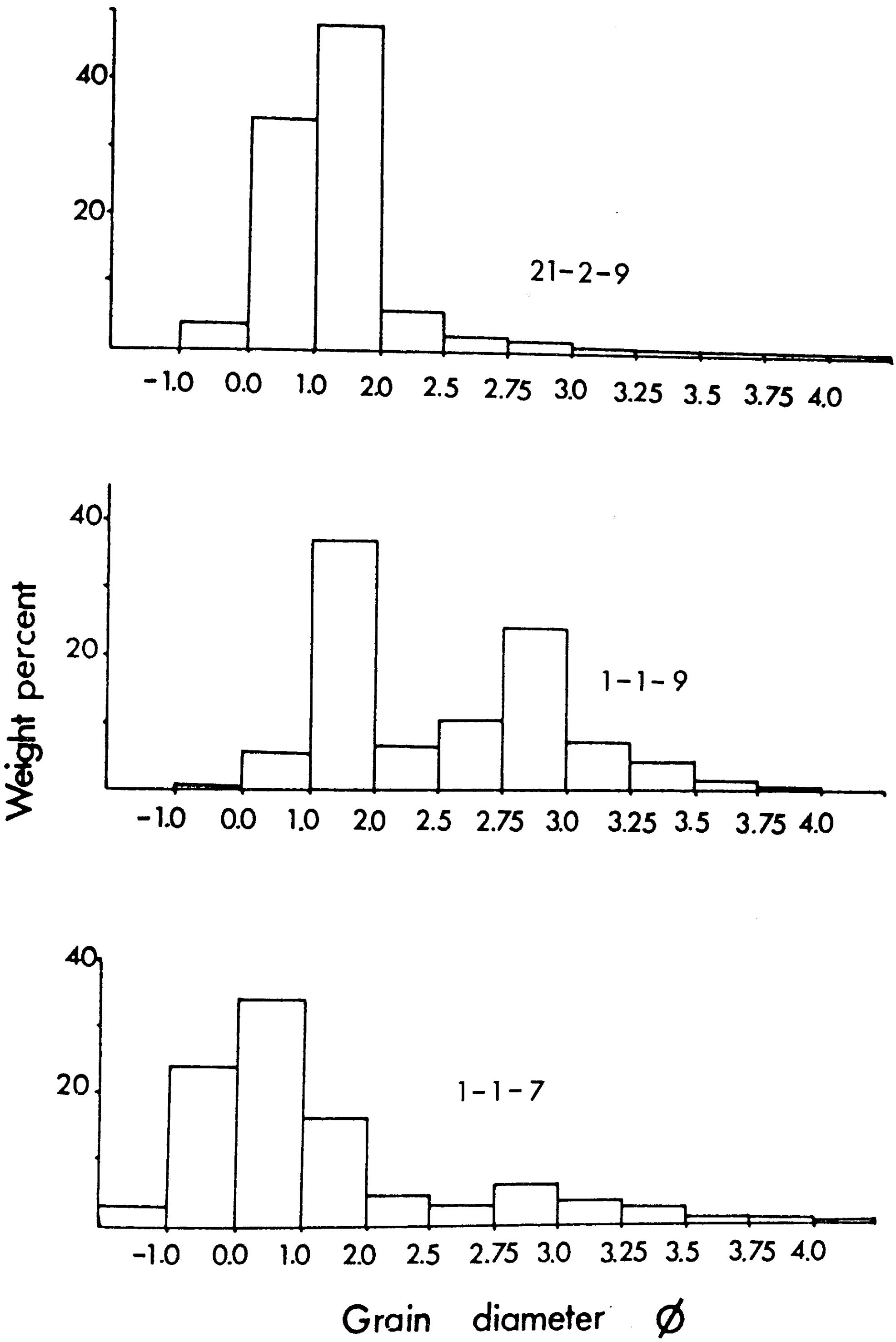


FIG. 33 Histograms of selected samples from Lower Saq Sandstone.

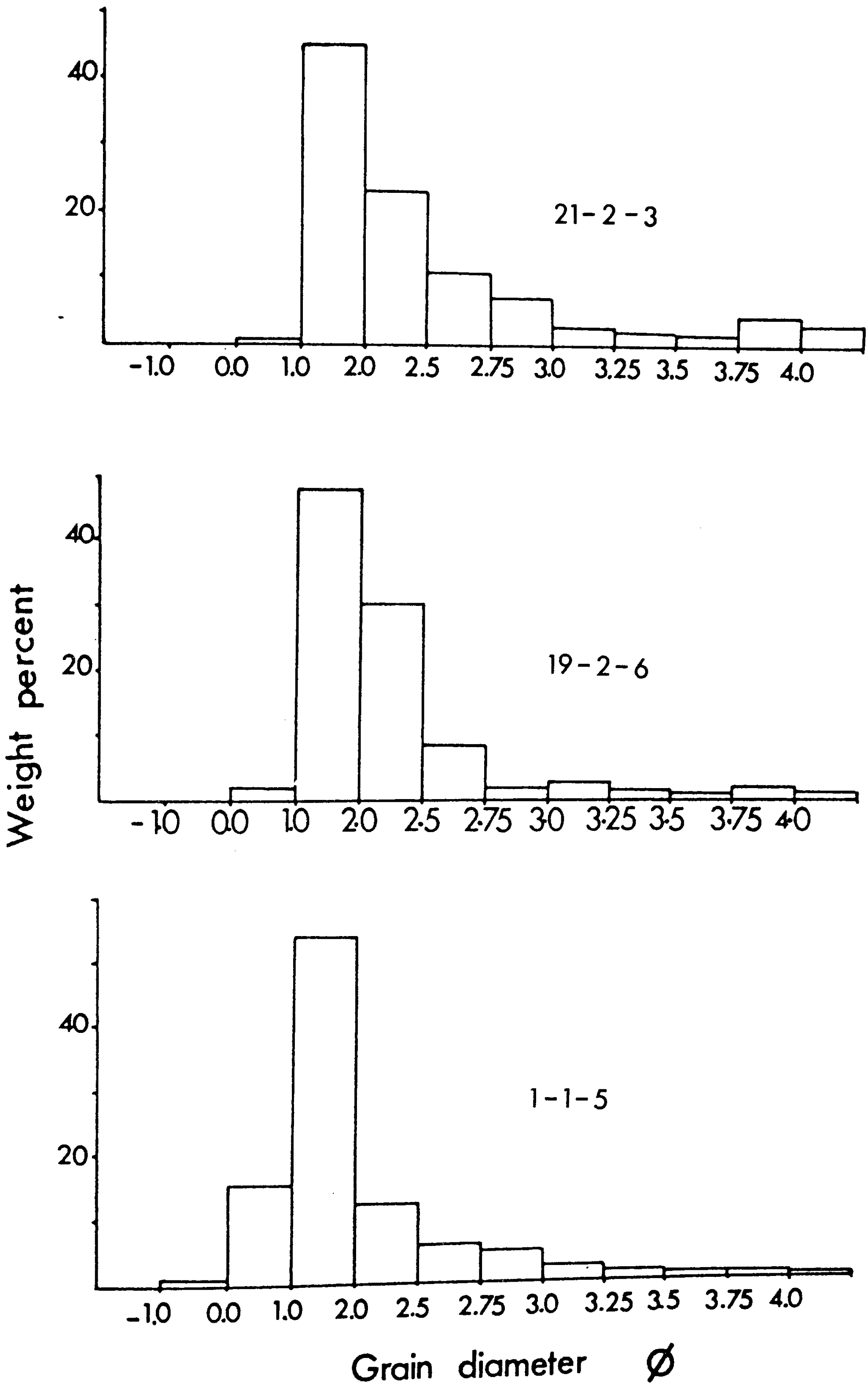


FIG. 34 Histograms of selected samples from Lower Saq Sandstone.

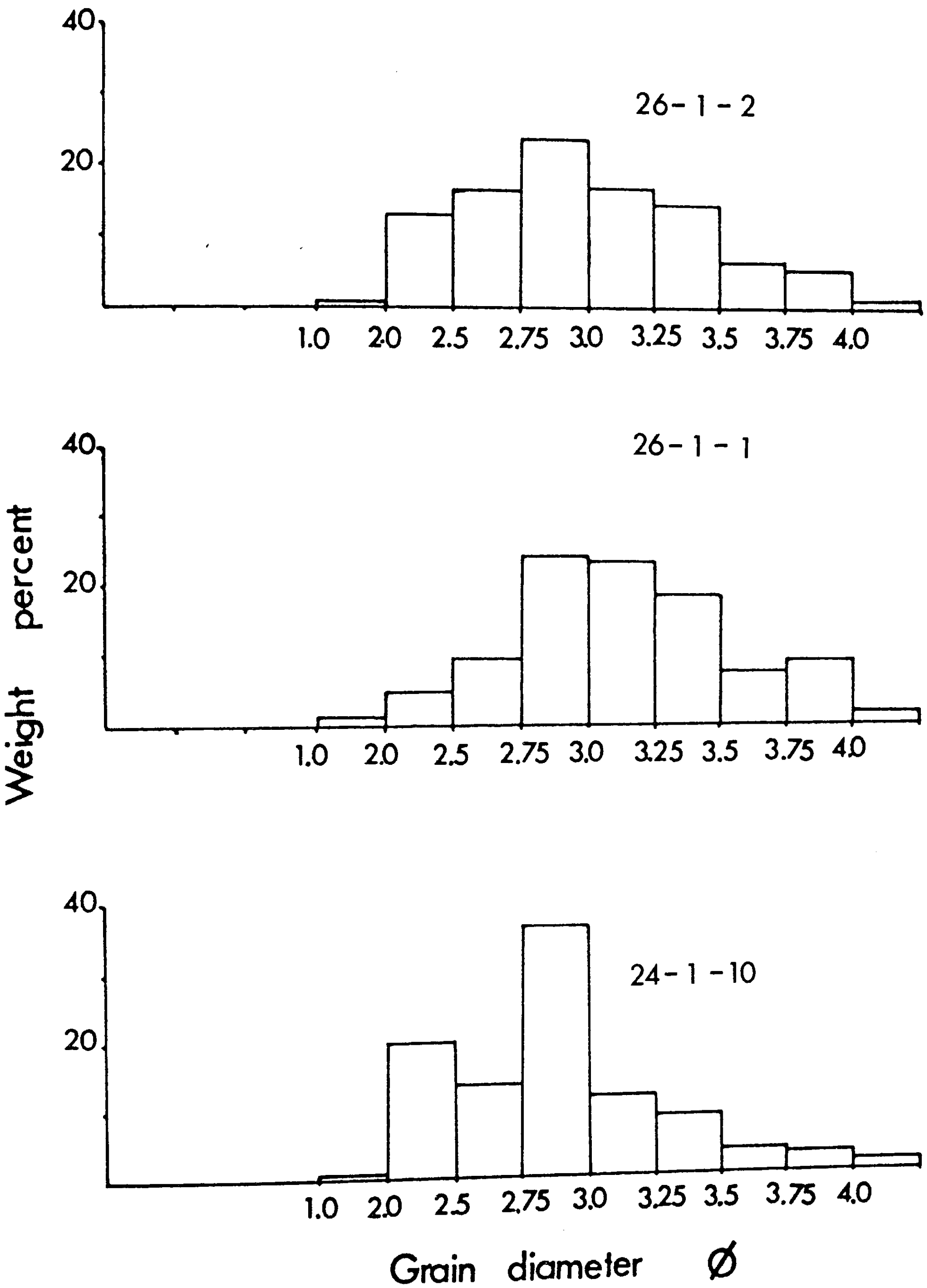


FIG. 35 Histograms of selected samples from Upper Saq Sandstone.

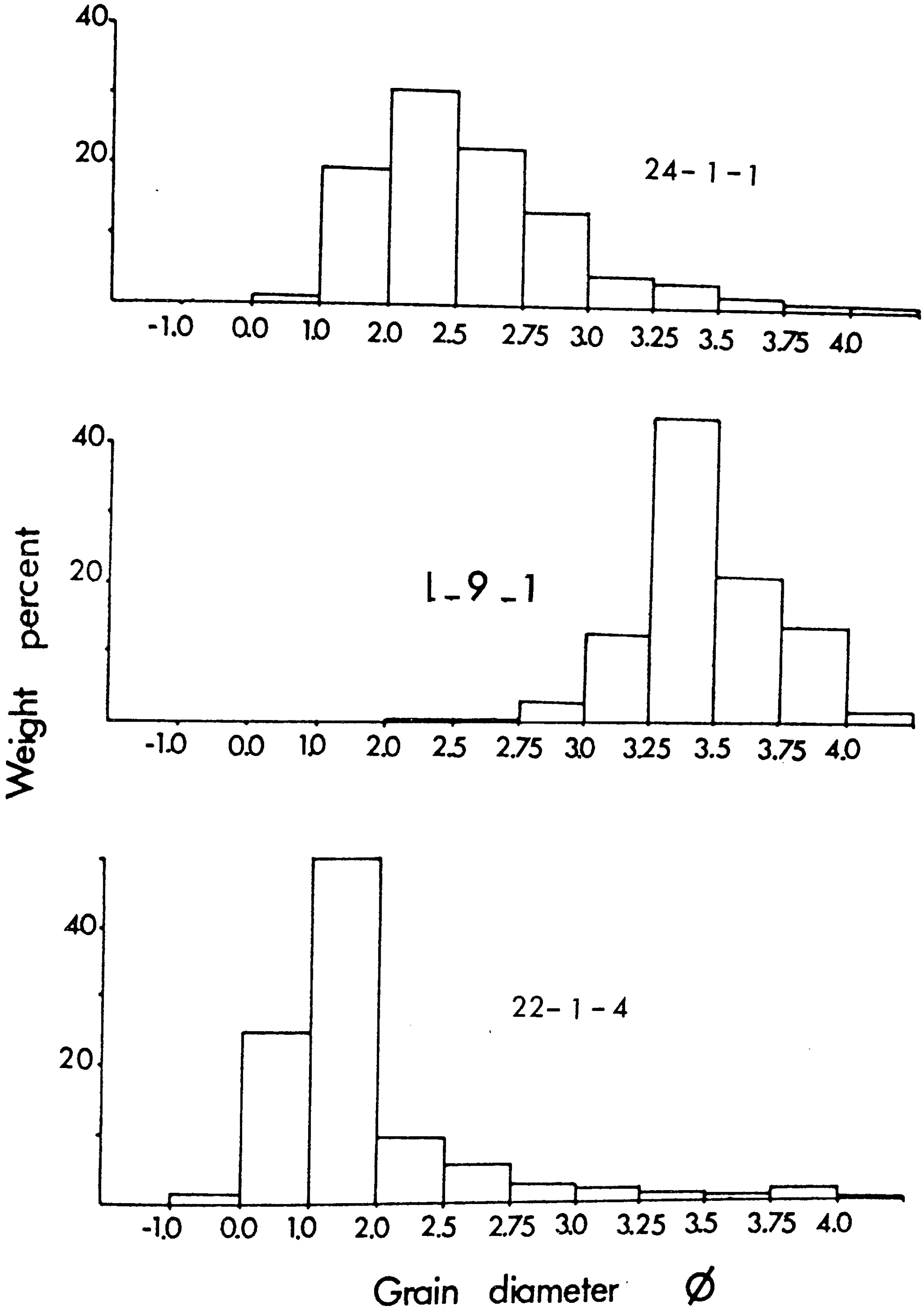


FIG. 36 Histograms of selected samples from Upper Saq Sandstone.

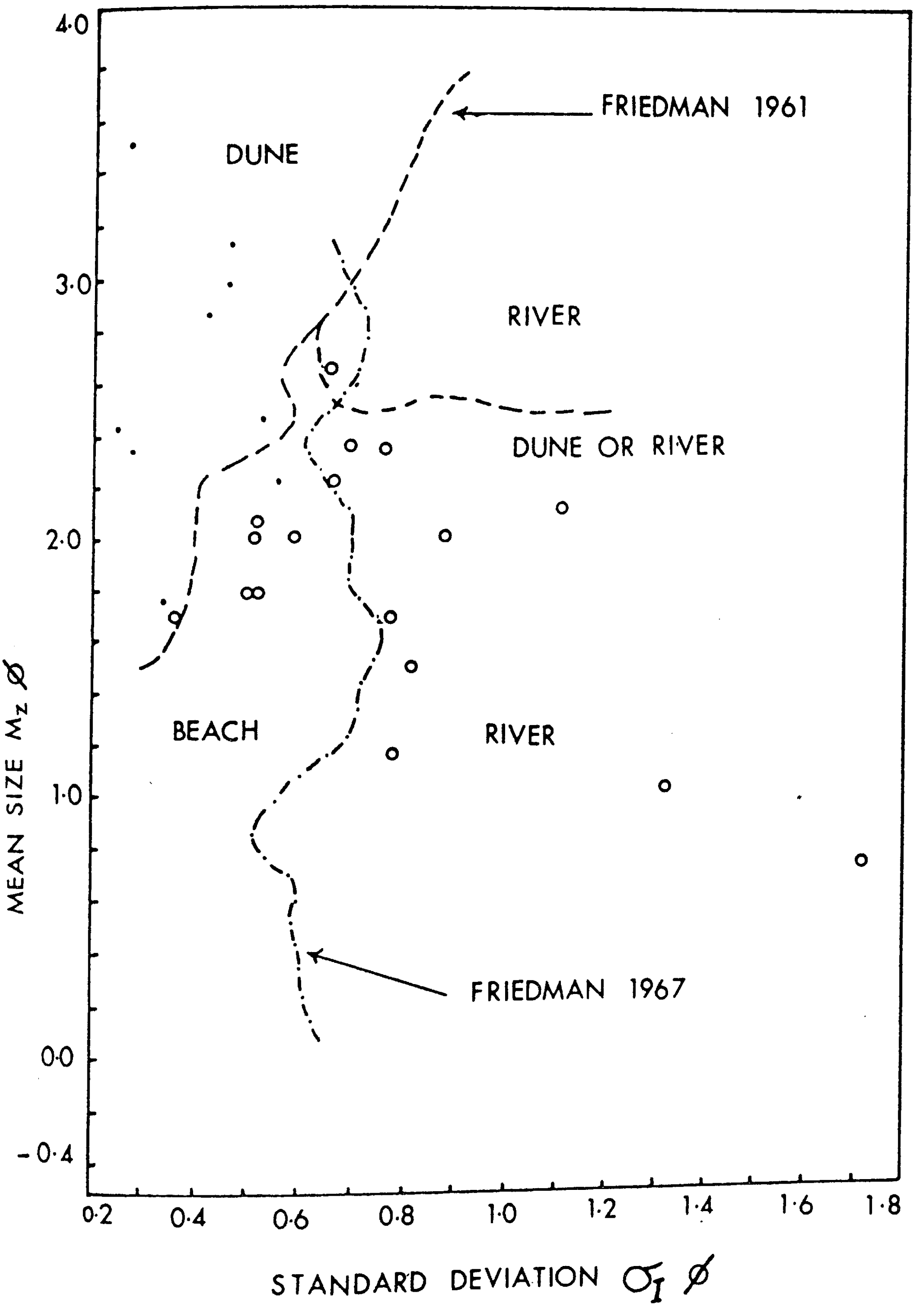


FIG. 37 Plot of standard deviation vs mean size (after Friedman 1961, 1967).

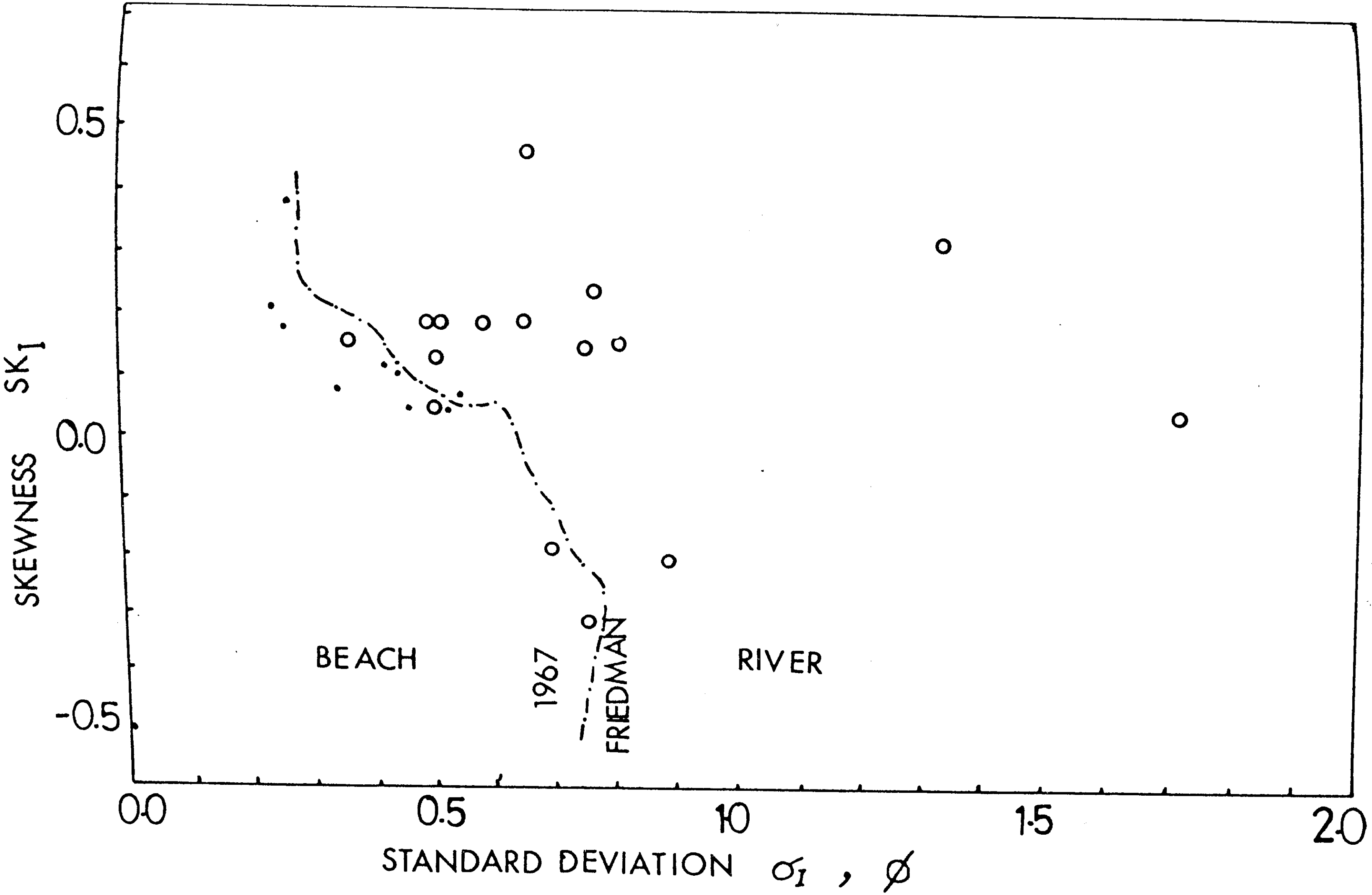


FIG. 38 Plot of standard deviation vs skewness (after Friedman 1967).

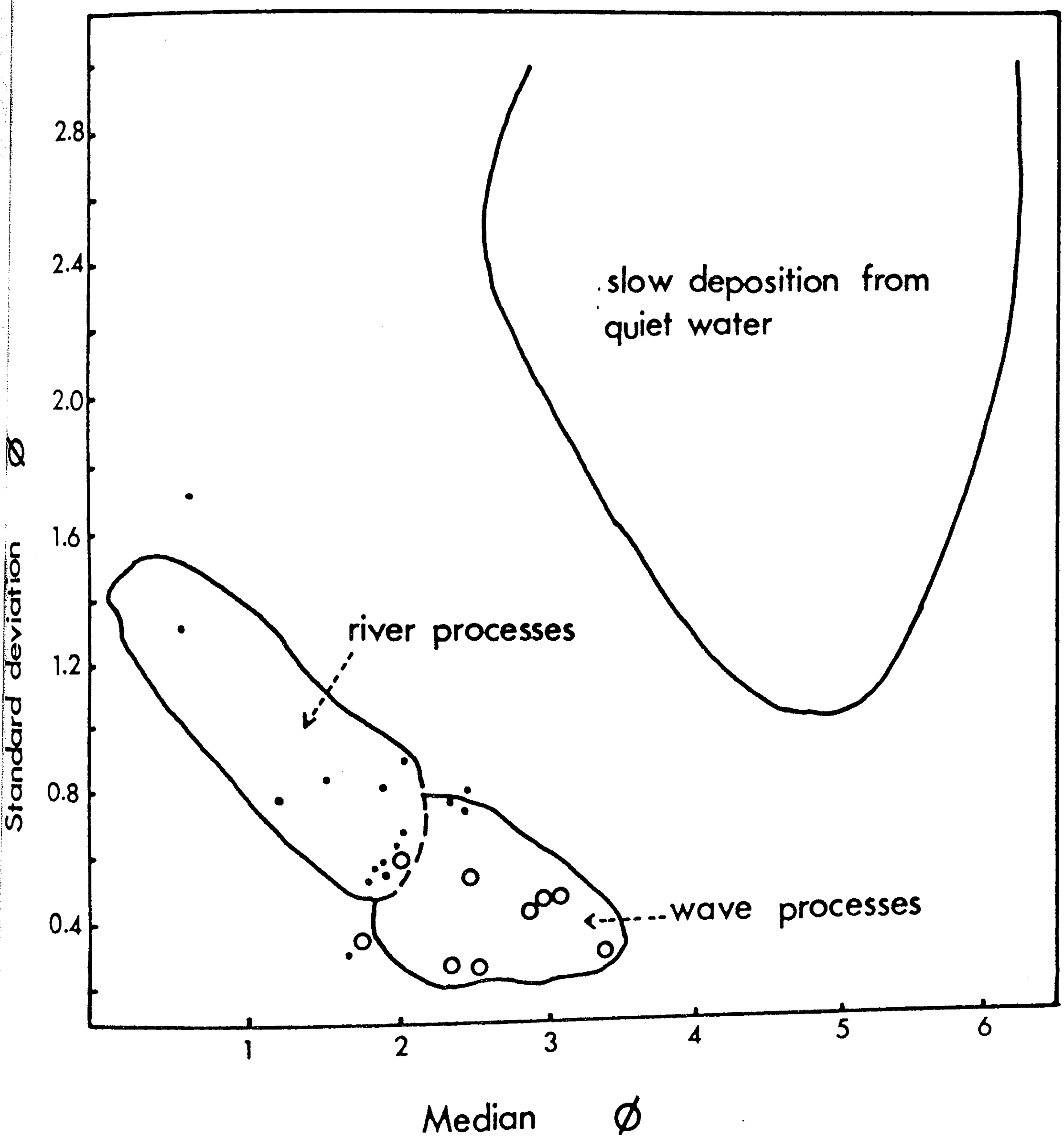


FIG. 39 Plot of standard deviation vs Median of Stewart's diagram (modified from Stewart 1958).

CHAPTER FIVE

CROSS-STRATIFICATION AND DISPERSAL IN SAQ SANDSTONE

The Saq Sandstone contains abundant cross-stratification, which is the most easily recognized primary structure. It is planar (Mckee and Weir, 1953; Allen, 1963) or tabular (Potter and Pettijohn, 1963), but some trough cross-stratification is present.

Cross stratification forms in the following ways:

1. Migrating small deltas of sand and gravel, which occur when sediment spills over from the main, into the abandoned pool channel, or into the transverse channel (Potter and Pettijohn, 1963; Bluck, 1974).

2. Cross-stratification produced by megaripples which are often characterized by having coarse sediment at the base and fine at the top of the unit. The cross-strata of this type are found in the sand-filled troughs of the abandoned channels, where they often dip in the direction of elongation of the trough, but also sometimes laterally infill it. (Allen, 1963; Bluck, 1974).

3. Ripple topped bars or transverse bars (Smith, 1972) are commonly seen on some of the sandbars either as infills (lateral and downfills) of the channel or as levee-like deposits laid down where the water has swept over the cut bank.

4. Cross-stratification produced by the migrating steep accretionary margins of large bars (Bluck, 1974).

Techniques.

Dip, dip directions and thickness of more than 1700 cross-strata were measured, but because of the very low ($<2^{o}$) regional dip none was untilted. The number of cross-strata measured in the Lower Saq Sandstone (1384 reading) exceeds the number measured in the Upper (353 reading), because of the greater exposure of the Lower.

The measurements were plotted in 30^{o} class intervals on a rose diagram, and the vector mean and vector magnitude (Reiche, 1938; Curry, 1956) were calculated in the following way:

$$\bar{\theta}_i = \tan W/V$$

$$V = \sum n_i \, \text{Cos} \, \theta_i$$

$$W = \sum n_i \, \text{Sin} \, \theta_i$$

$$R = \sqrt{V^2 + W^2}$$

$$L = (R/n) \, 100$$

where

$\bar{\theta}_i$ = the azimuth of vector mean.

θ_i = the mid-point azimuthal ith class interval.

n_i = the number of observations in each class.

n = the total observation.

R = the magnitude or length of vector mean.

L = the magnitude of vector mean in terms of percentage.

Cross-stratification of Lower Saq Sandstone.

The dip directions of 1384 foresets were measured to determine the regional palaeocurrent orientation, and to assess if there was any change in palaeoflow through time (Figs. 40, 41).

Almost all localities have unimodal rose diagrams of cross-stratal dips which, with only one exception, show a palaeoflow to the NE. The vector mean, the magnitude of vector mean and the standard deviation for Lower Saq Sandstone are shown in Table 16.

Dip of cross-stratification.

The angle of inclination of 1384 cross-strata was measured and ranges from 5^{o} to 40^{o}, the frequency distribution is symmetrical with an average angle of $20^{o}44'$ (Fig. 42).

Thickness of cross-stratification.

Cross-stratification ranges in thickness from 5 to 240cm, average 25.9cm. The thickness of cross-stratification generally follows a lognormal distribution (Fig. 43). Most cross-stratification thickness is less than 40cm, but a few more than 40cm thick and two 240cm thick was found.

These data on cross-stratal thickness do not support an aeolian origin.(Hunter, 1977). Cross-stratification of aeolian origin can be very thick. Norris and Norris (1961) reported that individual dunes in California were more than 66m thick.

Basal unit of Lower Saq Sandstone.

The basal beds of Lower Saq Sandstone are characterized by having a fine conglomerate c.5 metres thick. More than 175 cross-stratal dip orientations were measured in this unit (Loc.17/2 and Loc. 16/1) and plotted as a rose diagram (Fig. 44). These basal beds show the same flow towards NE (vector mean $64^{o}29'$) as the overlying sandstone.

Cross-stratification of Upper Saq Sandstone.

A distribution diagram of 353 measurements of cross-stratal dip direction (Fig. 45) shows an obvious unidirectional flow , in general, NE (vector mean 59°30') except localities 9 and 26/1, which show a direction to SE (vector mean 136°25'). Vector mean, the magnitude of vector mean and standard deviation of foreset dip orientation are shown in Table 17.

Dip of Cross-stratification.

The distribution of dips from the cross-stratification of Upper Saq Sandstone is more symmetrical than that obtained from the Lower Saq. The Upper Saq has cross-stratal dips ranging from 3° to 50° with an average of 18°44' (Fig. 46). Swett et al., (1971) measured the dip of inclination in Cambrian tidal sand and found 25°.

The average dip of cross-strata Upper Saq Sandstone is less than that of the Lower Saq Sandstone and this could be due to differing grain sizes of sandstone, with the Upper Saq being the finer of the two. Many workers (Van Burkalow, 1945; Miller and Byrne, 1966; Allen, 1970; Imbrie and Buchanan, 1965; Carrigy, 1970) reported that the angle of foreset is influenced by several factors including the properties of both the sediment population and the transport medium.

Thickness of cross-stratification.

The thickness of cross-stratification in Upper Saq Sandstone anges from 5 to 140cm, with an average of 19.8cm. The thickness of cross-stratification is shown in Fig.43 and generally follows a lognormal distribution. More than eighty per cent of Upper Saq cross-stratification has a thickness of less than 40cm and with relatively few units of thickness up to 140cm.

Interpretations.

Palaeoflow in the Lower Saq Sandstone is unidirectional in a north-northeasterly direction (vector mean $62^{o}27'$)(Fig. 47). This direction of flow is roughly the same as obtained from the conglomerate basal unit of the sequence, and similar to the palaeoflows characterizing the Upper part of the Saq sequences.

The consistency of palaeoflow orientation of an area $> 400km^2$ (Figs 40, 41) suggests a very uniform dispersing system, and/or a very extensive environment of which this is only a small part. However, at some localities there is a wide range in dip orientation which suggests flow paths in a variety of directions. The interpretation of the cross-stratal dip orientations cannot be done without knowing the environment of deposition. If the environment of deposition is alluvial, then the cross-strata dip is in the direction of palaeoslope; if marine-shelf, then they dip in the direction of tidal flow, and if aeolian, they dip in the direction of wind flow.

Evidence for environment of deposition is given in Chapter Seven where the most diagnostic criteria available are (1) Cruziana trails in Location 23/1 and, (2) beds with broken brachiopod shell debris at Location 10; (3) beach sandstone at the top of the sequence at Location 10.

Cross-stratification near Location 23/1 has the same palaeoflow direction as the dominant direction seen for the Formation, so that if beds in Location 23/1, and the associated bed, are marine in origin, then there is no reason to believe that the rest of the sandstones are anything other than marine.

Accepting a marine origin for these sandstones, the unidirectional flow paths may be interpreted. Many workers reported unidirectional palaeocurrents from sandstone that are interpreted as shallow marine deposits (Narayan, 1971; Banks, 1973a; McCave, 1973; Anderton 1976;

Nio, 1976; Spearing, 1976; Hereford, 1977; Johnson, 1977a; Brenner, 1978).

Levell (1980) has attributed the unidirectional palaeocurrents in the Lower Sandfjord Formation in north Norway to three mechanisms, operating in shallow marine environments:

1. Regional transport dominance.

Stride (1963), Belderson & Stride (1969) and Kenyon & Stride (1970) have documented persistent transport dominances over several hundreds of square kilometres of seafloor which result in unidirectional transport paths. These arise because sediment transport during one tidal phase systematically exceeds that during the other. This asymmetry of the tidal ellipse is caused by the way in which the tidal wave is propagated into the basin as a whole, and thus depends upon the shape of the basin (Johnson & Belderson, 1969; Mofjeld, 1976). In the case when the subordinate current is below threshold, or that the volumes of sediment it transports are insufficient to reverse the megaripple forms, it might be possible for such small reversing currents to leave the dominant one as the sole record in the larger type bed forms. A unidirectional cross-stratification then results.

2. Local transport dominance.

On a smaller scale than (1), these are likewise due to the deformation of the tidal wave by bottom friction, reflection shielding (Postama, 1967) and can probably result in transport dominances capable of producing unidirectional cross-stratification (Terwindt, 1971).

3. Preservational considerations.

(A) Large bedforms commonly display partial reversal when the subordinate tidal current produces a cut-back form (Van Veen, 1935;

McCave, 1971).

(B) The lateral migration postulated for large subtidal sand bars (Houbolt, 1968; Caston, 1972) is extremely regular, and may lead to the preferred preservation of only one element of the ebb/flood circulation system, and hence to unidirectional cross-stratification.

Levell (1980) argued that these mechanisms cannot be used to explain unimodal palaeocurrent patterns in tidal sandstones that are huntreds of metres thick, simply because a series of bar and channel deposits affected by different dominant current direction would be expected.

In the absence of any evidence to the contrary, most of the Saq Sandstone sequence is assigned to a marine shelf environment in which there was a dominant tidal flow to the NE: this sea transgressed over a planed Precambrian surface.

Structure of sedimentary bar in Lower Saq Sandstone (Loc.21/1).

Bars are the principal depositional element of all rivers and may occur widely in tidal seas. Their recognition is a prerequisite to a more certain identification of the types of processes operating in the environment of deposition. The use of bar type in determining fluvial style has emerged from studies of relationships between geomorphological elements and internal structure in modern river deposits (e.g. Coleman, 1969; Bluck, 1971; Jackson, 1976; Cant and Walker, 1978). As a river aggrades, bars merge to form a sediment body whose gometry and internal structure depends on bar morphology and growth pattern (Kirk, 1983). Bar structures have also been recognized in tidal deposits where they have a similar structure to those described from tidal marine basins.

The Saq Sandstone comprises sequences of cross-strata which can, in some instances, be clearly seen to be organized in bars. In this chapter an example of a sedimentary bar is taken (Fig. 48) and its structure illustrated.

The Saq Sandstone is particularly well exposed in the hills at Locality 21/1, (Fig. 8), where abundant cross-stratification is organized in two litho-facies:-

Facies 1. Comprises tabular cross-strata with clear bottom sets and top sets. Since the top sets and bottom sets are parallel, these cross-strata were deposited by transverse bars or cross-stratified sand sheets (Bluck, 1974, 1979), or megaripples with a long wave length. The cross-strata amalgamate with each other in the direction of cross-stratal dip, suggesting a body with a source of sand upstream and migrating downstream over slower moving sand sheets.

One good reason for overtaking of this kind occurs when sand moves from shallow water to deep water. Small bars near the crest of the major bedform, being in shallower water, may migrate swiftly and overtake slower moving bars which have passed the crest and are in deeper water. This facies represents the stoss and crest zones of a bar complex.

Facies 2. This facies comprises large foresets down which smaller foresets have migrated to form a stack of intrasets (Fig. 49). This facies is produced by the leading edge of the bar as it migrated downstream, being fed by sand moving from the stoss and crestal zones of Facies 1.

The environment which deposited this bar is not easy to establish, but bars with similar structure have been described by Kirk (1983), from fluvial sandstones in the Carboniferous of Scotland. However, Nio (1976) has also described similar bars from marine sandstone from Roda Sandstone Formation of the southern Pyrenees. In view of the faunal association (see Chapter Seven) a marine origin is postulated for this bar complex. The bar thickness at Locality 21/1 is 5m and this is the minimum water depth. In the North Sea bars up to 15m thick are seen in high water depths (Van de Graff, 1972; Nio, 1976; Level, 1980).

There is clearly a need to describe alluvial and marine bars in even greater detail than has been done so far, so that criteria for their distinction may be obtained.

TABLE 16. Vector mean, magnitude of vector mean (L), standard deviation (S) and variance (S^2) of Lower Saq.

Location	n	Vector mean (°)	L (%)	S (°)	S^2 (variance)
19-1	25	49°43'	79.3	41°	1681
17-2	106	76°30'	64.7	51°	2601
20-1	99	55°40'	90.9	26°	676
8	147	60°27'	60.4	58°	3364
16-1	75	52°28'	67.6	51°	2601
5	62	52°24'	84.2	36°	1296
21-1	120	52°32'	60	58°	3364
21-2	76	33°20'	87.9	34°	1156
1	452	51°21'	56.3	62°	3844
2	218	109°23'	60.4	58°	3364
ALL	1380	62°27'	63.4	54°	2916

TABLE 17. Vector mean, magnitude of vector mean (L), standard deviation (S) and variance (S^2) of Upper Saq.

Location	n	Vector mean (°)	L (%)	S (°)	S^2 (variance)
9	71	139°12'	63.5	55	3025
24-1	40	300°48'	37.6	81	6561
26-1	51	133°48'	86.5	35	1225
11	82	12°54'	63.7	54	2916
27	80	72°19'	69.8	49	2401
12	50	46°42'	91.9	26	676
TOTAL	353	59°30'	40	78	6084

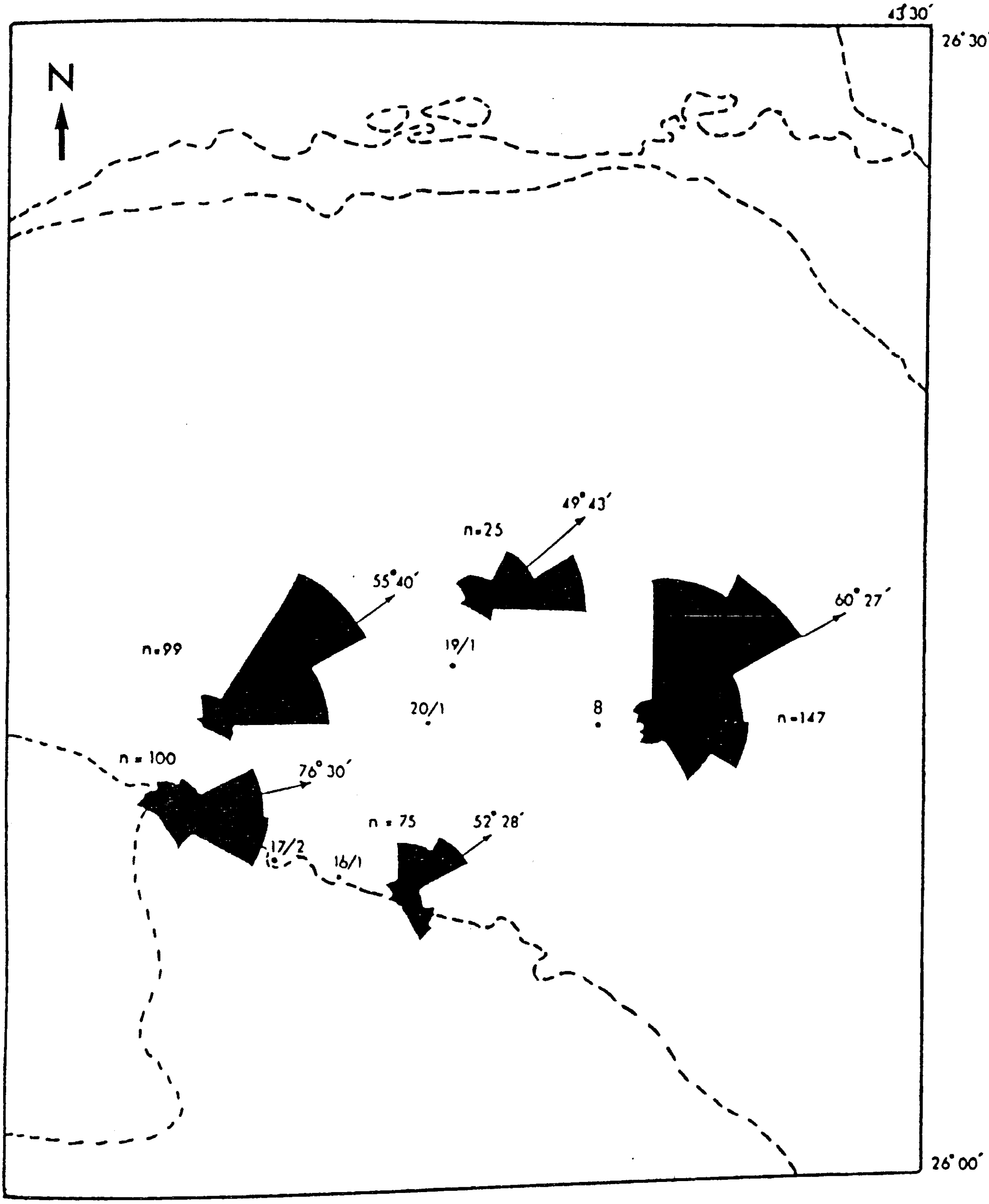


FIG. 40 Rose diagram to represent palaeocurrent of lower part of Lower Saq Sandstone.

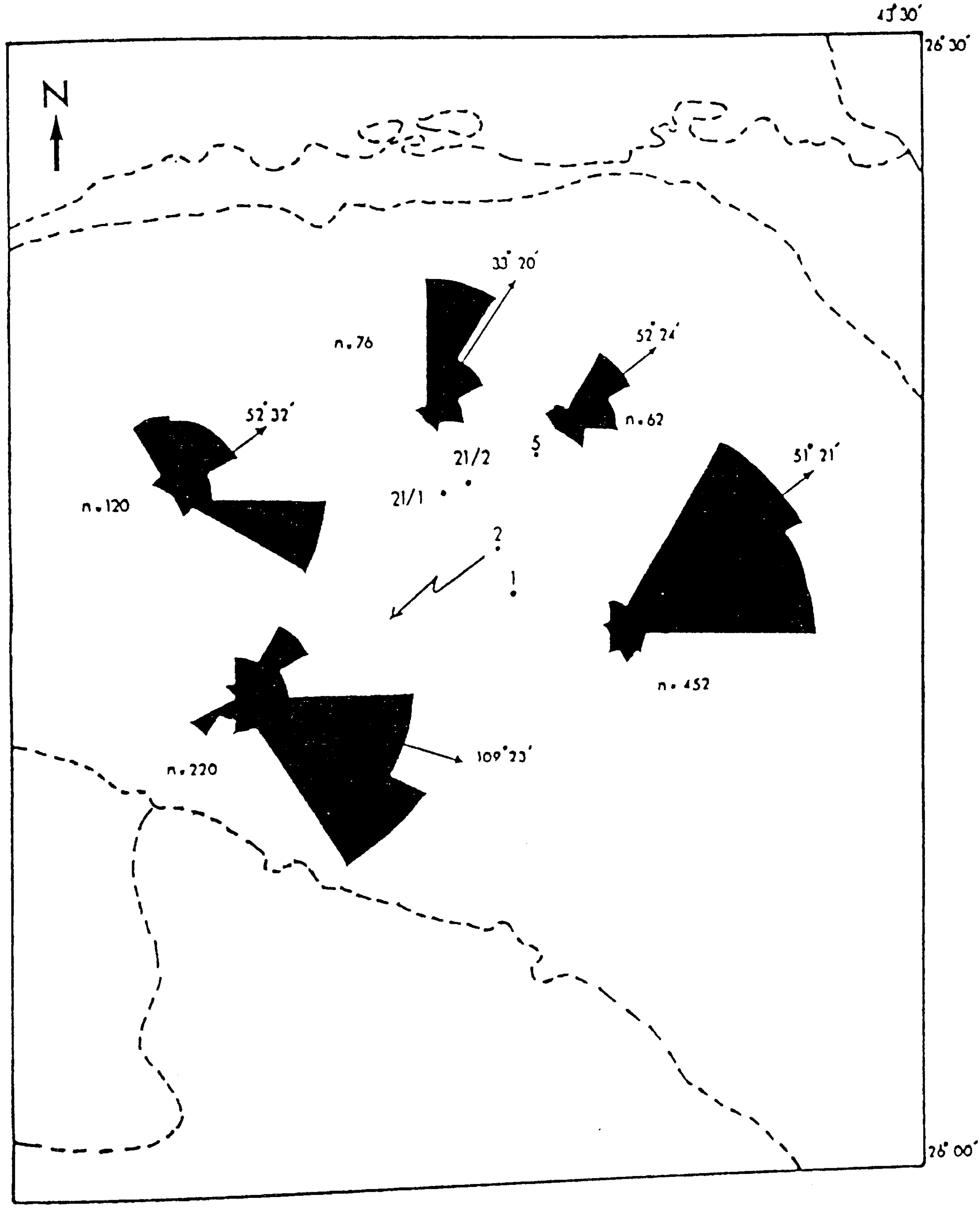


FIG. 41 Rose diagram to represent palaeocurrent of upper part of Lower Saq Sandstone.

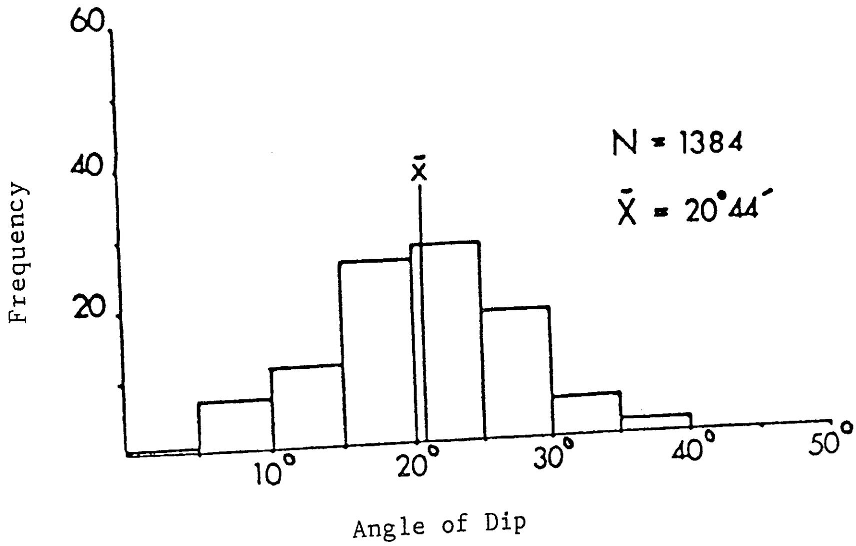


FIG. 42 Distribution of dip angle of cross-stratification of Lower Saq Sandstone.

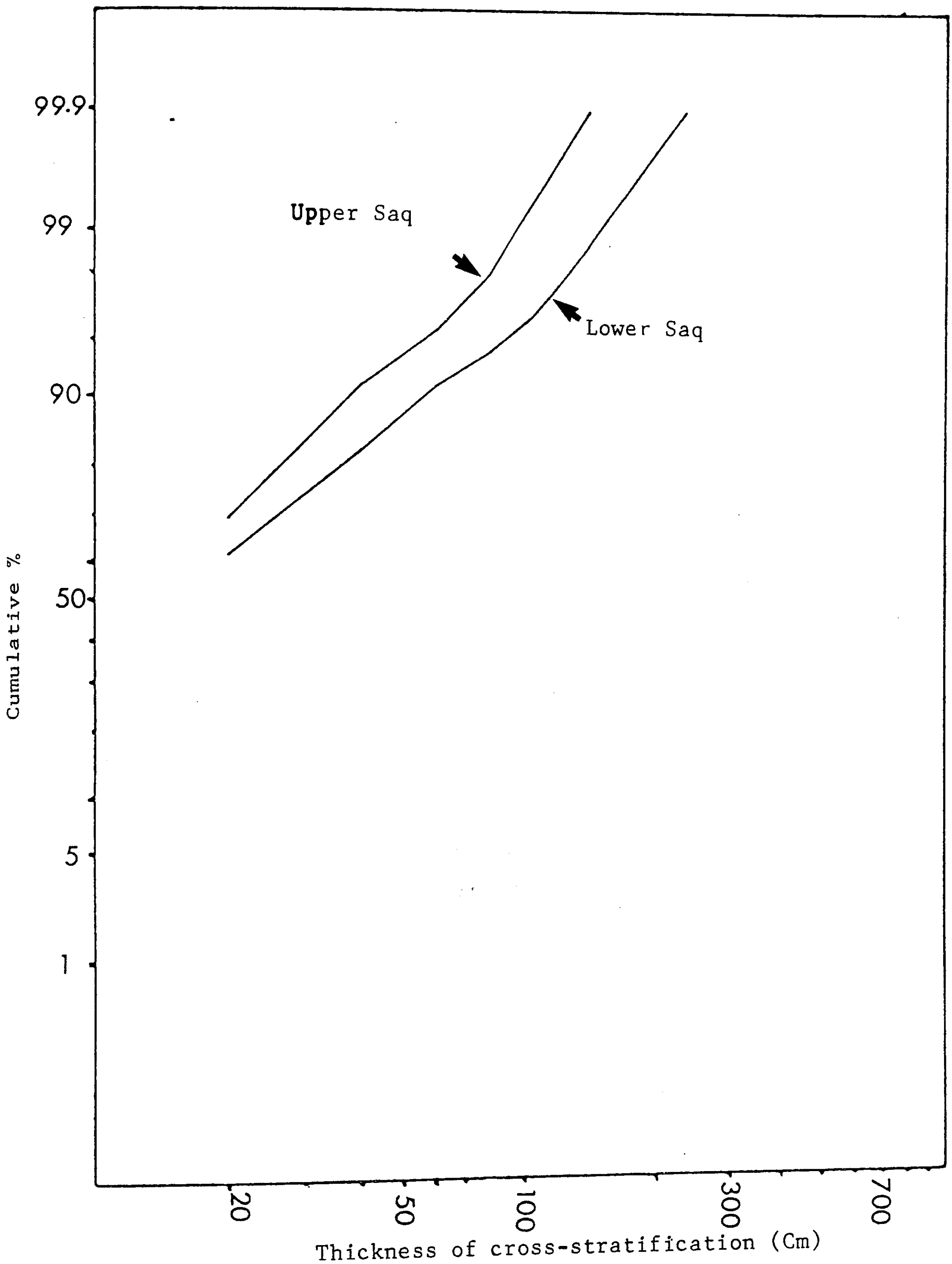


FIG. 43 Log probability plot of cross-stratification thickness.

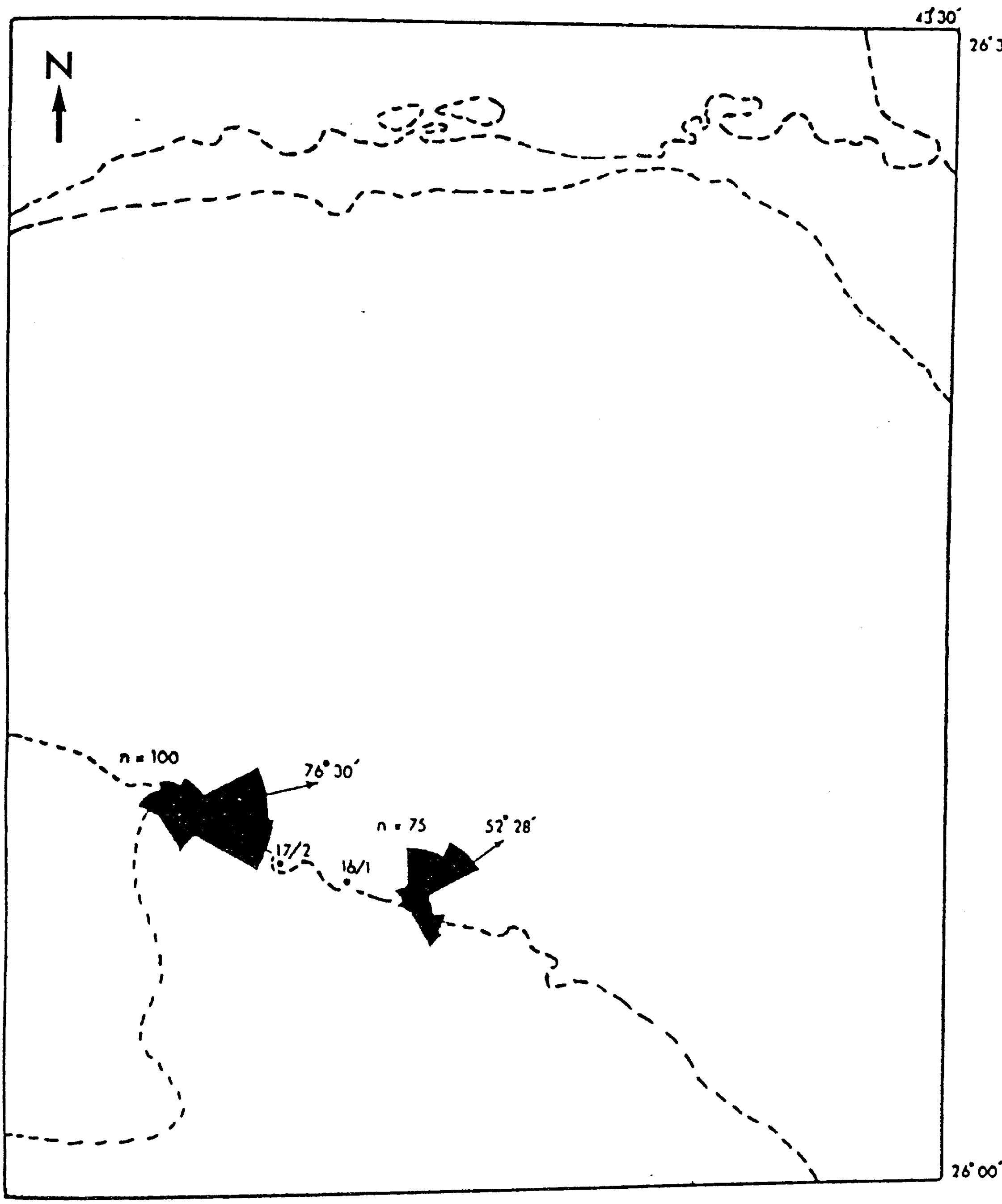


FIG. 44 Rose diagram to represent palaeocurrent of basal unit of Lower Saq Sandstone.

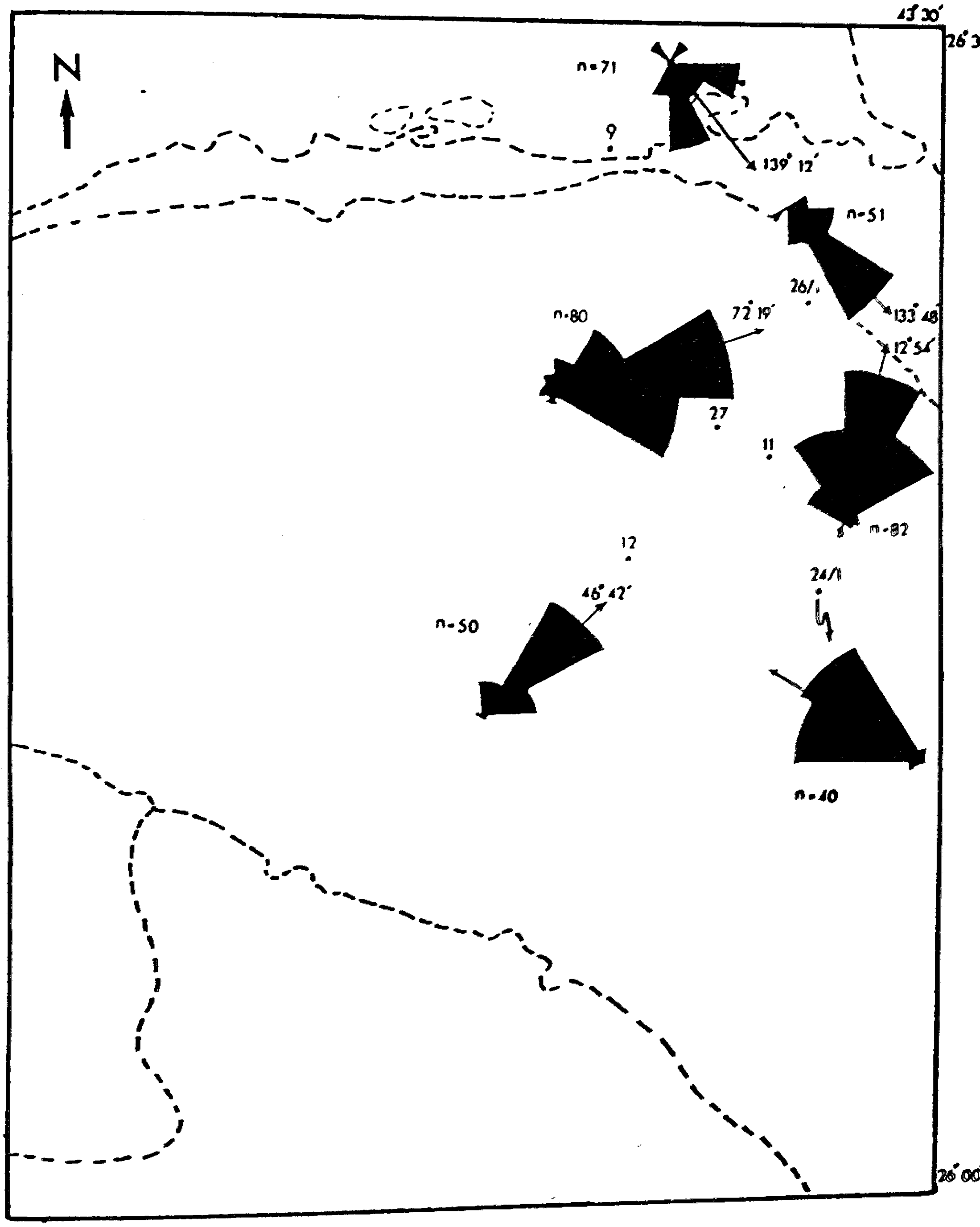


FIG.45 Rose diagram to represent palaeocurrent of Upper Saq Sandstone.

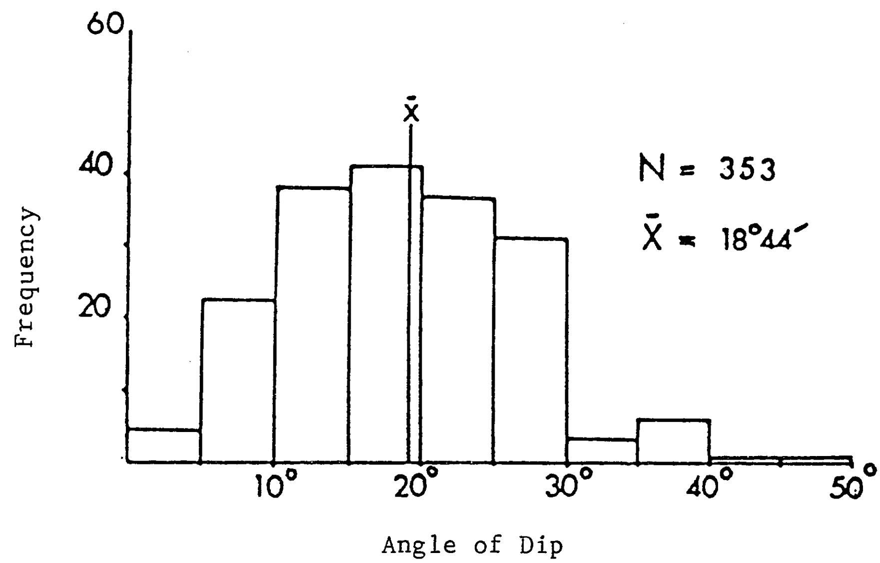


FIG. 46 Distribution of dip angle of cross-stratification of Upper Saq Sandstone.

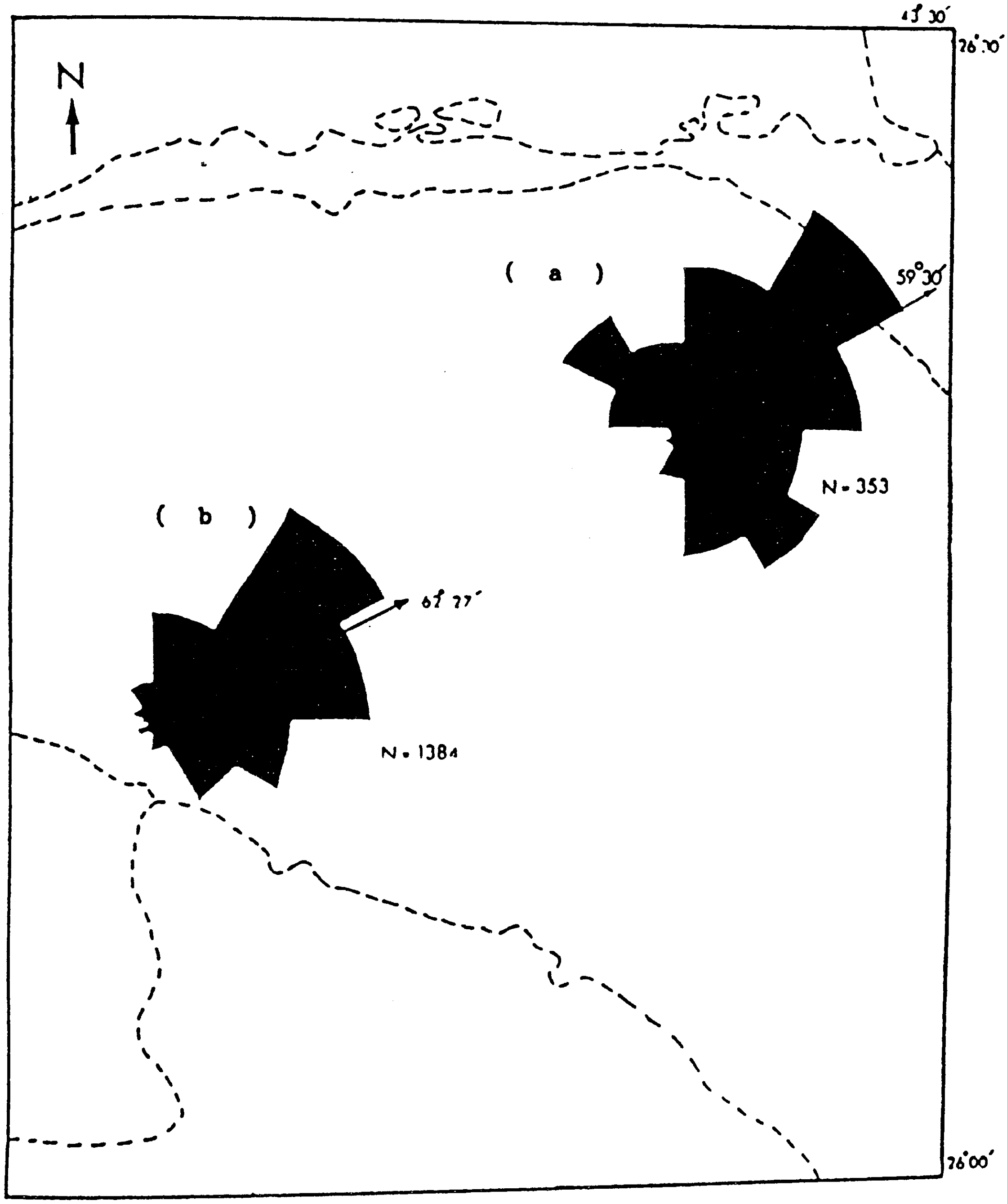
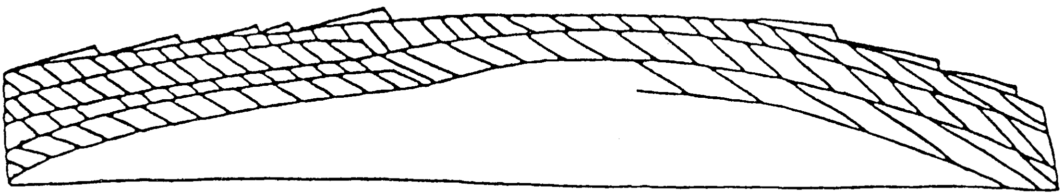


FIG. 47 Rose diagram to represent palaeocurrent of Upper (a) and Lower (b) Saq Sandstone.

A BAR STRUCTURE (LOWER SAQ)



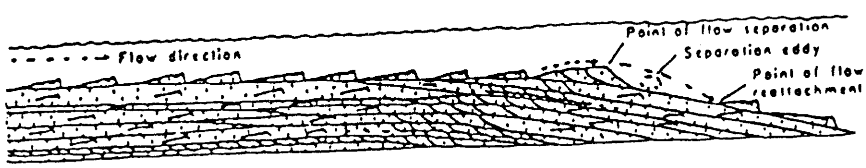
FACIES 1

1. amalgamation by over-tacking to form larger foresets.
2. bounding surface to sets dip upcurrent

FACIES 2

1. bounding surface dip downcurrent

B ALLUVIAL BAR (KIRK, 1983)



C MARINE BAR (NIO, 1976)

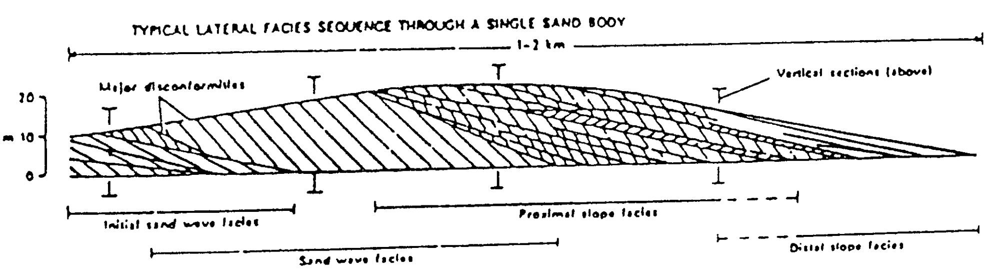


FIG.48 Structure of sedimentary bar from Lower Saq Sandstone (A) compared with a similar structure from fluvial bar (B) and marine bar (C)

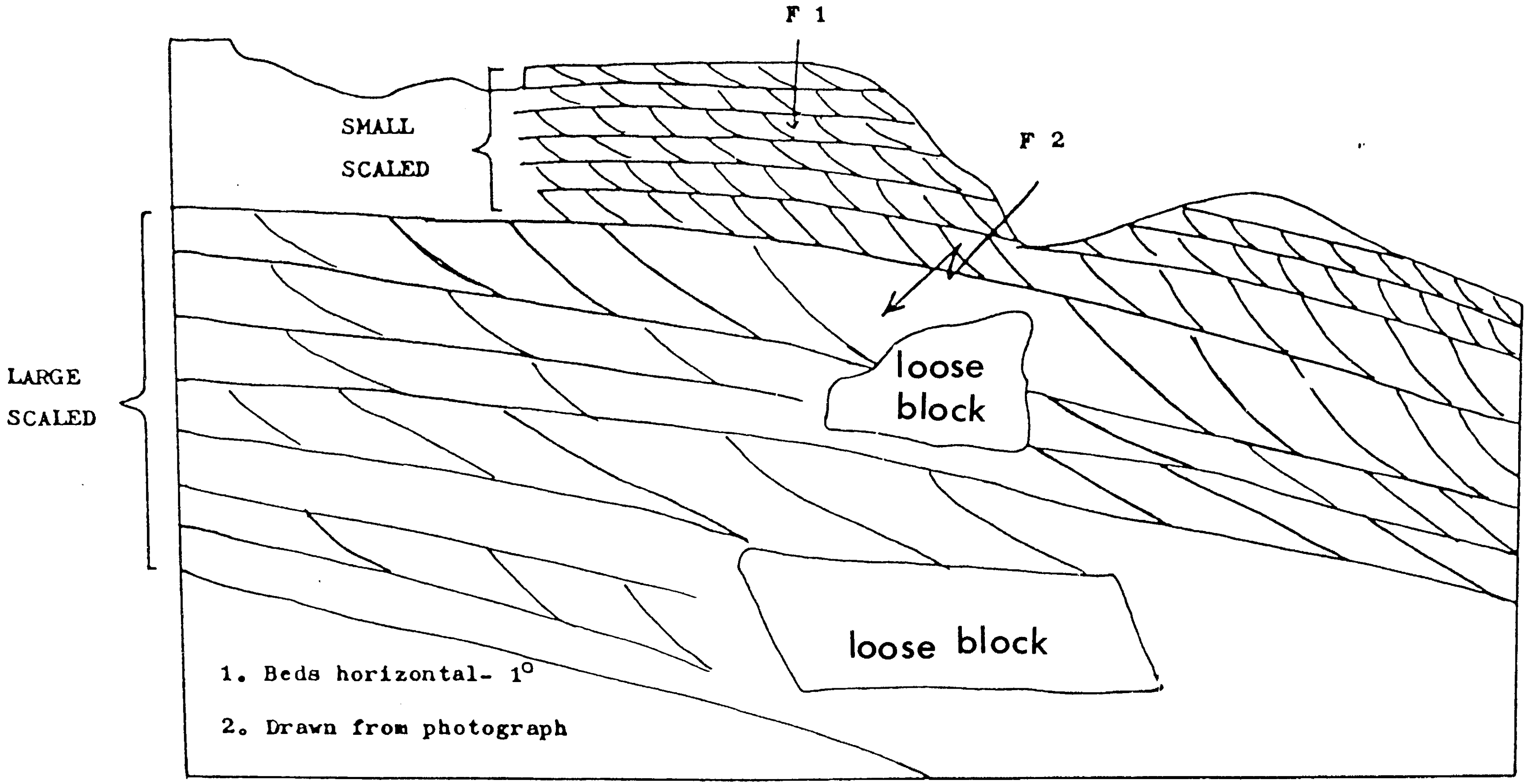


FIG. 49 Facies 2: on downstream part of bar with large-scaled foresets F2 with smaller F1.

CHAPTER SIX

HEAVY MINERALS IN SAQ SANDSTONE

Accessory heavy constituent minerals are usually scattered throughout the sandstone and may also occur as distinctive laminae in some deposits such as beach deposits (Plate 7). Rarely heavy minerals exceed one per cent and commonly form less than 0.1 per cent of the rock constituents.

Heavy detrital minerals are derived from the minor accessory minerals of the parent rock, and are surviving remnants of a population which may have originally included a wide variety of heavy mineral species.

The heavy minerals are extremely valuable constituents of sediments because they can provide clues to both the provenance and maturity of sediments, but may also be used, with caution, in correlation and palaeogeographical studies (Pettijohn, 1975).

Heavy minerals vary in their resistance to breakdown. Tourmaline and zircon, which often occur in comparatively large amounts in any source rock are resistant to mechanical and chemical attack.

Amphiboles and pyroxene on the other hand are often abundant constituents of some source rock, but offer little resistance to decay, so seldom survive beyond the first cycle. Since some heavy mineral survive the hazards of weathering, transport and diagenesis and occur in a restricted range of provenance types, they are most useful for source rock interpretation (Pettijohn et al., 1972).

The mineral suites characteristic of source rock types have been summarized in Table 18.

TABLE 18: Shows heavy minerals and related source rock type.

Source	Mineral suites
Acid igneous rocks	Apatite, Zircon (euhedral)
Ultra-basic igneous and some metamorphic rocks	Anatase, rutile, Magnetite, ilmenite
Pegmatite Reworked sediments	Tourmaline Rutile, zircon (rounded)
Dynamic metamorphic rocks	Andalusite, garnet

(After Pettijohn, 1975)

Method

Heavy minerals were obtained from 10 samples from each of Upper and Lower Saq Sandstone using the technique which is described below:

The rocks were crushed using a jaw crusher and mortar and pestle and then passed through a set of sieves (10, 140, 280 mesh size) using a ro-tap shaker for at least 15 minutes. The heavy minerals were then separated from the light by setting in bromoform (s.p. gr = 2.81). They were then washed, dried and put in an ultrasonic vibrator for 5-10 minutes in order to remove the coating.

The dominant heavy minerals recovered by this method are opaque minerals, zircon, tourmaline, rutile, apatite, epidote and sphene. (Plates 8, 9, 10).

Opaque minerals.

This is the dominant heavy mineral in the Saq Sandstone and it ranges in shape from sub-rounded to rounded in Lower Saq and rounded to well-rounded in Upper Saq Sandstone.. Magnetite comprises more than 90% of opaque minerals and the rest are ilmenite characteristic of an oxidizing environment and are dissolved readily in reducing environments (Miller and Folk, 1955).

Zircon.

Zircon is an ultra-stable mineral; it is very hard and inert and can survive much recycling (Folk, 1974).

Zircon constitutes 22% of the total heavy minerals in the Lower Saq and 25% of the Upper Saq Sandstone. It ranges in shape from euhedral (11%) to rounded (89%) in Lower Saq, and sub-rounded (6%) to well-rounded (94%) in Upper Saq Sandstone; most zircons are colourless with a variety of inclusions .

Tourmaline.

Tourmaline, also an ultra-stable mineral, averages 19% of the total heavy mineral population in Lower Saq and 16% in the Upper Saq Sandstone. It ranges in shape from euhedral (16% to sub-rounded (84%) in Lower Saq and sub-rounded (37%) to rounded (63%) in Upper Saq, and occurs in a variety of colours, yellow to pale brown, olive and blue (Schörlite).

Murray (1972) reported that yellow and brown tourmaline may be exclusive to rocks of metamorphic origin.

Rutile.

Rutile is the fourth in abundance of heavy minerals in Saq Sandstone. It comprises 13% of total heavy minerals in the Lower Saq Sandstone and 10% in the Upper. It ranges in shape from sub-rounded (70%) to rounded (30%) in the Lower Saq and rounded (83%) to well-rounded (17%) in Upper Saq Sandstone. The colours range from reddish-brown to dark red.

Apatite.

Apatite is moderately stable, colourless, prismatic to rounded, parallel extinction.

Epidote.

Epidote is colourless to yellowish-green, granular aggregates, high relief.

Sphene

Sphene is colourless, most grains in Upper and Lower Saq Sandstone are sub-rounded to rounded.

The distribution of heavy minerals is given in Table 19. There is a little vertical change in which the opaque minerals, zircon and apatite, increase upward while tourmaline, rutile, epidote and sphene decrease.

The roundness of heavy minerals changes vertically in the profile through the Saq Sandstone. They are rounded in Lower Saq and well-rounded in the Upper Saq Sandstone.

From these data the following conclusions are drawn:

1. The total Saq Sandstone comprises a resistant, mature heavy mineral assemblage, but the presence of euhedral zircon as well as rounded zircon, could be interpreted as we have a first cycle as well as a polycyclic source.

2. The heavy mineral assemblage becomes more mature, and grains become better rounded in Upper Saq Sandstone.

In view of the fact that the Upper Saq Sandstone is characterized by (a) Low feldspar content $< 2\%$, (b) low polycrystalline quartz $< 9\%$, (c) less strained quartz than Lower Saq and (d) beach environment, it is concluded that the Upper Saq Sandstone is more mature than the Lower Saq Sandstone and that the heavy mineral assemblages indicate a combination of a major pre-existing sedimentary source as well as a minor metamorphic source.

TABLE 19. Distribution of heavy minerals in Upper and Lower Saq Sandstone.

Heavy Minerals	Lower Saq %	Upper Saq %
Opaque minerals	37	44
Zircon	22	25
Tourmaline	19	16
Rutile	13	10
Apatite	1	2
Epidote	4	3
Sphene	2	1

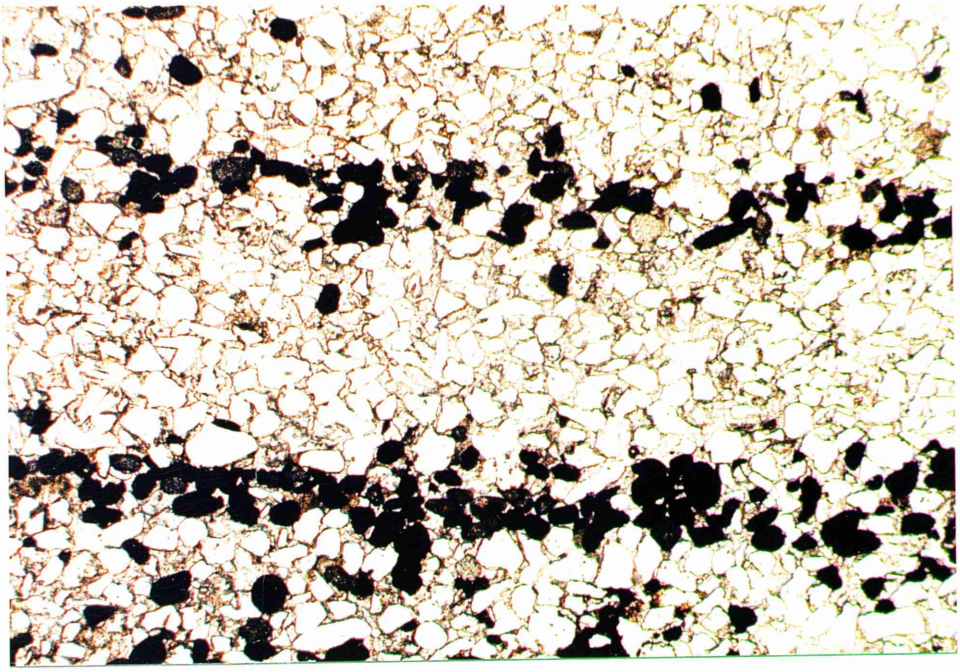


PLATE No. 7: Lamina of heavy mineral in beach deposits (Upper Saq Sandstone) Cross nicoles x 40.

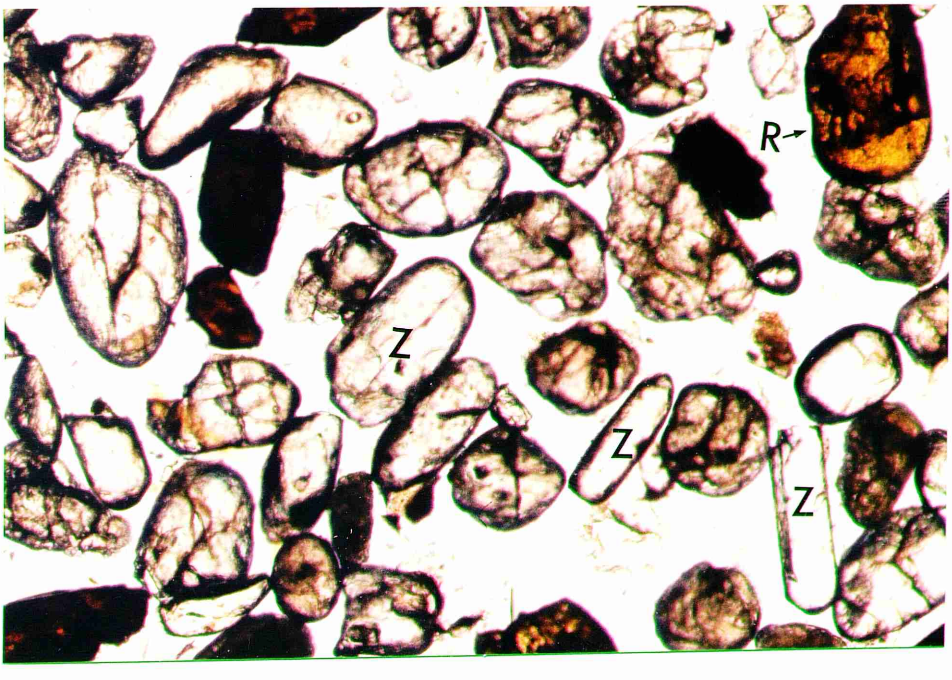


PLATE No. 8: Heavy mineral from Upper Saq Sandstone (Z: zircon; R: rutile) x 40.

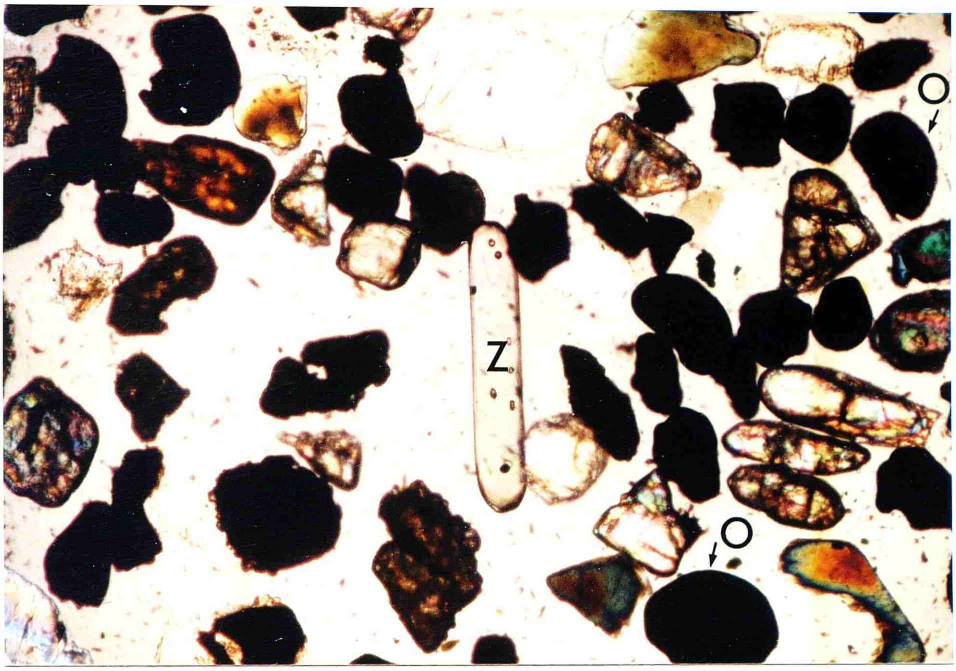


PLATE No. 9: Heavy mineral from Upper Saq Sandstone (O: opaque; Z: zircon) x 40

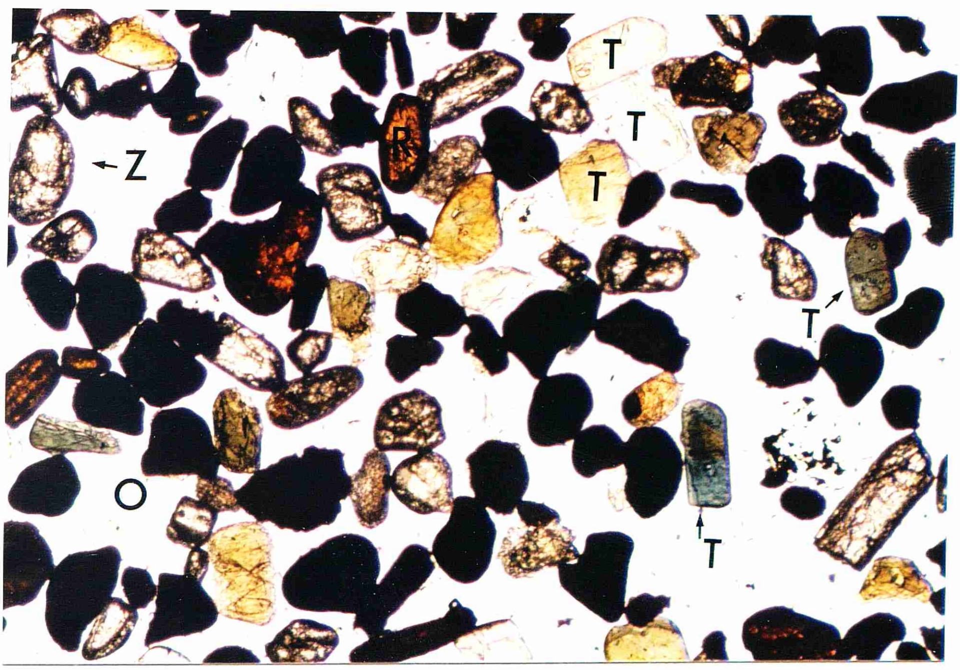


PLATE No.10: Heavy minerals from Lower Saq Sandstone (O: opaque; Z: zircon; T: tourmaline; R: rutile) x 40

CHAPTER SEVEN

DEPOSITIONAL ENVIRONMENT & PALAEOGEOGRAPHICAL SETTING OF SAQ SANDSTONE.

The Saq Sandstone is a laterally extensive blanket of mature quartz arenite which can be traced 1200km along strike from south Jordan ($31^{o}30'$N) to AD-Dwadimi ($24^{o}29'$N) and finally disappears under a Permian Khuff Formation. Within this wide area the sandstone varies very little in thickness from 700m in Jordan to 600m in Saq.

A marine environment is envisaged for part or all of this sandstone, for the following reasons:

1. The presence of rounded and abraded brachiopod shells at some horizons in Upper Saq Sandstone (Plate 13).

2. Abundance of trace fossils (Cruziana, Plates 11, 12) at two levels in the Saq Sandstone. These trails are produced by trilobites, and many quartzose sandstones have trails but with no body fossils (e.g. Ordovician Armorican quartzite in Brittany). In the Saq, as with other formations, the shells may have been dissolved out during diagenesis, so trace-fossil evidence is particularly important in these circumstances. Trilobites are exclusively marine organisms and their tracks can be considered to be direct evidence of marine conditions (Sielacher, 1970; Selly, 1970; Goldring, 1985).

3. The presence of beach deposits, comprising low-angled, often laminated, cross-strata dipping at north-east $< 7^{o}$. These strata have many heavy mineral bands (Plates 7, 14), some cutting each other on various, but low angles. Thompson (1937); Rao, 1957; Schmidt

and Asad, 1962; Emery and Noakes, 1968; Clifton, 1969; Hails, 1969; Hobday and Tankard, 1978) have identified deposits with the same characteristics as Upper foreshore sandstone. These Upper Foreshore sandstones are found in the Upper Saq Sandstone.

4. The compositional maturity of the sandstone:

Mineralogical maturity in sandstone may be produced by inheritance from a pre-existing mature sandstone, but the consistent maturity of the sandstones in these deposits suggests that the environment was too energetic to allow first cycle sand from the basement to be present. Studies by Russell (1937) and Pollack (1961) have demonstrated that the mineralogical composition of fluvial sand does not change appreciably over distances of transport of 1083 miles and 675 miles respectively (Sweet et al. 1971). Thus the high maturity of the sand could be due to the action of wave or wind, and it is possible that this Cambro-Ordovician sea reworked aeolian sandstones as it migrated over the platform of Precambrian rock.

5. Palaeocurrents:

The unidirectional palaeocurrent is the only line of evidence which is not consistent with a marine environment, the reasons for which have been mentioned in Chapter Five.

6. The presence of algal laminates in different horizons in Saq Sandstone.

In summary, the Saq Sandstone is thought to have formed in an extensive shelf environment which included some near-shore beach deposits. Sand bars, similar to sub-tidal bars described by other workers, have been found but no certain supra-tidal sediments have yet been seen. However, in an environment of this type aeolian dunes, lagoons and barrier deposits are possible (Fig. 50).

There are four main lithological associations in the Saq Sandstones which can now be interpreted in terms of a shallow marine tidal shelf:

1. Fine gravels and shell beds. These occur at intervals in the Saq sequence, mainly when they occur in alternation with sandstones. These are thought to be the lag-sheets associated with scour surfaces in zones of bed load parting (although in Saq Sandstone there is no symmetrical bed load parting). They may represent the zone of gravel with sand ribbons described by Stride (1963) and Kenyon (1970).

2. Cross-stratified sand. This association is dominant in the Saq Sandstone. It comprises cross-strata, mainly 2m thick, where bounding surfaces are variously inclined or lenticular. These beds may be produced by megaripples.

3. Areas of sediment bars. Here various cross-stratal units combine into larger scaled bed forms, perhaps similar to those described by Houbolt (1968).

4. Shales, getting dark, sometimes red (by post-depositional weathering?), occur in association with 3. above. These may accumulate in the down current regions beyond the zone of 3., where strong tidal currents are not present. The possible integration of these associations are illustrated in Fig.51, where they are compared with similar associations described by Anderton (1976).

PALAEOGEOGRAPHICAL SETTING

The Arabian Peninsula has been interpreted as a continental platform in Cambrian to Ordovician times. Sedimentation was= dominantly terriginous, but towards the east in Iran and the Arabian Gulf carbonates and evaporite deposits become an important part of the geological record (Figs. 53 to 57). A major source area was thought to have existed to the west over eastern Africa, and towards the north deeper water, with thick shales, sandstones and limestone occurs in Syria and Turkey.

The palaeogeography of the Middle East, summarized by Holland (1981) is as follows:

In the Infracambrian and Cambrian, four major marine transgressions are indicated by marine faunas. The oldest is represented by the Infracambrian Hormuz Salt Formation and its carbonate equivalents in Oman, the Arabian Gulf, and Iran. The presence of algal stromatolites and massive dolomites, relatively free of significant terriginous detritus, strongly suggests a genesis in relatively shallow water. In the other areas of the Middle East, mainly sedimentary rocks of continental origin.

The next marine transgression is of middle (to late) Early Cambrian age as indicated by the faunal assemblage with redlichiid trilobites and Cruziana distributed all over Iran and as far to the west as Jordan. Intercalation of oolites indicate shallow water condition. Contemporaneously, in Arabia continental (to littoral) environments prevailed, and in Turkey non-fossiliferous carbonate and clastics were probably formed in marine environments. The Middle Cambrian transgression mainly affected the southern part of Turkey: in Afghanistan, a temporarily lagoonal environment prevailed during the Middle Cambrian. Except for Oman, all over the Arabian Peninsula continental condition continued.

Late Cambrian transgression left fossiliferous carbonates only in Iran and Afghanistan, which the oolites, massive limestones and shell layers indicate shallow water conditions, while continental environments continued in the entire Arabian Peninsula.

This study has resulted in a modification of the palaeogeography of Late Cambrian to Early Ordovician times (Fig. 52). These modifications are:

1. There is no evidence for the 'continental-littoral' band of rock as illustrated in Figures 53-57. This has been interpreted as a band of littoral-tidal shelf deposits.

2. The 'source area' has had to be moved further to the West and the Saq Sandstone seen to be a transgression on it.

3. The 'source area' is probably not a source in the same sense as a mountain belt - but a broad plain or peneplain, over which the Cambrian sea transgressed.

4. There is no direct evidence for the age of the Saq Sandstone, so it may represent any interval or intervals from Early Ordovician to Early Cambrian.

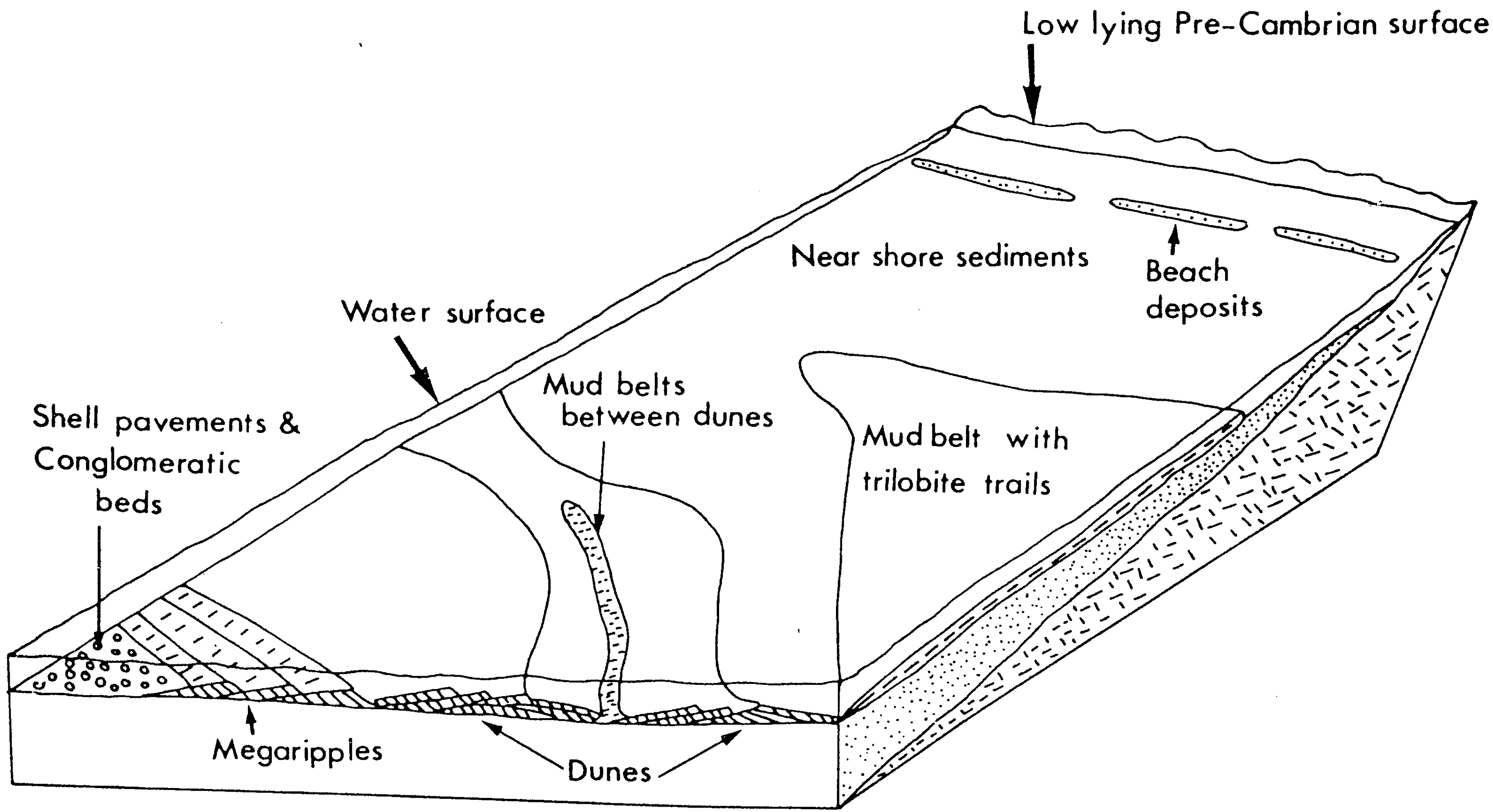


FIG. 50 Idealized reconstruction of shelf model of Saq Sandstone

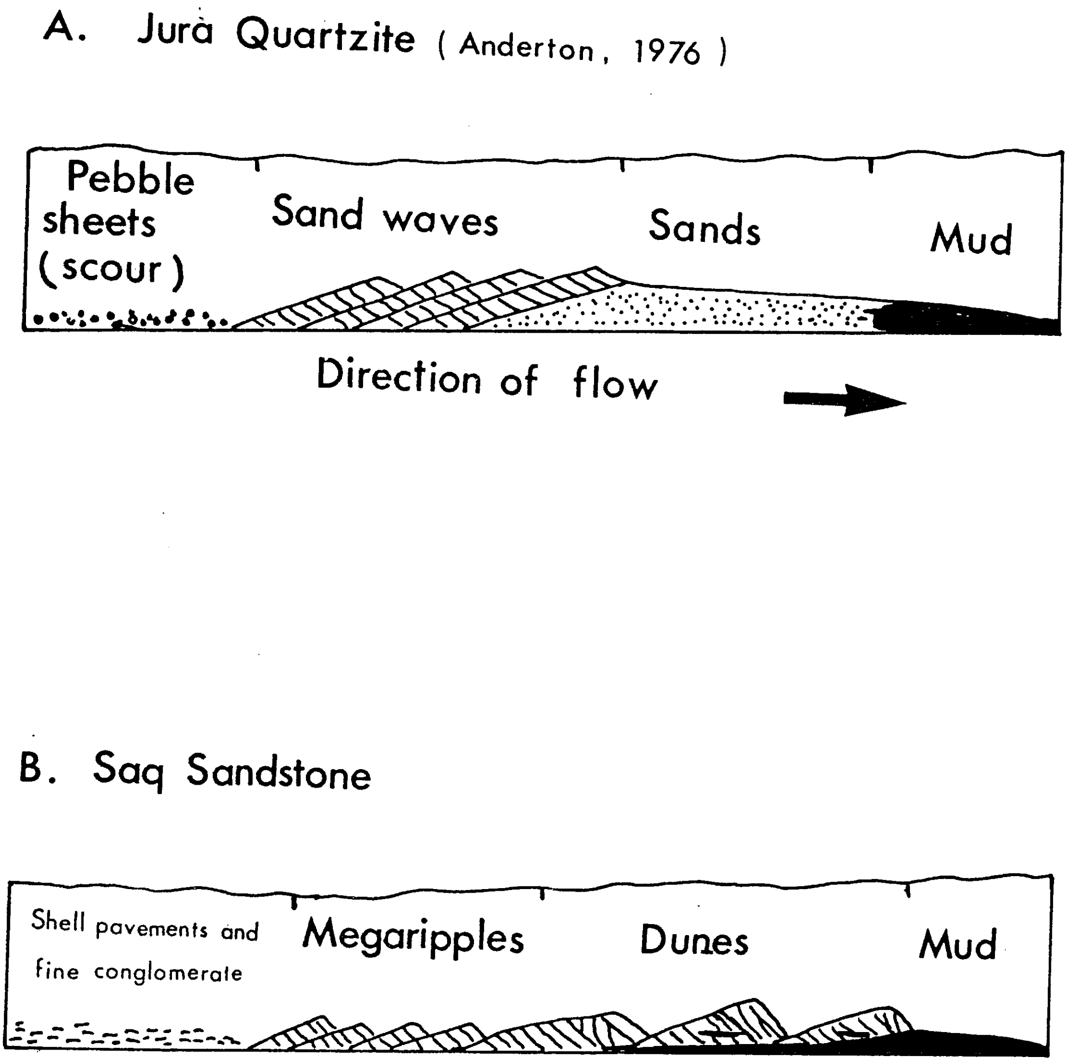


FIG. 51 Model illustrating major sedimentary facies of Saq Sandstone (B) compared with similar facies of Jura Quartzite (A).

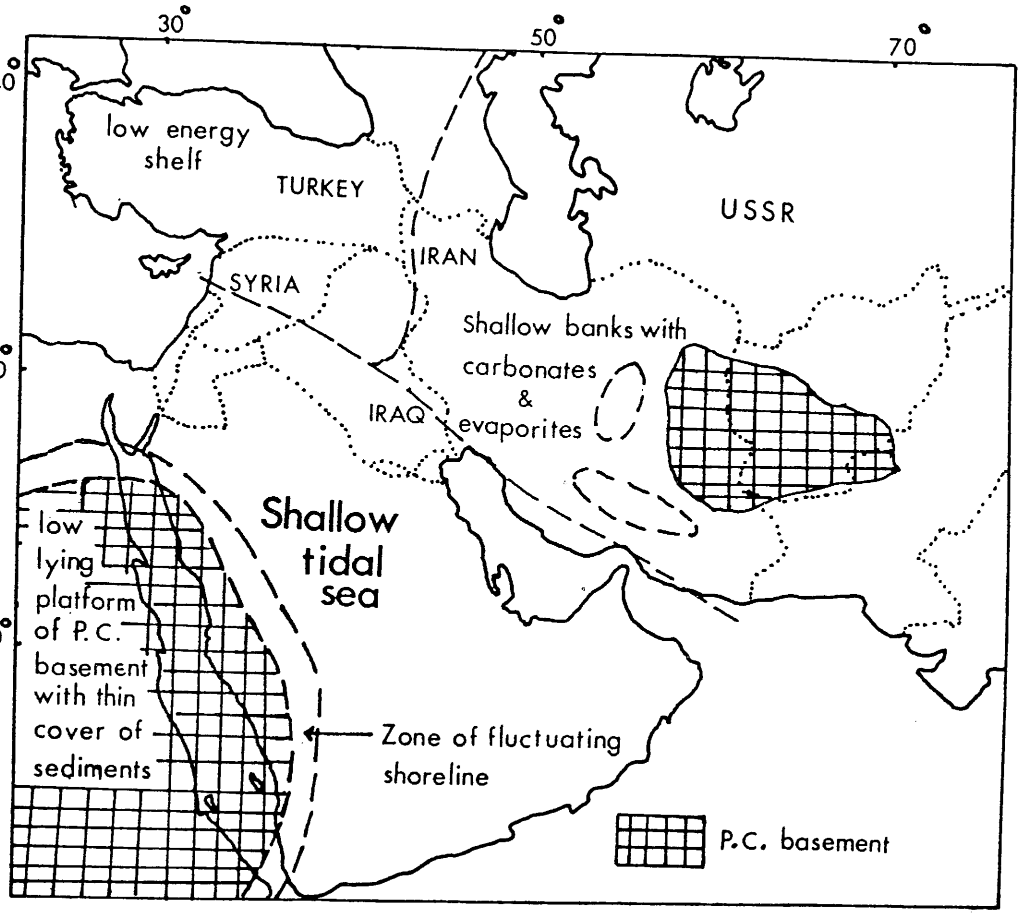


FIG. 52 Palaeogeographical map of Late Cambrian to Early Ordovician.

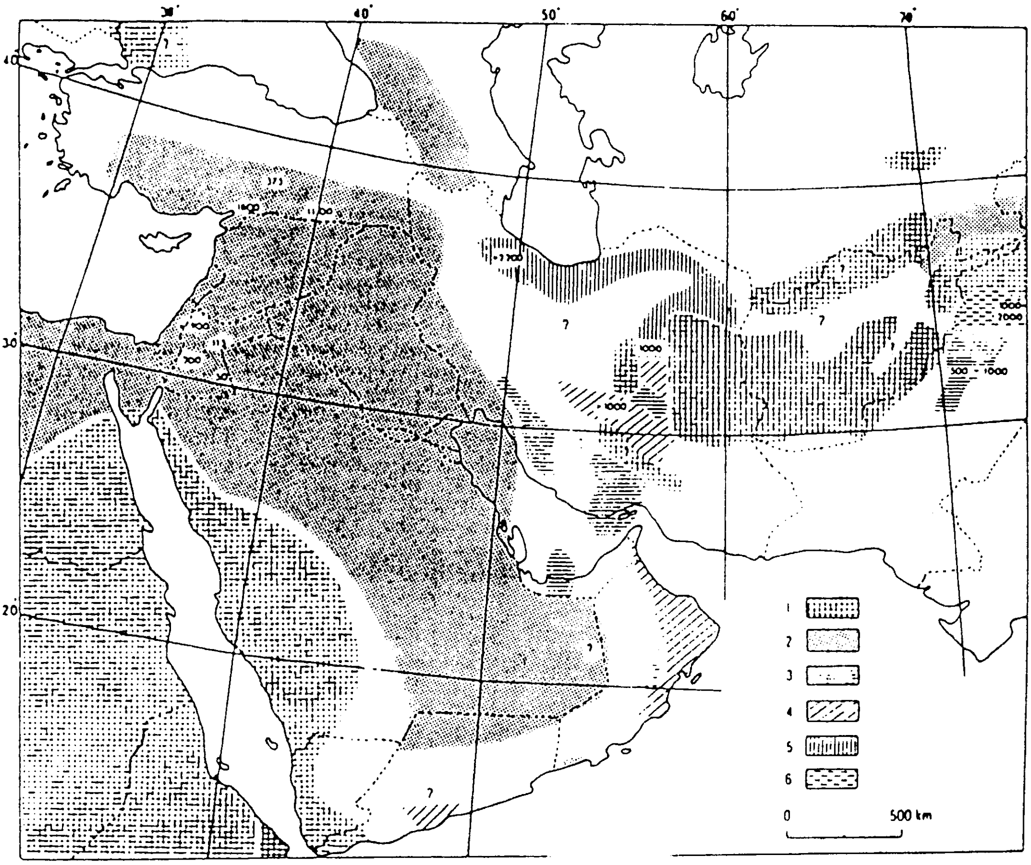


FIG. 53 *Palaeogeography*—late Pre-Cambrian to early Early Cambrian. 1, Potential source area; 2, continental to littoral environment (conglomerate, sandstone, shale, regionally volcanics); 3, lagoonal environment (shale, dolomite, gypsum, salt); 4, alternating continental and marine environment (conglomerate, sandstone, volcanics, limestone, dolomite, gypsum, salt ?); 5, mainly marine environment (dolomite, shale); 6, marine environment (shale). Thicknesses in metres.

(after Holland, 1981)

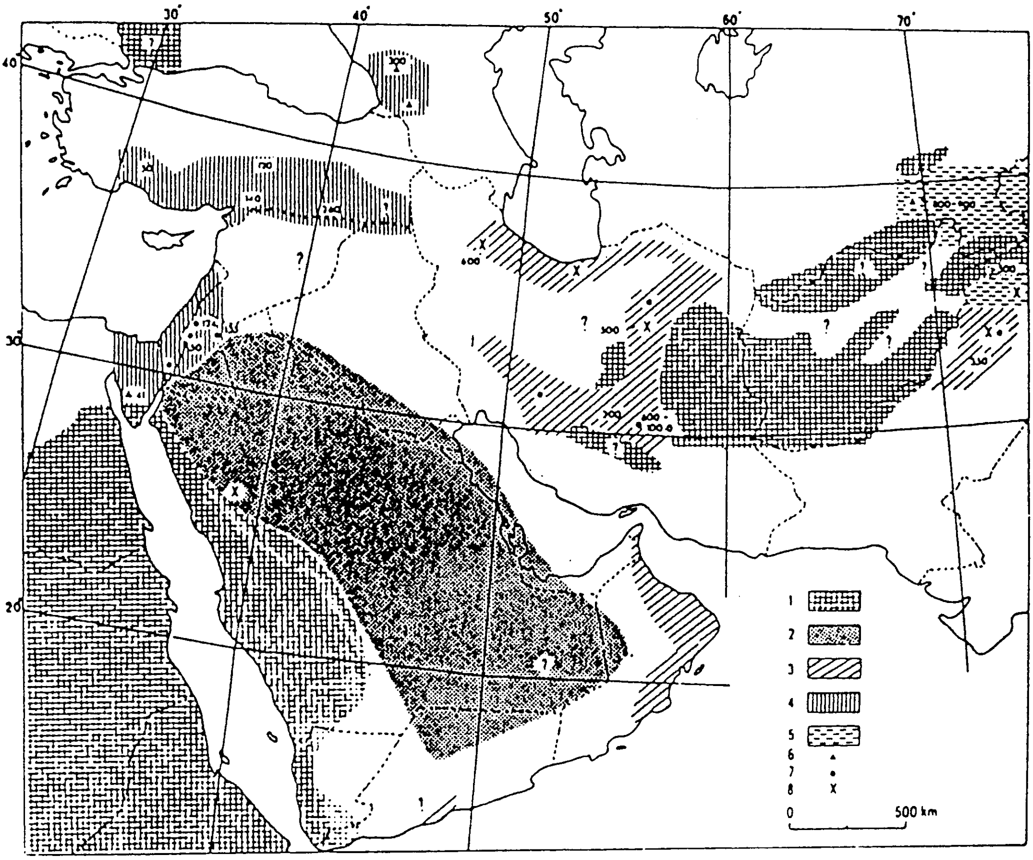


FIG 54 *Palaeogeography*—middle to late Early Cambrian. 1, Potential source area; 2, continental to littoral environment (sandstone, shale); 3, marine following continental environment (sandstone, shale, dolomite, limestone); 4 and 5, marine environment; 4, dolomite, limestone, shale, sandstone; 5, shale, sandstone; 6, Archaeocyathidae (in Soviet Union associated with Siberian and south Asiatic faunas); 7, Redlichiidae, Ptychopariidae, *Orthotheca* (south Asiatic faunas); 8, *Cruziana*, *Rusophycus*, and other trace fossils. Thicknesses in metres.

(after Holland, 1981)

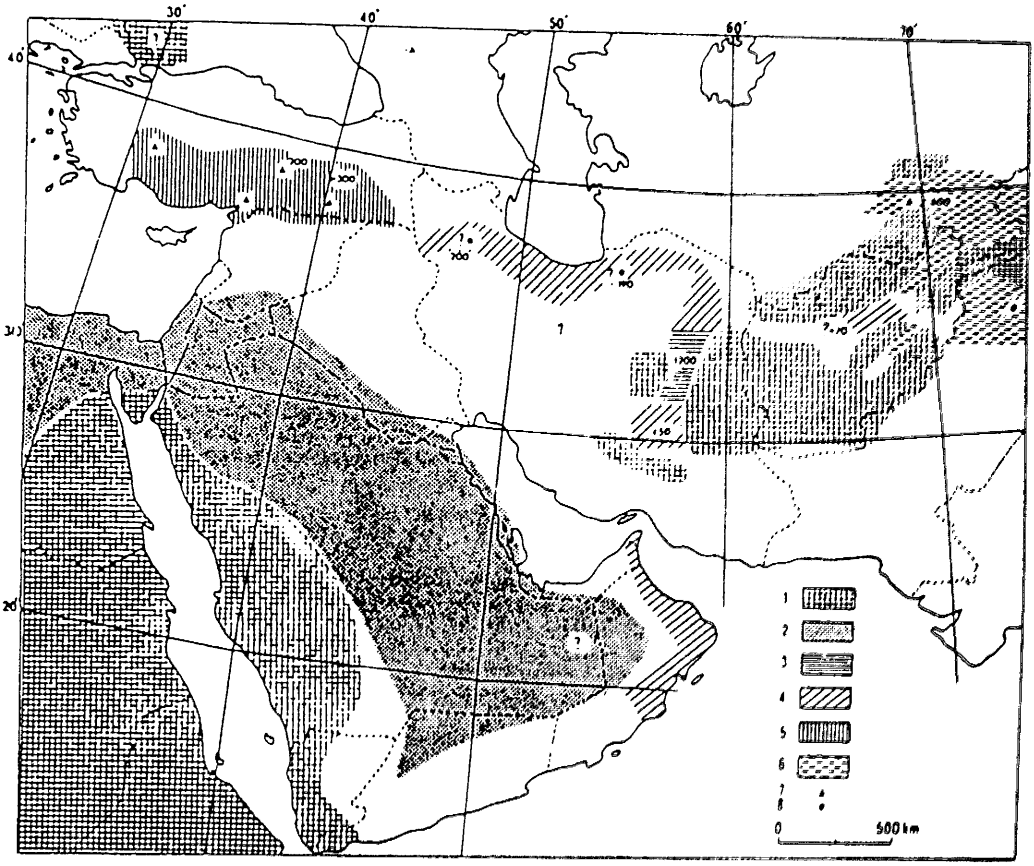


FIG. 55 *Palaeogeography*—Middle Cambrian. 1, Potential source area; 2, continental to littoral environment (sandstone, shale); 3, lagoonal to marine environment (dolomite, dolomitic marl with gypsum, limestone); 4–6, marine environment; 4, dolomite, dolomitic marl, limestone; 5, limestone, shale sandstone; 6, shale with intercalations of limestone; 7, faunas mainly composed of Atlantic elements; 8, faunas composed of south Asiatic and Atlantic elements. Thicknesses in metres. (after Holland, 1981)

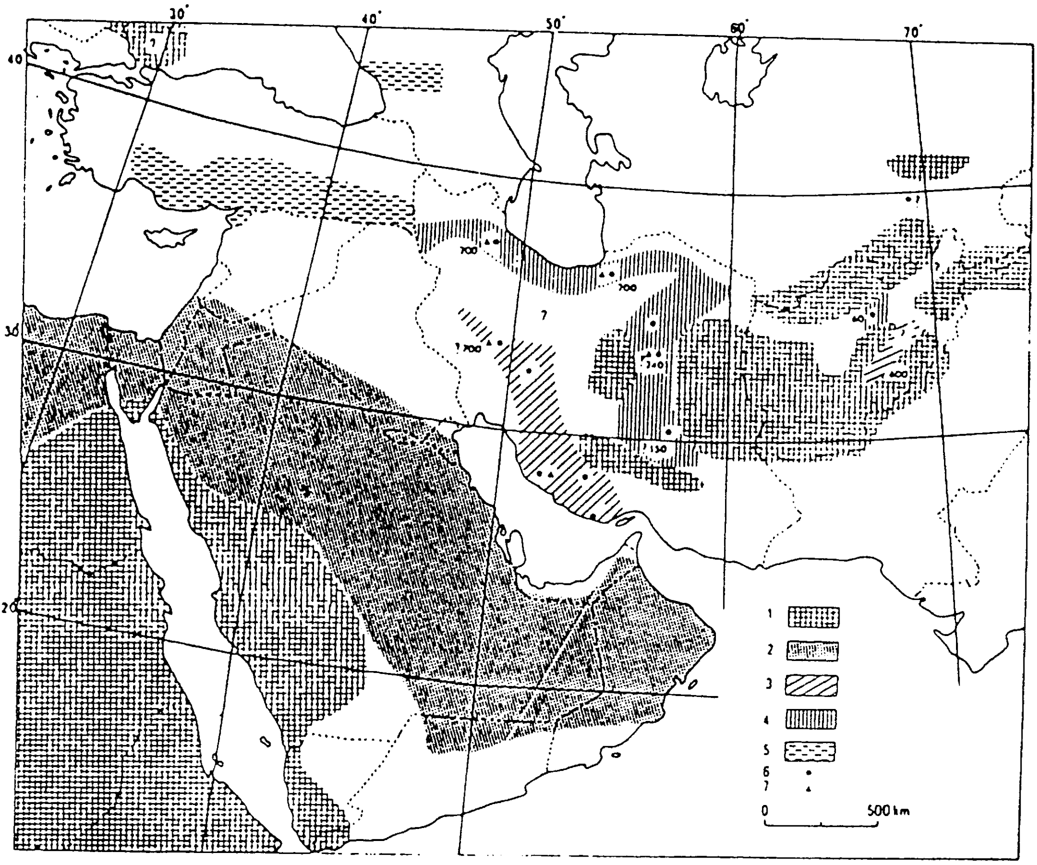


FIG 56 *Palaeogeography*—Late Cambrian. 1, Potential source area; 2, continental to littoral environment (sandstone, shale); 3–5, marine environment, 3, sandstone, limestone, dolomite; 4, limestone, marl; 5, sandstone, shale; 6, early Late Cambrian faunas (Kushanian); 7, late Late Cambrian faunas (Changshanian to Daizanian). Thicknesses in metres.

(after Holland, 1981)

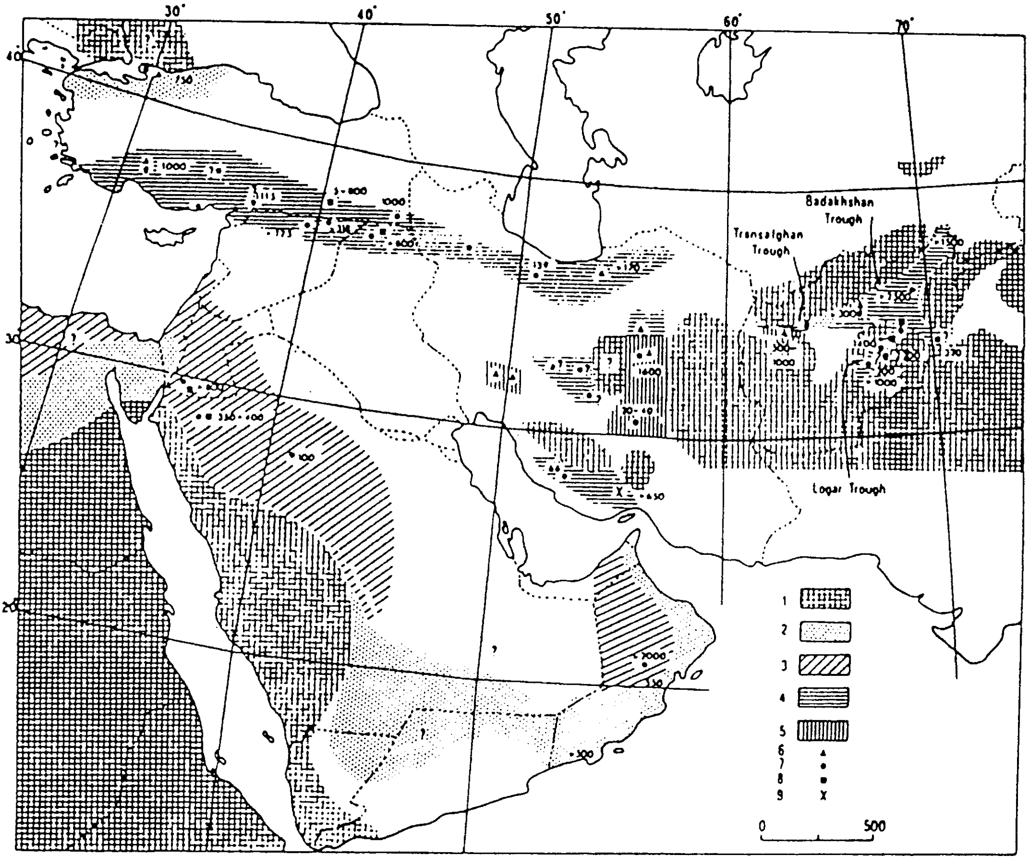


FIG. 57 Ordovician palaeogeography. (1) Potential source area; (2) continental to littoral environment (conglomerate, sandstone, shale); (3)-(5) marine environment; (3) sandstone, shale; (4) quartzite, sandstone, shale, sandy limestone; (5) predominantly marl and limestone; (6) Tremadoc faunas; (7) Arenig to Llandeilo faunas; (8) Caradoc to Ashgill faunas; (9) trace fossils. Total thicknesses in metres. In north-western Saudi Arabia, the boundary between Cambrian and Ordovician rocks is uncertain. (after Holland, 1981).

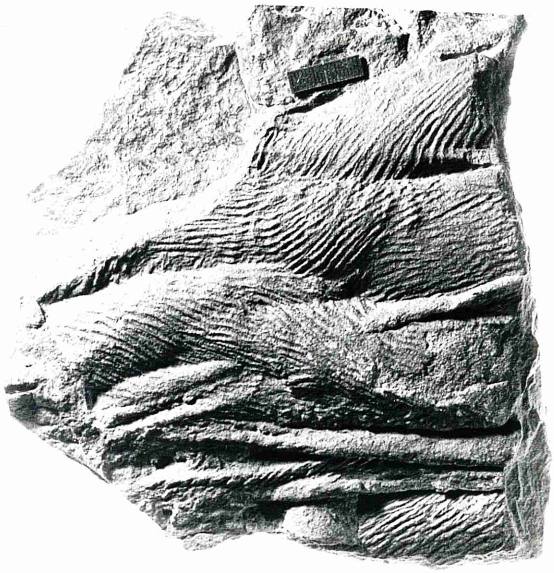


PLATE No. 11 Trace fossils (Cruziana) from Upper Saq Sandstone

PLATE No. 12 Trace fossils (Cruziana) from Lower Saq Sandstone

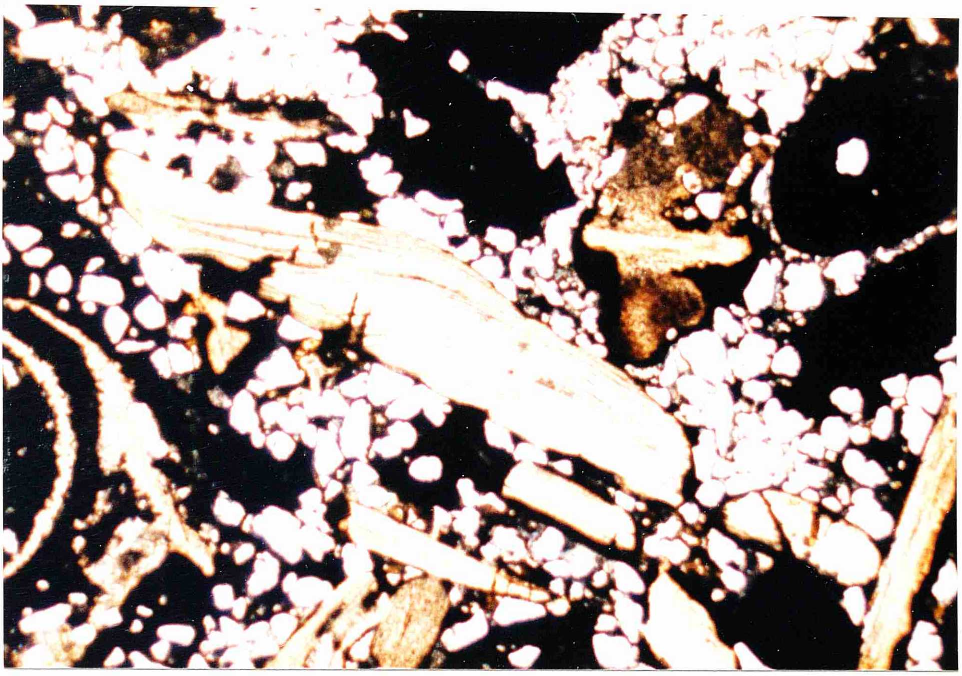


PLATE No. 13 Debris of brachiopod shell (Upper Saq Sandstone) x 40

PLATE No. 14 Beach deposits (Upper Saq Sandstone).

CHAPTER EIGHT

CONCLUSIONS

1. The Cambro-Ordovician Saq Sandstone is a blanket quartz-arenite covering at least 90,000 km^2 of Precambrian basement.

2. There is evidence in beaches, algal beds, fossils and trace-fossils of marine origin for at least part of the Saq Sandstone. Most of the sequence is abundantly cross-stratified and was probably laid down in a tidal shelf. Bipolar cross-strata are not seen, so that a symmetrical tide is assumed.

3. The cross-strata are arranged in large scaled bed Forms which resemble the subtidal bed form described by other workers, but which also resembles the bed forms produced in rivers. There is a need for further research to determine the difference between the structures produced in these diverse environments.

4. The Saq Sandstone, which is resting unconformably on the Precambrian, contains very little detritus from it. The basal breccia is often < 1 meter, and lithic fragments from the basement do not persist upward in the sandstone. This observation suggests (a) that the Precambrian was eroded to a planar surface which was different from the cycle which deposited the quartz-arenite (b) the quartz-arenite were derived from a pre-existing sandstone. This conclusion finds support in some of the petrographic details.

5. The Saq Sandstone is an upward maturing sequence. The petrography study shows that the quartz increases upward from 85% in Lower Saq to 88% in Upper Saq and the Geochemistry shows the SiO_2 increase upward.
The unstable minerals such as feldspars decrease upward and also the assemblage of heavy minerals which are more mature in Upper Saq than in the lower part.

6. Sandstone resembling the Saq are found abundantly on the African craton. They are found in Jordan, Al-Jerrea, Moraco and record a time when the early accretions of arcs and other terranes had become stabilized into an extensive, cohesive craton.

REFERENCES

ALLEN, J.R.L. 1963. The classification of cross-stratified units units with notes on their origin. Sedimentology 2, 93-114.

_____ 1970. The avalanching of granular solids on dune and similar slopes. J. Geol. 78, 326-351.

AMARAL, E.J. & PRYOR, W.A. 1977. Depositional environment of the St Peter Sandstone deduced by textural analysis. J. sediment. Petrol. 47, 151-180.

ANDERTON, R. 1976. Tidal shelf sedimentation: an example from the Scottish Dalradian. Sedimentology, 23, 429-459.

BANKS, N.L. 1973a. Tide-dominated offshore sedimentation, Lower Cambrian, North Norway. Sedimentology, 20, 213-228.

BASU, A., YOUNG, S.W., SUTTER, L.J., GALUIN, J.W. & MACK, G.H. 1975. Re-evaluation of the use of undulatory extinction and poly-crystalline in detrital quartz for provenance interpretation. J. sediment. Petrol. 45, 873-882.

BAUBRON, J.C., DELFOUR, J. & VIALETTE, Y. 1976. Geochronological measurements (Rb/Sr; K/Ar) on rocks of the Arabian Shield, Kingdom of Saudi Arabia. Bur. Rech. Geol. Min. 76, JED22.

BELDERSON, R.H. & STRIDE, A.H. 1969. Tidal currents and sand-wave profiles in the northeastern Irish Sea. Nature, 222, 74.

BHATIA, M.R. 1983. Plate tectonics and geochemical composition of sandstone. J. Geol. 91, 611-627.

_____ & CROOK, A.W. 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. Contrib. Mineral. Petrol. 92, 181-193.

BLATT, H. 1967. Origin characteristics of clastic quartz grains. J. sediment. Petrol. 37, 401-424.

_____ & CHRISTIE, J.M. 1963. Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance of sedimentary rocks. J. sediment. Petrol. 33, 559-579.

_____, MIDDLETON, G. & MURRAY, R. 1972. Origin of sedimentary rocks. Prentice-Hall Inc., Englewood Cliffs, N.J., 634p.

BLUCK, B.J. 1974. Structure and directional properties of some valley sandur deposits in Southern Iceland. Sedimentology, 21, 533-554.

_____ 1978. Sedimentation in late orogenic basin: The Old Red Sandstone of the Midland Valley of Scotland. In: Bowes, D.R. & Leake, B.L. (eds).

_____ 1979. Structure of coarse grained braided stream alluvium. Trans. R. Soc. Edinburgh, 70, 181-221.

BOKHARI, F.Y. & KRAMERS, J.D. 1981. Island arc character and Late Precambrian age of volcanics at Wadi Shaws, Hijaz, Saudi Arabia: geochemical and Sr and Nd evidence. Earth Planet. Sci. Lett. 54, 409.

BOKMAN, J. 1952. Clastic quartz particles as indices of provenance. J. sediment. Petrol. 22, 17-24.

BRAMKAMP, R.A., RAMIRES, L.F., BROWN, G.F. & POCOCK, A.E. 1963. Geology of the Wadi ar Rimah Quadrangle, Kingdom of Saudi Arabia. U.S. Geol. Surv. Map I - 206A, Washington.

BRENNER, R.L. 1978. Sussex sandstone of wyoming - example of Cretaceous offshore sedimentation. Bull. Am. Assoc. Petrol. Geol. 62, 181-200.

BRIDGE, J.S. 1981. Hydraulic interpretation of grain size distributions, using physical modal for bedload transport. J. sediment. Petrol. 51, 1109-1124.

BURTON, J.D., CULKIN, F. & RILEY, J.P. 1959. Abundance of Gallium and Germanium in terrestrial materials. Geochim. Cosmochim. Acta, 16, 151-180.

CARRIGY, M. 1970. Experiments on the angles of repose of granular materials. Sedimentology, 14, 147-158.

CASTON, V.N.D. 1972. Linear sand banks in the southern North Sea. Sedimentology, 18, 63-78.

CLIFTON, H.E. 1969. Beach lamination: Nature and origin. Mar. Geol. 7, 553-559.

DAS, N. 1985. Geochemical studies of Caithness Flags. Unpubl. Ph.D. Thesis, University of Glasgow.

DAVIES, D.K. & ETHRIDGE, F.G. 1975. Sandstone composition and depositional environments. Bull. Am. Assoc. Petrol. Geol. 59, 239-264.

DAVIS, J.C. 1973. Statistics and data analysis in geology. John Wiley & Sons, New York, 550p.

DE BRAY, E.A. 1983. Reconnaissance geology of Jabal Saq Quadrangle, Kingdom of Saudi Arabia. U.S. Geol. Surv., Open File Report, 83-447.

DICKINSON, W.R., BEARD, L.S., BRACKENRIDGE, G.R., ERJAVEC, J.L., FERGUSON, R.C., INMAN, K.F., KNEPP, R.A., LINFBERG, F.A. & RYBERG, P.T. 1983. Provenance of North American Phanerozoic sandstone in relation to tectonic setting. Geol. Soc. Am. Bull. 94, 222-235.

_____ & SUCZEK, C.A. 1979. Plate tectonics and sandstone compositions. Bull. Am. Assoc. Petrol. Geol. 63, 2164-2182.

DUYVERMAN, H.J., HARRIS, N.B.W. & HAWKESWORTH, C.J. 1982. Crustal accretion in the Pan African: Nd and Sr isotope evidence from the Arabian Shield. Earth planet. Sci. Lett. 59, 315-326.

EMERY, K.O. 1978. Grain size in Lamine of beach sand. J. sediment. Petrol. 48, 1203-1212.

_____ & NOAKES, L.L. 1968. Economic placer deposits of the continental shelf. Geol. Survey Japan Bull. ECAFE, 1, 95-111.

FOLK, R.L. 1960. Petrography and origin of the Tuscarora, Rose Hill and Keefer formations, Lower and Middle Silurian of eastern West Virginia. J. sediment. Petrol. 30, 1-58.

_____ 1974. Petrology of sedimentary rocks. Hemphill Publishing Company, Austin, Texas, p.182.

_____ & WARD, W.C. 1957. Brazos River bar: a study in the significance of grain size parameters. J. sediment Petrol. 27, 3-27.

FREEMAN, W.E. & VISHER, G.S. 1975. Stratigraphic analysis of Navajo Sandstone. J. sediment. Petrol. 45, 651-668.

FRIEDMAN, G.M. 1961. Distinction between dune, beach and river sand from the textural characteristics. J. sediment. Petrol. 31, 514-529.

_____ 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands. J. sediment Petrol. 37, 327-354.

GILLIGAN, A. 1919. The petrography of the Millstone Grit of Yorkshire. Q.J. Geol. Soc. London, 75, 251-292.

GLAISTER, R.P. & NELSON, H.W. 1974. Grain size distribution, an aid in facies identification. Bull. Can. Petrol. Geol. 22, 203-240.

GOLDRING, R. 1985. The formation of the trace fossils (Cruziana). Geol. Mag. 122, 1, 65-72.

GRACE, J.R., GROTHAUS, B.T. & EHRLICH, R. 1978. Size frequency distributions taken from within sand Laminae. J. sediment. Petrol. 48, 1193-1202.

GRAHAM, S.A., INGERSOLL, R.V. & DICKINSON, W.R. 1976. Common provenance for lithic grains in Carboniferous sandstone from Ouachita Mountains and Black Warrior Basin. J. sediment. Petrol. 46, 620-632.

GRANMAYEH, A. 1978. Petrography and provenance of the Torridonian rocks N.W. of Scotland. Unpubl. M.Sc. Thesis University of Glasgow.

GREENWOOD, W.R., HADLEY, D.G., ANDERSON, R.G. FLECK, R.J. & SCHMIDT, D.L. 1976. Late Proterozoic cratonization in southwestern Saudi Arabia. Philos. Trans. R. Soc. London, Ser. A, 280, 517-527.

HAILS, J.R. 1969. The nature and occurrence of heavy minerals in three coastal areas of New South Wales. J. Proc. R. Soc. New South Wales, 102, 21-39.

HARLAND, W.B., COX, A.V. LLEWLLYAN, P.G., SMITH, A.G. & WALTERS, R. 1983. A geologic time scale. Cambridge University Press, 132p.

HARVEY, P.K., TAYLOR, D.M., HENDRY, R.D. & BANCROFT, F. 1973. An accurate fusion method for the analysis of rocks and chemically related materials by X-ray fluorescence spectrometry. X-ray Spectrometry, 2, 33-44.

HELAL, A.H. 1965. Stratigraphy of outcropping Paleozoic rocks around the northern edge of the Arabian Shield (within Saudi Arabia). Z. deutsch Geol. Ges. Bd 177, 506-543.

HEREFORD, R. 1977. Deposition of the Tapeats Sandstone (Cambrian) in central Arizona. Geol. Soc. Am. Bull. 88, 199-211.

HICKMAN, A.H. & WRIGHT, A.E. 1983. Geochemistry and chemostratigraphical correlation of slates, marbles and quartzites of the Appin Group, Argyll, Scotland. Trans. R. Soc. Edinburgh, Earth Sci. 73, 251-278.

HOBDAY, D.K. & TANKARD, A.J. 1978. Transgressive-barrier and shallow-shelf interpretation of the Lower Palaeozoic Peninsula Formation, South Africa. Geol. Soc. Am. Bull. 89, 1733-1744.

HOLLAND, C.H. 1981. Lower Palaeozoic of the Middle East, Eastern and Southern Africa and Antarctica. John Wiley & Son, N.Y. 331p.

HOLLAND, H.D. 1978. The chemistry of the atmosphere and oceans. John Wiley & Sons, N.Y. 351p.

HOLMES, D.W. & OLIVER, T.A. 1973. Source and depositional environments of the Moose Channel Formation, Northwest Territories. Bull. Can. Petrol. Geol. 21, 435-478.

HOUBOLT, J.J.H.C. 1968. Recent sediments of the southern Bight of the North Sea. Geol. Mijnb. 47, 245-273.

HUNTER, R.E. 1977. Basic types of stratification in small aeolian dunes. Sedimentology, 24, 361-388.

IMBRIE, J. & BUCHANAN, H. 1965. Sedimentary structure in modern carbonate sands of the Bahamas. In: Middleton, G.V. (Ed), Primary sedimentary structures and their hydrodynamic interpretation. Soc. Econ. Paleontol. Mineralog. Spec. Pub. 12, 149-172.

JOHNSON, H.D. 1977a. Shallow marine sandbar sequences: an example from the late Precambrian of North Norway. Sedimentology, 24, 245-270.

JOHNSON, M.A. & BELDERSON, R.H. 1969. The tidal origin of some vertical sedimentary changes in epicontinental seas. J. Geol. 77, 353-357.

KENYON, N.H. 1970. Sand ribbons of European tidal seas. Marine Geol. 9, 25-39.

_____ & STRIDE, A.H. 1970. The tide swept sediments between the Shetland Isles and France. Sedimentology, 14, 159-173.

KIRK, M. 1983. Bar development in a fluvial sandstone (Westphalian 'A'), Scotland. Sedimentology 30, 727-742.

KLOVAN, J.E. & BILLINGS, G.K. 1967. Classification of geological samples by discriminant-function analysis. Bull. Can. Petrol. Geol. 15, 313-330.

KRYNINE, P.D. 1940. Petrology and genesis of the Third Bradford Sand. Bull. Pennsylvania State Coll.Min. Ind. Exp. Sta. 29, 13-20.

LEAKE, B.E., HENDRY, G.L., KEMP, A., PLANT, A.G., HARREY, P.K., WILSON, J.R., COATS, J.C., AUCOTT, J.W., LUNEL, T. & HOWART, R.J. 1969. The chemical analysis of rock powders by automatic X-ray fluorescence. Chem.Geol. 5, 7-86.

LE MAITRE, R.W. 1982. Numerical petrology: statistical interpretation of geochemical data. Elsevier, Amsterdam, 281p.

LEVELL, B.K. 1980. Evidence for currents and associated waves in late Precambrian shelf deposits from Finnmark, North Norway. Sedimentology, 27, 153-166.

MACKIE, W. 1896. The sands and sandstones of eastern Moray. Trans. Geol. Soc. Edinburgh, 7, 148-172.

McBRIDE, E.F. 1963. A classification of common sandstones. J. sediment. Petrol. 33, 664-669.

McCAVE, I.N. 1971. Sand waves in the North Sea off the coast of Holland. Mar. Geol. 10, 199-225.

_____ 1973. The sedimentology of transgression: Portland Point and Cooksburg members (Middle Devonian) New York State. J. sediment Petrol. 43, 484-504.

McKEE, E.D. 1940. Three types of cross-lamination in Paleozoic rocks of northern Arizona. Am. J. Sci. 238, 811-824.

_____ & WEIR, G.W. 1953. Terminology of stratification and cross-stratification. Geol. Soc. Am. Bull. 64, 381-390.

MIDDLETON, G.V. 1962. A multivariate statistical technique applied to the study of sandstone composition. Roy. Soc. Canada Trans. Ser III, No.106, 119-126.

MILLER, R.L. and BYRNE, R.J. 1966. The angle of repose for a single grain on a fixed rough bed. Sedimentology, 6, 303-314.

MOFJELD, H. 1976. Tidal currents. In: Marine sediment-transport and environmental management D.J. Stanley & D.J.P. Swift (Eds), 53-64, John Wiley & Sons, N.Y.

MOORE, J.R. 1963. Bottom sediment studies, Buzzard Bay, Massachusetts. J. sediment Petrol. 33, 511.

MOSHRIF, M.A. 1980. Recognition of fluvial environments in the Biyadh-Wasia sandstone (Lower Middle Cretaceous) as revealed by textural analysis. J. sediment Petrol. 50, 603-612.

MURRAY, E.G. & ADAMS, J.A.S. 1958. Thorium, uranium and potassium in some sandstone. Geochim. Cosmochim. Acta, 13, 260-269.

NARAYAN, J. 1971. Sedimentary structure in the Lower Greensand of the Weald, England and the Bas-Boullonaise, France. Sediment. Geol. 6, 73-109.

NIO, S.-D. 1976. Marine transgressions as a factor in the formation of sandwave complexes. Geol. Mijnb. 55, 18-40.

NORRIS, R.M. & NORRIS, K.S. 1961. Algodones dunes of southeastern California. Geol. Soc. Am. Bull. 72, 605-620.

PASSEGA, R. 1957. Texture as characteristic of clastic deposition. Bull. Am. Assoc. Petrol. Geol. 41, 1952-1984.

_____ 1964. Grain size representation by CM patterns, a geological tool. J. sediment. Petrol. 34, 830-847.

PETTIJOHN, F.J. 1963. Data of geochemistry. Chapter 5. Chemical composition of sandstones - excluding carbonate and volcanic sands. U.S. Geol. Surv. Prof. Pap. 440-S.

PETTIJOHN, F.J. 1975. Sedimentary rocks, Harper & Row, 628p.

______, POTTER, P.E. & SIEVER, R. 1972. Sand and sandstone, Springer-Verlag, 618p.

POLLACK, J.M. 1961. Significance of compositional and textural properties of South Canadian River and Channel Sands, New Mexico, Texas and Oklahoma. J. sediment. Petrol. 31, 15-37.

POSTMA, A.H. 1967. Sediment transport and sedimentation in the estuarine environment. In: Estuaries. G.H. Lauff (Ed), 158-179. Am. Assoc. Adv. Sci., Washington D.C.

POTTER, P.E. & PETTIJOHN, F.J. 1963. Paleocurrents and basin analysis. Springer-Verlag, N.Y. 296p.

POWER, R.W., RAMIREZ, L.F., REDMOLD, C. & ELBERG E.L. Jr. 1966. Geology of the Arabian Peninsula, Sedimentary geology of Saudi Arabia. U.S. Geol. Surv. Prof. Pap. 560D, 147p.

RANKAMA, K. & SAHAMA, T.G. 1950. Geochemistry. Chicago Univ. Chicago Press, 912p.

RAO, C.B. 1957. Beach erosion and concentration of heavy mineral sand. J. sediment. Petrol. 27, 143-147.

REICHE, P. 1938. An analysis of cross-lamination: the conconico sandstone. J. Geol. 46, 905-932.

RUSSELL, R.D. 1937. Mineral composition of Mississippi River sands. Geol. Soc. Am. Bull. 48, 1307-1348.

SAGOE, K.O. & VISHER, G.S. 1977. Population breaks in grain size distribution of sand - a theoretical model. J. sediment. Petrol. 47, 285-310.

SCHWAB, F.L. 1975. Framework mineralogy and chemical composition of continental margin-type sandstone. Geology, 3, 487-490.

SCHMIDT, R.G. & ASAD, S.A. 1962. Beach placers containing radioactive minerals, Bay of Bengal, East Pakistan. U.S. Geol. Surv. Prof. Pap. 450-C, 12-14.

SCIELACHER, A. 1970. Cruziana stratigraphy of non-fossiliferous, Palaeozoic sandstone. In: Trace fossils. T.P. Crimes & J.C. Harper (Eds), 447-476. Seel House Press, Liverpool.

SELLEY, R.C. 1970. Ichnology of Palaeozoic sandstone in southern desert of Jordan: a study of trace fossils in their sedimentological context. In: Trace fossils. T.P. Crimes and J.C. Harper (Eds), 477-488, Seel House Press, Liverpool.

_____ 1972. Diagnosis of marine and non-marine environments from the Cambro-Ordovician sandstone of Jordan. Q. J. Geol. Soc. London, 128, 135-150.

SMITH, N.D. 1972. Some sedimentological aspects of planar cross-stratification in sandy braided river. J. sediment. Petrol. 42, 624-634.

SORBY, H.C. 1877. "The application of the microscope to geology". Mon. Microsc. J. 17, 113-136.

_____ 1880. On the structure and origin of non-calcareous stratified rocks. Proc. Geol. Soc. London, 36, 46-92.

SPEARING, D.R. 1976. Upper Cretaceous Shannon sandstone an offshore shallow marine sand body. 28th Ann. Field Conf. Wyo. Geol. Soc. Gdbk 65-72.

STACEY, J.C. & AGAR, R.A. 1985. U-Pb isotopic evidence for the accretion of continental microplate in the Zalm region of Saudi Arabia Shield. J. Geol. Soc. London, 142, 1189-1203.

STEINK, M., BRAMKAMP, R.A. & SANDER, N.J. 1958. Stratigraphic relations of Arabian Jurassic oil. In: Habitat of oil. L.C. Weeks (Ed), Spec. Publ. Am. Assoc. Petrol. Geol. 1294-1329.

STEWART, H.B. Jr. 1958. Sedimentary reflections of depositional environments in San Miguel Lagoon, Baja California, Mexico. Bull. Am. Assoc. Petrol. Geol. 42, 2567-2618.

STRIDE, A.H. 1963. Current-swept sea floors near the southern half of Great Britain. Q.J. Geol. Soc. London, 119, 175-199.

SWETT, K., KLEIN, G.D. & SMIT, D.E. 1971. A Cambrian tidal sand body - the Eriboll Sandstone of northwest Scotland: An ancient-recent analog. J. Geol. 49, 400-415.

TERWINDT, J.H.J. 1971. Sandwaves in the southern Bight of the North Sea. Mar. Geol. 10, 51-67.

THOMPSON, W.O. 1937. Original structure of beaches, bars and dunes. Geol. Soc. Am. Bull. 48, 723-752.

VISHER, G.S. 1969. Grain size distribution and depositional process. J. sediment. Petrol. 39, 1074-1106.

_____ & HAWARD, J.D. 1974. Dynamic relationship between hydraulics and sedimentation in the Altamaha Estuary. J. sediment. Petrol. 44, 502-521.

WEDEPOHL, K.H. 1978. Handbook of geochemistry: 22-k-1, 11-k-2, 25-k-1, 18-k-1, 56-k-1, 27-k-2, 19-k-1, 30-k-1, 31-k-1, 90-A-1

YOUNG, S.W. 1976. Petrographic texture of detrital polycrystalline quartz as an aid to interpreting crystalline source. J. sediment. Petrol. 46, 595-603.