STATE OF BAHRAIN

Ministry of Works, Power and Water

BAHRAIN SURFACE MATERIALS RESOURCES SURVEY

Volume II

Introduction

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Survey Directors and Senior Consultants

VOLUME II

INTRODUCTION

Bahrain Surface Materials Resources Survey, 1976

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BAHRAIN SURFACE MATERIALS RESOURCES SURVEY

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+ Indicates participant only in first period of fieldwork (Dec. 1974).

* Indicates participant only in second period of fieldwork (April 1975).

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A CAUTIONARY NOTE

Every effort has been made to record both fully and accurately those significant aspects of the geomorphology, geology and pedology of Bahrain which were observed by the survey team and which have a bearing on its surface materials resources.

Nevertheless, for the reasons stated in the body of this report, there may remain errors of omission which necessitate that this report and the accompanying maps must be treated as work carried out at a reconnaissance level. In particular all the maps must be used with the understanding that they indicate relative locations and relationships rather than the exact dimensions of features and deposits.

For the most part the scientific terms used are defined in the text and appendices. In many instances this report follows the recommendations in The Preparation of Maps and Plans in terms of Engineering Geology (Quart. Jl. Eng. Geol. 5(4), 1972). However, as the members of the team are in the main neither engineers nor engineering geologists by profession, and some of the evaluations therefore may not be in precise engineering (soils and rock) terms, and must not be construed to be such.

This report presents the results of a feasibility study. It is not a site investigation. The data only provides a guide for future site investigations. The pit descriptions that accompany this report are those of geologists, geomorphologists and pedologists working in the field. They are therefore subjective and should not be taken as precise engineering descriptions.

All laboratory results are valid only within the constraints and limitations imposed by the tests employed.

The Universities who employ the survey members are in no way responsible for any element of this report.

II INTRODUCTION

II.1 THE STRUCTURE OF THE REPORT

This report is presented to meet the brief originally given to the Senior Consultants in August, 1974, and set out in Volume I. It has the nature of a geological regional memoir, containing factual data and scientific interpretations. It has been separately bound in eleven volumes consisting of texts describing the findings of the survey; appendices of factual, analytical or subsidiary information relating to the main body of the report; and maps which record the distribution of soils, bedrock and related environmental phenomena examined by the survey team.

The report is sub-divided under the general headings of:

Geology (Vol. III)

Geomorphology and Superficial Materials (Vol. IV)

Hazards Associated with Salt Weathering in Bahrain (Vol. V)

A Reconnaissance Survey of Soils and Land Capability for Agriculture (Vol. VI)

The large amount of data has in general been assembled by map sheet location, by geomorphological regions, or by stratigraphic horizon as seemed to be most convenient. The larger map sheets which are produced separately include a set of geological maps (Map Volume B) and a set of geomorphological maps (Map Volume C) at a scale of 1:10,000, whose boundaries and sheet numbers are shown on Figure II.1. (These maps include the locations of section lines and pits from which detailed descriptions are provided). For regional planning purposes, and for those who require an overall view of surface materials the synoptic 1:50,000 maps (Map Volume A) may be of most immediate value. The maps depicting the Soils for Agriculture and Land Capability are to be found together in Map Volume E. Some computer analyses have been undertaken on existing borehole records. The results are displayed in map form (Map Volume D) and as block-diagrams within Volume III.

FIGURE II.1
INDEX TO 1:10,000 MAP SHEETS

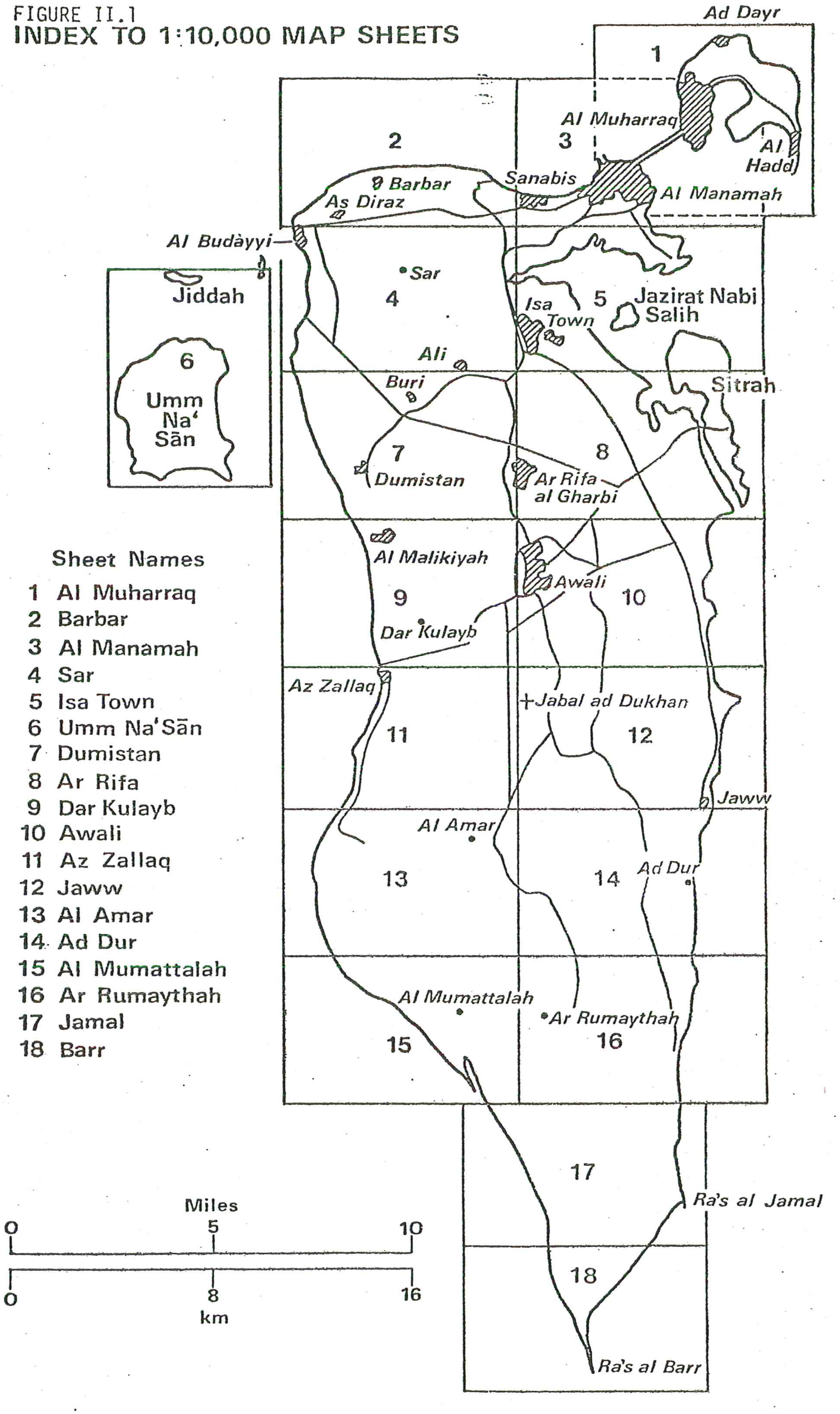
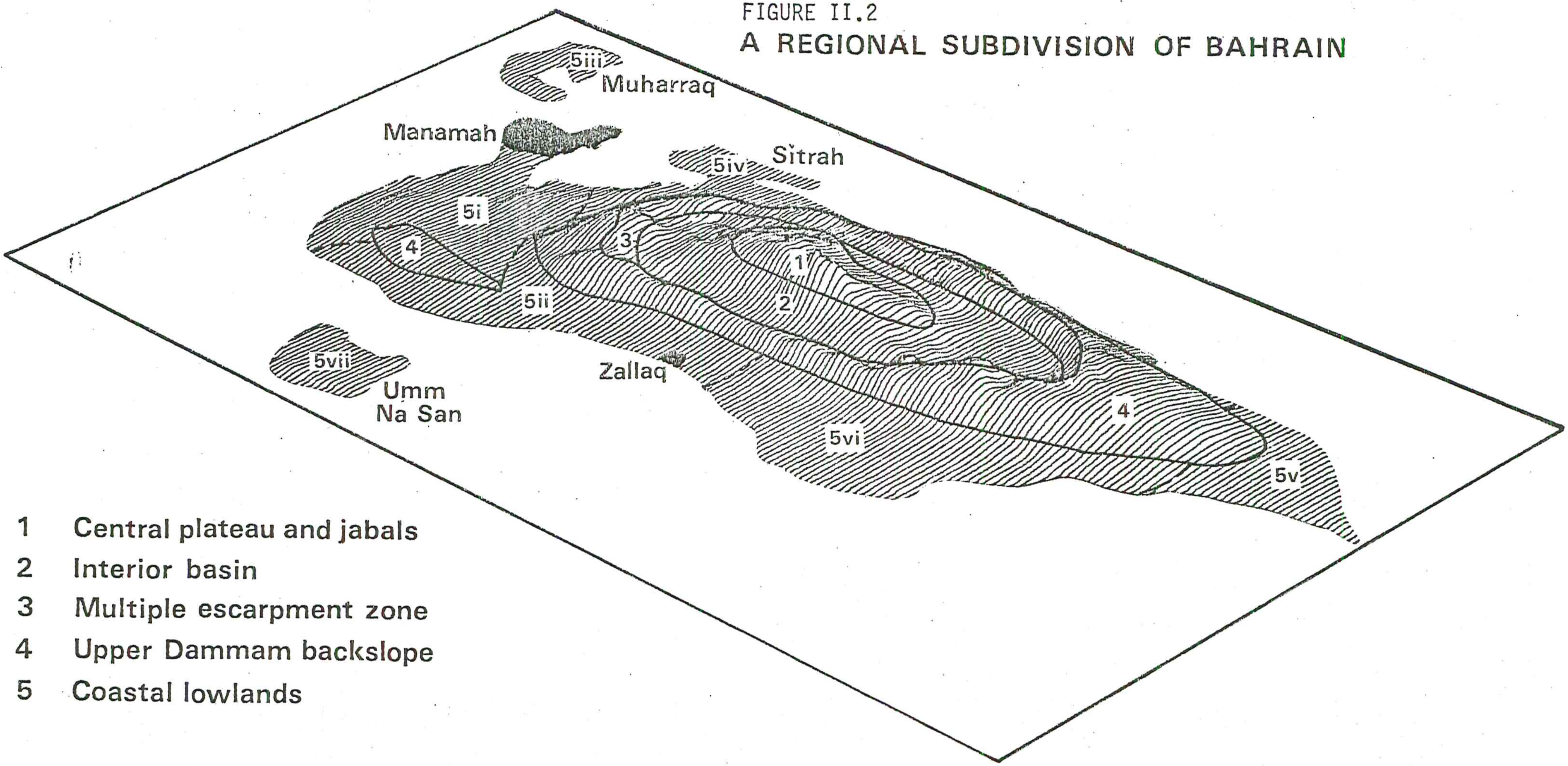


FIGURE II.2

A REGIONAL SUBDIVISION OF BAHRAIN



1 Central plateau and jabals
2 Interior basin
3 Multiple escarpment zone
4 Upper Dammam backslope
5 Coastal lowlands

Much of the discussion and descriptions that follow are based on a regional sub-division of Bahrain (Fig. II.2), which divides Bahrain into areas of differing relief characteristics. These regions are described in Section II.3.

Before dealing with Bahrain in particular it is necessary to place it in its wider regional context, for only by doing so can some of the findings on Bahrain be explained. This is followed by an account of its climatic characteristics as these have an important bearing on many of the material properties and engineering hazards in Bahrain. Finally in this volume the background to the work of the survey team is described as is the way in which the team carried out its brief.

II.2 REGIONAL SETTING OF BAHRAIN

II.2.1 Situation

The State of Bahrain consists of thirteen islands (Table II.1) and numerous small patches of land and coral reef lying at approximately latitude 26^{O}N, longitude 50^{O}30'E, in an arm of the Arabian Gulf known as the Gulf of Salwa which separates the Qatar peninsula and Saudi Arabia. The main islands occur in two unequal groups. The larger including Bahrain Island itself, Al Muharraq, Sitrah, Jiddah and Umm Na'Śan are located in the centre of the Gulf, while a second and smaller, north-south oriented chain including Hawar and Sawad occurs near the Qatar coast (Fig. II.3).

The Arabian Gulf is a shallow epicontinental sea with an average depth of 3-35m, although water depth increases in the east where it joins the Indian Ocean. The Bahrain islands lie on the shelf area of Saudi Arabia on a part of the interior platform (Fig. II.4), sometimes known as the Hasa Terrace and are surrounded by shallow water which rarely exceeds 10 fathoms (18m) in depth.

II.2.2 Geological Setting

Geologically, the Bahrain Islands lie at the junction of two great structural provinces, the Iranian Fold Belt to the north and the stable Precambrian Shield and the Arabian Foreland (Shelf) to the south and west. The Iranian Fold Belt consists of Mesozoic and Cainozoic strata which have been tectonically disturbed to form the northwest-southeast to east-west aligned folds and thrust ranges of the Zagros Mountains. Tectonic activity was very vigorous in this part of the Alpine-Himalayan Orogenic Belt beginning in the Cretaceous and reaching a peak in the Mio-Pliocene. The occurrence of earthquakes indicates that tectonic activity is still continuing. The Arabian Shield, in contrast, is essentially stable. It consists of Precambrian rocks covered by gently north-east dipping sediment of Palaeozoic

TABLE II.1

THE ISLANDS OF THE STATE OF BAHRAIN

Island	Sq. Miles	Sq. Kms
Bahrain	217.50	563.33
Muharraq	5.36	13.88
Sitrah	3.68	9.53
Nabih Saleh	0.28	0.72
Jida	0.13	0.33
Umm Na'San	7.33	18.98
Rubaz	0.90	2.33
Mahzoora	0.21	0.54
Hawar	15.96	40.63
Ajaira	0.03	0.08
Sawadl North	1.17	3.03
Sawadl South	2.97	7.69
Busdad	0.03	0.08
TOTAL	255.55	661.15

Source: Public Works Directorate in Statistical Abstract 1972, (Statistical Bureau, Ministry of Finance and National Economy, State of Bahrain, Dec. 1973).

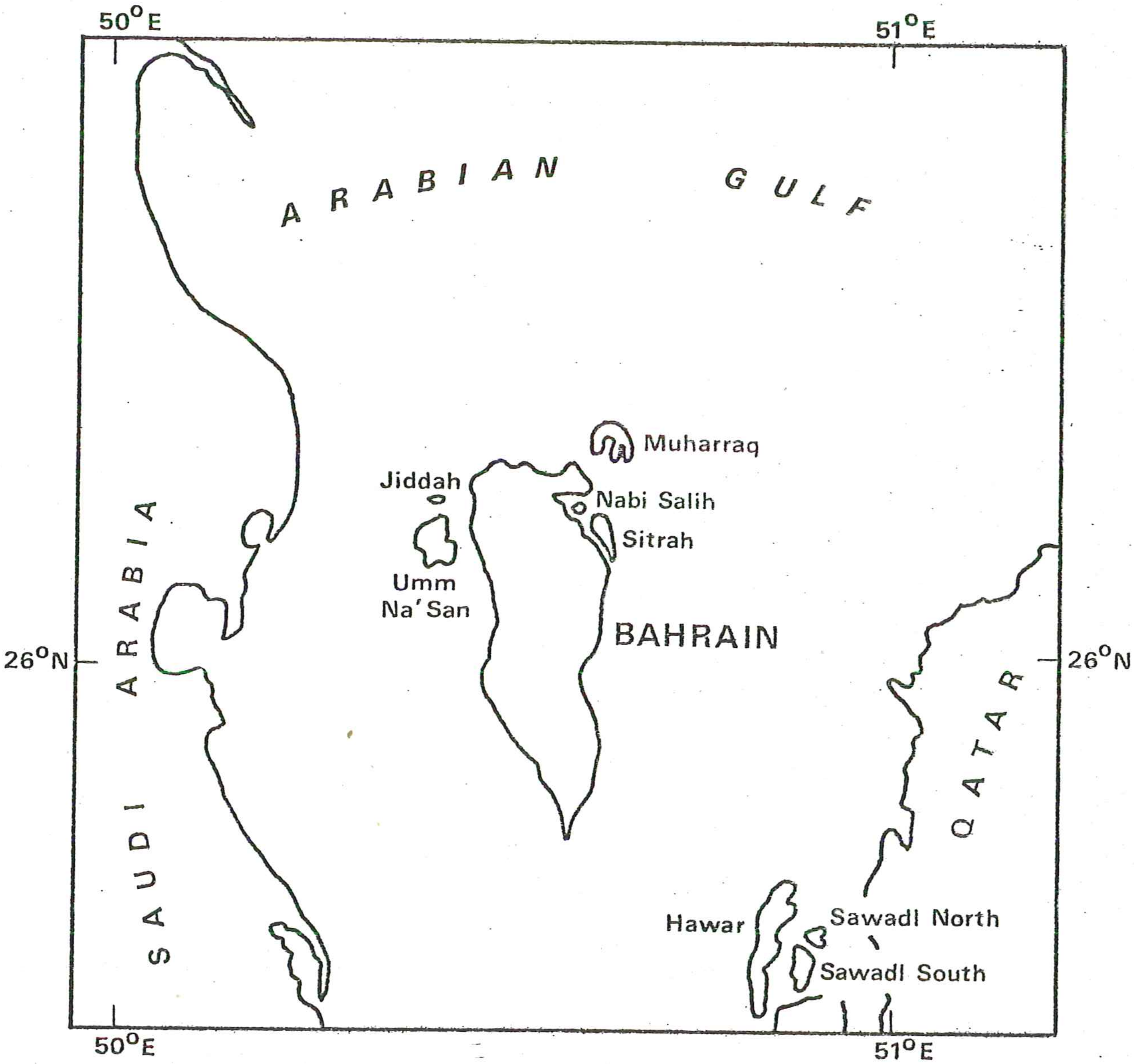


FIGURE II.3 THE LOCATION MAP OF THE BAHRAIN ISLANDS

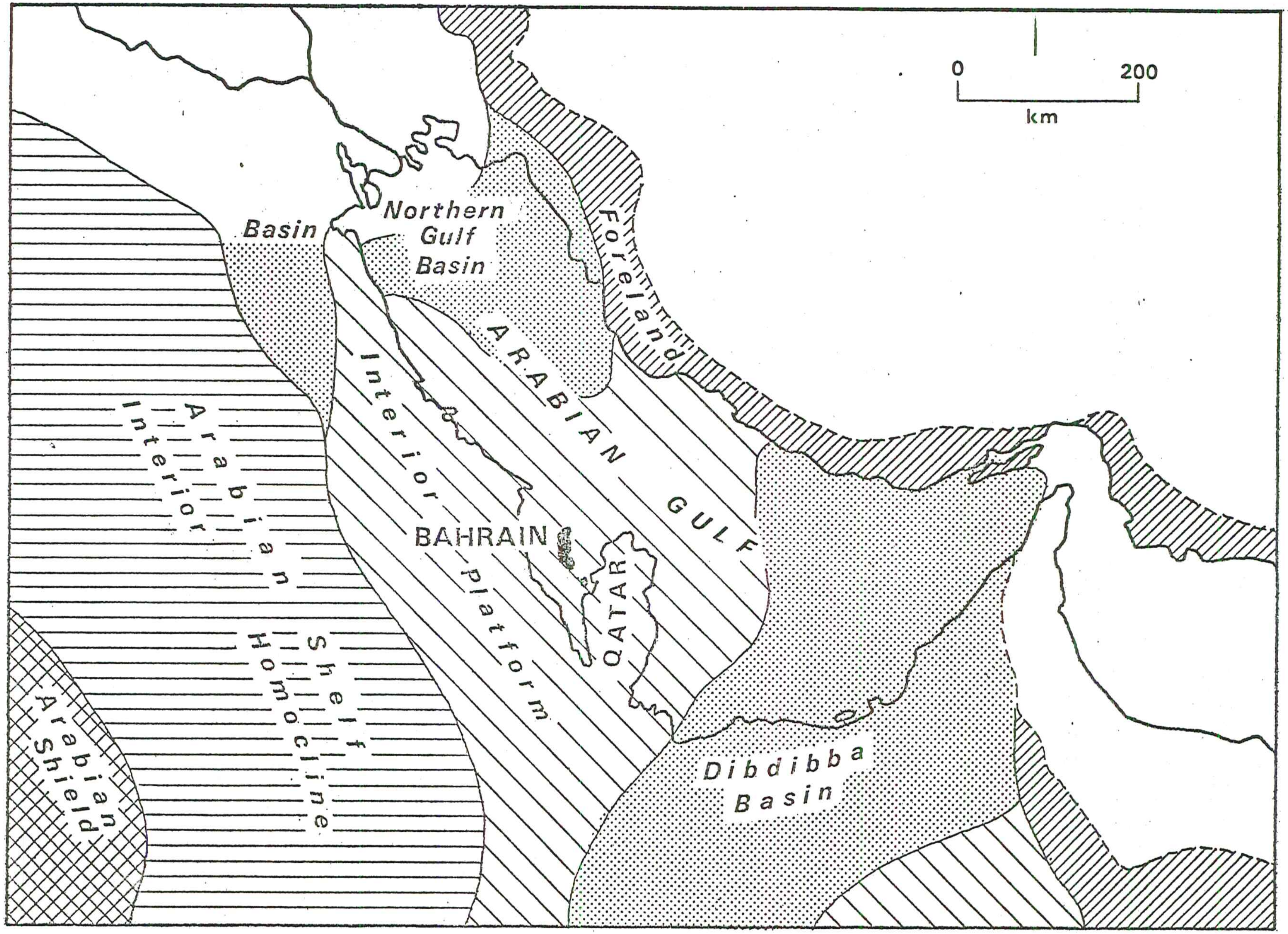


FIGURE II.4 THE LOCATION OF BAHRAIN WITH RESPECT TO THE STRUCTURAL PROVINCES OF THE ARABIAN GULF AREA to Cainozoic age, warped along generally north-south axes (north-south to northeast-southwest) (Lees, 1948). The effects of Plio-Pleistocene folding and faulting and salt diapirism are, however, superimposed on these older structures (Kassler, 1973).

These two great structural provinces meet in the vicinity of Bahrain and there is much physical evidence for the interference and superimposition of Arabian and Zagros (Iranian) lineaments. Bahrain is, however, dominated by the Arabian trend, the most important structure being a north-south pericline or dome which controls both the geological and topographical form of Bahrain Island. Superimposed on this structural pattern are numerous minor or secondary structures of small amplitude which reflect the northwest-southeast Iranian trend as well as hitherto unidentified southwest-northeast flexures (see Vol. III for full details).

The disposition of the rocks is probably further complicated by the effects of uplift due to salt doming and collapse due to the leaching of buried evaporite deposits (Willis, 1967). Although the area may be considered as part of the Arabian Foreland and therefore essentially stable, there is some evidence (Kassler, 1973) that Bahrain has suffered continuing slow uplift and tilting over the last 6,000 years, but neither the amount of movement nor the mechanism has yet been substantiated.

Geographically, Bahrain lies in the core of an extensive arid area which extends from the Sahara northeastwards across Arabia and Afghanistan to the Gobi Desert (Fig. II.5). To the north lie the arid Zagros Mountains and the extensive area of continental sedimentation in the large interior basins of Dasht-i Khavir, Dasht-i-Lut and Garkhuni, while to the southwest lie the huge sediment traps of the Great Nafud, Dalina and Rub al Khali deserts of Arabia. To the far northwest are the alluvial plains and delta of the Tigris-Euphrates and Karun Rivers while to the east occur the Oman Mountains and the narrow exit to the Gulf in the Straits of Hormuz.

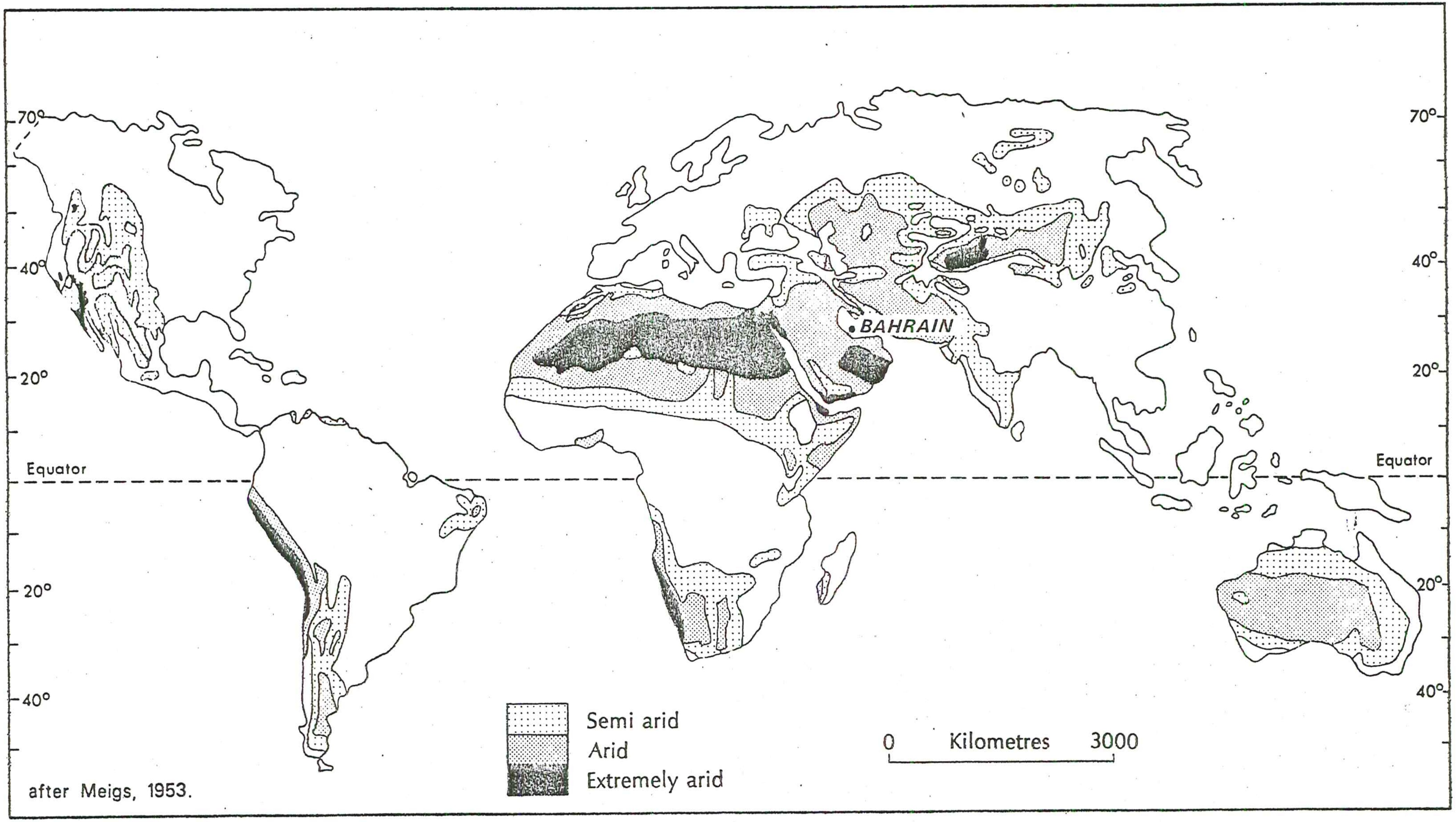


FIGURE II.5 Map showing the main arid areas of the world

II.3 A REGIONAL SUB-DIVISION OF BAHRAIN

The broad anticlinal dome of Bahrain Island has been denuded along its crest to form an interior basin which is characterised by inland drainage. There is an inward-facing multiple escarpment within the dome, inside which stand several residual hills (most notably the Jabal ad Dukhan, 122m), and from which there stretches coastwards in every direction, a gently-inclined backslope (or dipslope). At the coastal margins there occur low tracts of country, some of which are very wide and composed of mainly coastal deposits (e.g. the southwestern Sabkha, area 5vi in Fig. II.2), some are wide and carry few coastal deposits (e.g. the northern coastal plain), while yet others are very narrow and almost devoid of coastal deposits (e.g. the southeastern coastal fringe).

Such a description, however, grossly over-simplifies the geological and geomorphological character of Bahrain. The domal structure is complicated by cross-folds, most of which have not previously been described (see Volume III). The interior basin is composed of a complex assemblage of desert landforms, playa basins, bedrock and bedrock surfaces superficially covered with soil. The processes of salt weathering, wind and water erosion are each active in moulding the present complex of landforms which hitherto have not been described, analysed or mapped in Bahrain (see Volume IV). Similarly, the inward-facing multiple escarpment varies in its magnitude, form and complexity, while the backslope varies in its length, width and height dimensions, generally as a reflection of variations in bedrock structure and erosional history.

The apparent simplicity of the extensive, almost uniformly flat surface of the southwest sabkha is an illusion masking the variety in its geomorphologica components and the different deposits which it bears.

This implication that the mainland of Bahrain is not of such simple geology and geomorphology as has previously been presumed can be carried into almost every separate region identified in Figure II.2. The same is true of some of the adjacent islands. The detailed accounts of geology (Vol. III) and geomorphology (Vol. IV) describe the complexities that occur. Here the regional framework is presented so as to provide a means of easy locational reference in the rest of the report.

The geomorphological sculpturing of the main structure has resulted in a topographic pattern characteristic of unroofed upfolds. The relatively simple pattern of concentric geological outcrops is reflected in the topographic form which is dominated by infacing escarpments. Even though the relief of the island is small (122.4m) with well over half of the surface lying below 20m, and mainly low angle slopes, it is still possible to clearly identify five major physiographic regions, which occur as concentric belts. These are, from the centre of the island outwards:-

1. <u>The Central or Ar Rumanum Plateau and Jabals</u>

A fairly flat area developed almost entirely on resistant rocks of the Rus Group (see Table II.2) exposed in the core of the denuded pericline. The general surface level at 40-60m is surmounted by a number of steep-sided and flat topped residual hills, or Jabals, which rise to a maximum elevation of 122.4m at Jabal ad Dukhan (545795). The surface is best developed to the north of Jabal ad Dukhan, for it declines in elevation and becomes increasingly dissected towards the south.

2. <u>The Interior Basin</u>

An asymmetrical ring of lowlands surrounding the Central Plateau, ranging in width from 2kms in the west to a maximum of 8kms in the south. The surface elevation falls outwards from the centre, from just over 70m (2kms southeast of Awali -5682) to less than 20m around the margin of the basin, minimum elevations of 12m (524853) and 5m (583812) being recorded in the northwest and south-southeast respectively. Surface form is very variable and includes wind faceted, bedrock surfaces near the Central Plateau, gypcrusted erosion surfaces, marginal sedimentary basins and former playa basins. The characteristic form of this area is of a number of outward inclined erosion surfaces which cut discordantly across the Rus outcrop, slight differences in lithology being picked out to form small escarpments and residual hills.

3. The Multiple Escarpment Zone

Surrounding and overlooking the Interior Basin is a virtually continuous belt of low multiple infacing escarpments produced by the outcrops of the Al Buhayr, Dil'Rafah, Hafirah and Awali formations[1] (Table II.2). A large number of beds are scarp formers, the magnitude of the features produced depending on lateral variations in lithology and the intensity of recent erosion at the base of the escarpment zone. Thus the form of this zone shows considerable variation, ranging from a single bold escarpment (54686) to multiple steps and benches forming a belt up to ½km wide (520833), the pattern being further complicated in the northwest and southwest by the effects of secondary flexures which result in the development of irregular and repeated scarps as well as outlier masses. The crestal elevation varies considerably. It exceeds 40m in the northwest, south and southwest, reaching a maximum of 67m (536730) in the latter area, while in the east and parts of the west it declines to between 20m and 35m. Relative relief shows a similar pattern of variation, exceeding 20m in parts of the northwest and much of the south and southwest, rising to a maximum of 35m in the latter area (536730), while in the east and west it is much lower, failing to reach 10m in several places. The continuity of this topographic feature is impressive, for apart from some relatively small and shallow high-level cols, the rim is breached only twice by major wind gaps. Both the Zallaq (517818) and Wasmiyah (517785) gaps are located on the western flank and represent the former routes of

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1 These formation names are fully defined in Volume III.

TABLE II.2 GEOLOGICAL NOMENCLATURE USED IN THIS REPORT FOR THE EOCENE STRATA COMPARED WITH EARLIER NOMENCLATURES

SAUDI ARABIA Powers et al., 1966 Fig. 11		BAHRAIN (Willis, 1967)		BAPCO Geo-photo	BAHRAIN SURFACE MATERIALS RESOURCE SURVEY - this report	
DAMMAM FORMATION	Alat Limestone Marl	DAMMAM FORMATION	White Limestone Orange Marl	Teda Tedo	DAMMAM GROUP	Jabal Hisai Carbonate Formation West Rifa Flint Formation
	Khobar Limestone Marl		Brown Crystalline Limestone	Tedk		Al Buhayr Carbonate Formation Foraminiferal Carbonate Formation
	Alveolina Limestone					
RUS FORMATION	Saila Shale Midra Shale		Shark's Tooth Shale	Teds		Dil'Rafah Carbonate Formation
	Limestone Marl and Limestone Limestone	RUS FORMATION	Not subdivided	Ter	RUS GROUP	Hafirah Carbonate Formation Awali Carbonate Formation
UMM ER RADHUMA FORMATION	Dolomite	UMM ER RADHUMA FORMATION	Not recognised in surface outcrop		UMM ER RADHUMA GROUP	Not recognised in surface outcrop

Notes: Powers et al., 1966, Fig. 11 put the boundary of the Rus and Dammam Formations between the Saila Shale and the *Alveolina* Limestone as shown in this table. In the text they place the boundary at the base of the Midra Shale. The BAPCO/ Geophto indices 'Teda' etc., are mnemonics which stand for Tertiary - eocene - dammam - alat, etc. The equivalent of the Alat Marl (Orange Marl of Willis, 1967) has not been recognised during the present survey.

major trunk streams which drained parts of what is now the Interior Basin during a wetter phase of the island's history.

4. The Upper Dammam Backslope

Declining away from the crest of the uppermost escarpment is an extensive, gently sloping (usually less than 5^o) surface developed on the upper part of the Dammam Group. Mapping has revealed that the topographic slope cuts across the bedding so that higher and younger beds in the sequences are encountered as the coast is approached. This indicates that the feature is erosional in origin and not a true dipslope. The term backslope is therefore used in this report (except in Vol. III). Structural influences, however, still have an important impact on landforms. First, the gross form of the backslope area, being broad and gently sloping in the north (5kms) and south (7kms maximum), rather narrower in the east (2-2.kms) and extremely narrow (1km) and rather steeper in the west, reflects the general asymmetrical shape of the main Bahrain Pericline. Second, the simplicity of this pattern is somewhat modified by the impact of secondary structures. Thus the northwestward extension of the upper part of the Dammam Group outcrop with its eastward facing escarpment near Hamala Camp, results from the denudation of a monocline. Apart from this feature, however, the area presents a rather monotonous landscape, the only local relative relief being provided by shallowly incised valleys created by drainage lines which only operate during intense storms.

5. The Coastal Lowlands

At the base of the backslope, solid geology gives way to a surrounding fringe of young, unconsolidated superficial deposits laid down by the combination of marine and aeolian processes. The surface of this area, which includes all the smaller islands, ranges up to 10m in elevation. In the northern part of Bahrain Island, small inliers of rock (mainly Pleistocene) emerge through the alluvial cover, which is itself heavily masked in the extreme north by man-made ground in the form of middens, tells and the debris associated with more recent urban developments. The local variation and landforms of the coastal zone are discussed in full in Volume IV.5.

II.4 CLIMATE OF BAHRAIN

The present climate (Fig. II.6, Table II.3) is fairly typical of the Arabian Gulf, reflecting the proximity of the tropics and the occurrence of a virtually land-locked sea bordered by extensive arid landmasses. Temperatures are generally high (see Table II.4) although there is a definite 'winter' season. Rainfall totals (Table II.5) are low and very variable (average 2.9", 73.7mm for Al Muharraq) and mainly occurs in the form of occasional heavy downpours during the period November-April, which often result in sudden or 'flashy' run-off in the channels and the occurrence of extensive sheets of standing water in the internal drainage basins. The high sea-water temperatures of the Arabian Gulf and the development of temperature inversions results in generally high humidity levels (see Table II.6). The occurrence of fog and dew is therefore not uncommon. Nevertheless, the combination of low annual precipitation and high potential evapo-transpiration means that Bahrain is extremely arid and must be classified as a true desert (Fig. II.5). Perhaps the most important feature of the climate, particularly with respect to landform development, is the 'Shamal", a very strong and persistent north-northwest to west-northwest wind which blows for several days or even weeks at a stretch, often reaching Beaufort Force 6-8 (Table II.7).

Long term climatic data is available from the records kept by the Meteorological Office of the Royal Air Force at Muharraq, and now continued by International Aeradio Limited at Bahrain International Airport. These data are presented in summary form in Table II.3. A second meteorological station has recently been set up at the Budayya Agricultural Research Station and a limited number of years observations is available.

TABLE II.3

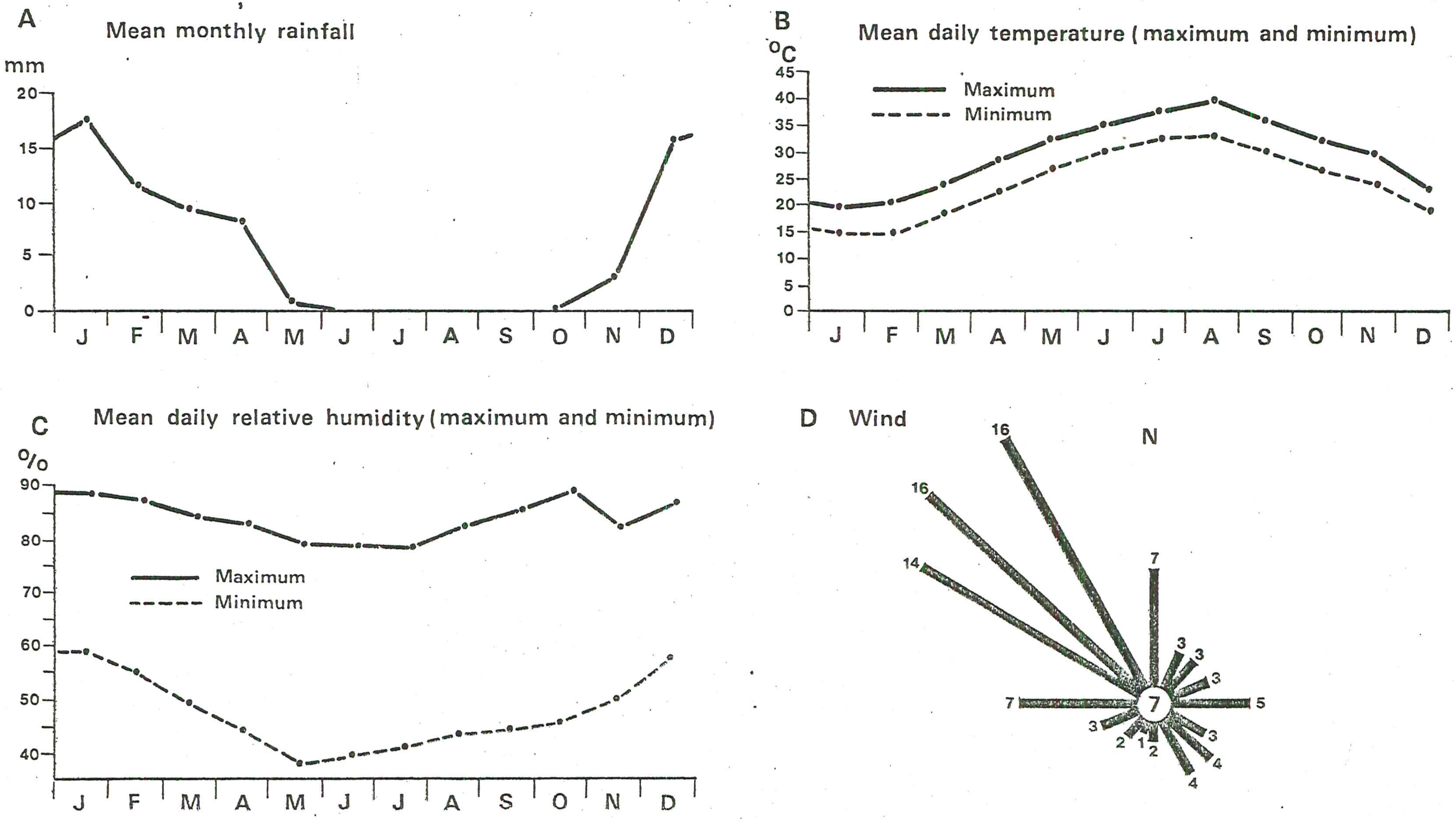
CLIMATOLOGICAL SUMMARY - BAHRAIN INTERNATIONAL AIRPORT

	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	Period Years
Mean daily maximum temperature °C	19.9	20.9	24.6	29.0	33.3	35.7	37.3	37.7	35.9	32.4	27.4	27.4	29
Mean daily minimum temperature °C	14.3	15.1	18.1	21.6	26.0	29.0	30.5	30.7	28.8	25.5	21.6	16.6	29
Highest maximum recorded	31.7	34.7	38.0	41.7	46.7	44.8	44.0	45.0	42.2	40.6	35.0	29.4	29
Lowest minimum recorded	2.8	7.2	7.8	13.9	18.7	22.7	25.3	27.4	24.4	20.6	13.5	6.4	29
Mean daily maximum wet bulb temp.	15.8	16.5	18.8	21.6	25.0	27.3	28.8	30.1	28.5	26.1	21.7	17.6	13
Highest wet bulb temp. recorded	21.1	22.2	23.9	27.6	30.6	32.1	32.2	34.0	31.8	30.0	28.5	23.9	13
Mean humidity	74	71	68	64	60	60	61	64	66	68	68	73	
Mean daily max. relative humidity	88%	87%	85%	83%	80%	80%	80%	84%	86%	90%	84%	88%	16
Mean daily min. relative humidity	59%	55%	50%	45%	39%	40%	41%	44%	45%	46%	52%	58%	16
Mean daily MSL pressure (mb)	1018.4	1017.1	1013.8	1010.8	1006.8	1000.9	997.4	999.0	1004.6	1011.8	1016.4	1018.2	44
Mean daily vapour pressure (mb)	14.8	15.2	16.9	20.3	25.2	27.9	31.8	34.7	32.1	27.2	21.7	17.1	44
Mean daily hours of sunshine	7.2	8.2	8.2	8.5	10.3	11.8	11.3	11.0	10.7	10.1	8.9	7.7	7
Mean monthly rainfall (mm)	17.8	12.2	9.7	8.9	1.6	0.0	*	0.0	*	0.3	3.2	16.3	29
Mean no. of rain days (1mm or more)	2.0	1.9	1.8	1.3	0.9	Nil	Nil	Nil	Nil	*	0.9	1.8	29
Highest rainfall in one day	54.8	29.4	18.6	64.0	8.0	0.0	*	0.0	*	8.9	13.5	42.7	29
Mean no. of days per month with:													
Fog (Vis. 1km or less)	1.7	0.8	0.5	0.1	0.2	0.2	0.2	0.1	*	0.7	0.8	1.0	29
Thick haze (Vis. 1km or less)	0.1	0.3	0.6	0.7	0.5	1.6	1.6	0.2	0.3	0.1	0.0	0.2	29
Thunder	1.2	0.9	1.8	2.0	1.0	0.0	0.0	0.0	0.0	0.1	1.2	0.8	29

NOTE:- * Indicates less than 0.05

Reproduced by kind permission of International Aeradio Ltd. (Revised 1st January 1975)

FIGURE II.6
SUMMARY OF CLIMATIC DATA FOR BAHRAIN



Data supplied by International Aeradio Ltd., Bahrain International Airport.

TABLE II.4

MONTHLY TEMPERATURES
(DEGREES CENTIGRADE; 1965-1972)

Month and Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Average daily maximum												
1965	20.2	21.1	25.0	28.9	35.0	37.2	37.8	38.9	37.2	35.6	27.8	22.2
1966	22.7	21.9	25.2	28.6	34.6	36.9	37.7	38.8	37.5	33.0	28.4	23.5
1967	21.2	19.6	23.5	27.2	33.2	34.0	36.9	36.7	36.0	33.9	27.9	20.5
1968	19.1	18.9	25.5	28.8	33.0	35.3	38.4	36.7	35.3	32.8	29.1	24.2
1969	21.3	20.9	20.8	28.3	34.3	37.7	37.4	37.9	36.5	34.9	26.5	24.0
1970	20.7	23.0	25.4	31.5	32.1	35.6	38.0	37.5	34.9	31.7	28.6	22.0
1971	20.6	21.7	25.2	27.7	34.9	35.4	37.5	37.4	36.4	32.1	27.3	21.5
1972	19.3	20.4	22.9	27.7	37.4	36.5	37.5	39.0	40.1	29.0	28.5	20.2
Average daily minimum												
1965	14.4	15.0	17.8	20.0	26.1	29.9	30.6	31.1	29.4	25.6	22.2	16.1
1966	15.3	16.3	17.4	21.0	26.5	30.0	30.2	30.8	29.3	26.8	22.3	17.3
1967	15.0	13.4	17.1	19.7	25.1	29.2	29.8	30.2	28.2	26.4	22.1	14.2
1068	13.1	12.8	18.4	21.2	26.2	29.3	30.2	30.0	28.1	25.4	22.1	18.4
1969	16.6	14.4	20.7	21.8	25.9	29.0	30.1	30.3	28.4	26.1	21.0	17.7
1970	14.5	16.6	18.8	22.2	25.0	28.4	30.6	30.6	27.9	24.9	21.7	16.3
1971	14.8	14.7	17.8	20.6	26.7	27.8	30.7	30.6	28.5	24.5	21.5	15.6
1972	13.6	13.7	16.9	20.3	25.3	29.8	29.7	30.4	30.8	27.0	22.5	15.6
Maximum temperature												
1965	24.4	26.1	30.6	35.6	44.4	41.7	41.7	42.2	40.0	40.0	32.8	27.2
1966	28.2	27.9	38.0	34.7	41.0	40.7	41.2	41.6	40.7	36.3	30.8	26.5
1967	26.5	26.2	32.9	33.7	41.1	39.5	42.9	38.3	40.0	40.6	32.4	28.8
1968	24.0	25.3	34.6	32.9	36.8	38.8	42.6	39.9	38.9	36.0	33.0	28.5
1969	25.4	32.0	35.7	38.0	41.1	41.0	42.2	41.6	39.5	39.4	32.6	26.6
1970	25.0	26.9	32.4	40.4	38.4	38.6	43.6	40.2	37.1	36.3	31.2	27.0
1971	17.7	18.2	21.5	24.3	30.8	31.6	34.1	34.0	32.4	28.3	24.4	18.5
1972	16.4	17.0	19.9	24.0	31.3	33.1	33.6	34.7	35.4	28.0	25.1	17.9

Source: Civil Aviation Directorate in Statistical Abstract 1972, (Statistical Bureau, Ministry of Finance and National Economy, State of Bahrain, Dec. 1973).

TABLE II.5

MONTHLY RAINFALL IN MM. (1967-1972)

Month	1967	1968	1969	1970	1971	1972
January	1.8	Trace	87.7	7.4	2.6	19.5
February	8.3	52.7	10.4	Trace	8.0	10.0
March	5.5	1.4	0.6	1.2	1.0	42.0
April	6.4	14.3	49.2	Trace	8.0	3.1
May	3.2	0.1	Trace	Trace	1.0	0.1
June	–	–	–	–	–	–
July	–	–	–	–	–	–
August	–	–	–	–	–	–
September	–	–	–	–	–	–
October	–	–	8.9	–	–	–
November	3.7	2.7	9.1	–	1.3	4.0
December	Trace	5.1	Trace	0.3	3.3	6.1
Totals	28.9	76.3	165.9	8.9	25.2	84.8

Source: Civil Aviation Directorate in Statistical Abstract 1972, (Statistical Bureau, Ministry of Finance and National Economy, State of Bahrain, Dec. 1973).

TABLE II.6

RELATIVE HUMIDITIES - PER CENT- (1965-1972)

Month and Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Monthly humidity relative												
1965	78	72	68	62	57	59	60	62	66	63	70	74
1966	78	72	63	69	55	57	59	63	63	68	69	72
1967	72	73	66	65	61	59	63	64	68	66	66	70
1968	70	72	62	61	64	59	58	60	67	69	69	74
1969	77	71	64	68	61	61	62	64	68	69	71	75
1970	73	71	66	59	61	58	57	63	65	67	72	72
1971	74	67	64	63	56	57	59	61	64	67	67	70
1972	84	82	83	83	80	78	74	87	87	90	82	84
Maximum % humidity												
1965	100	98	100	95	94	94	91	92	95	97	93	97
1966	100	99	97	100	92	93	93	95	94	96	97	97
1967	98	100	95	100	95	97	94	95	99	97	90	97
1968	100	99	94	93	98	91	95	90	95	100	97	97
1969	100	99	98	99	95	97	96	93	100	98	96	99
1970	93	97	97	92	98	92	91	90	94	97	96	98
1971	88	84	83	81	75	75	77	78	84	85	82	85
1972	66	49	53	53	39	49	42	43	40	54	53	54
Minimum % humidity												
1965	36	38	33	24	9	18	23	24	24	14	30	34
1966	39	29	21	23	17	25	15	23	14	25	27	29
1967	29	28	18	25	16	16	16	32	17	15	28	34
1968	22	31	21	19	28	29	11	22	25	22	31	33
1969	44	22	16	15	20	21	16	24	27	21	43	40
1970	43	37	22	9	15	28	22	27	24	21	37	35
1971	60	50	45	45	38	39	42	45	45	49	52	56
1972	75	65	68	68	59	63	58	65	63	22	67	69

Source: Civil Aviation Directorate in Statistical Abstract 1972, (Statistical Bureau, Ministry of Finance and National Economy, State of Bahrain, Dec. 1973).

TABLE II.7

SURFACE WIND STATISTICS FOR BAHRAIN INTERNATIONAL AIRPORT

(14 year summary based on observations made at 0000, 0600, 1200 and 1800 GMT)

Frequency of wind direction expressed as a percentage

	Calm	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Jan.	7	3	1	2	1	3	4	8	7	3	1	1	2	8	20	17	12
Feb.	5	5	3	1	2	6	4	7	6	2	1	1	1	4	14	18	20
Mar.	6	8	3	3	3	7	6	6	5	2	1	1	2	4	8	16	19
Apr.	4	11	5	4	6	8	6	5	5	3	2	2	3	4	7	11	15
May	5	11	4	4	4	4	3	2	4	2	1	1	3	7	11	16	18
June	5	8	3	2	1	2	1	1	1	1	2	2	4	8	17	20	22
July	6	8	4	4	4	5	2	3	2	1	1	3	4	8	13	18	14
Aug.	9	8	4	4	4	4	2	3	2	2	1	2	3	8	14	17	13
Sep.	9	8	5	3	3	4	2	2	2	1	2	2	3	7	14	16	17
Oct.	9	9	4	4	4	6	3	3	3	1	1	2	2	6	13	14	16
Nov.	7	5	3	2	3	5	4	5	6	3	2	1	2	7	16	15	14
Dec.	9	3	1	1	2	2	3	4	6	3	1	1	2	10	26	17	9
Year	7	7	3	3	3	5	3	4	4	2	1	2	3	7	14	16	16

Mean wind speed in knots

	Calm	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WDW	W	WNW	NW	NNW
Jan.	0	9	6	6	5	7	8	10	9	7	9	5	6	10	12	12	12
Feb.	0	9	7	7	7	9	9	9	9	8	6	6	6	8	11	13	14
Mar.	0	10	8	7	9	9	10	9	8	9	8	7	7	8	10	13	14
Apr.	0	11	9	8	8	10	9	9	8	7	6	7	7	7	10	12	14
May	0	10	8	7	8	9	7	8	7	7	7	6	6	7	9	12	13
June	0	10	7	6	7	7	5	7	6	6	4	6	6	7	10	14	14
July	0	9	7	7	7	8	6	7	6	5	4	6	6	8	10	12	12
Aug.	0	8	7	7	8	8	6	6	6	6	5	4	5	7	9	10	10
Sep.	0	7	6	6	7	6	6	6	5	5	5	6	6	7	9	10	11
Oct.	0	8	6	6	7	7	6	7	7	6	6	6	6	7	9	11	12
Nov.	0	7	6	6	7	8	7	8	8	8	7	5	6	10	11	11	11
Dec.	0	9	7	7	7	7	8	8	9	7	6	6	7	10	12	12	11
Year	0	9	7	7	7	8	7	8	7	7	6	6	6	8	10	12	12

Maximum gust in knots

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
51	44	47	60	39	39	45	39	29	39	45	41

II.4.1 Temperature

The mean annual temperature at Muharraq is about 27°C which includes an annual variation from a mean daily minimum in January of 14°C to a mean daily maximum 38°C in August. The lowest minimum temperature recorded is 3°C and the highest maximum monthly temperature is 27°C. Frost is absent. Some temperature details for Muharraq are given in Table II.4.

II.4.2 Rainfall

The rainfall of Bahrain is little in amount and irregular in its occurrence. The average annual rainfall is 72.5mm but this figure includes a range of 1.6mm (1946) to 168.9mm (1959). Means of precipitation also vary considerably during the year. June and August have no recorded rainfall, while July, September and October have only a trace and amounts build up to 16.3 and 17.8 in December and January respectively. Amounts decrease steadily from February to May, after which the summer drought ensues (Table II.3). Precipitation comes mainly from thunder-showers and squalls, is heavy and of short duration often with a very localized area of occurrence.

In such circumstances flash floods can occur in the wadis and on the lowland flooding can occur before the water can infiltrate into the soil or flow away.

Amounts of rainfall are insufficient for any form of agriculture and but for the presence of irrigation waters, Bahrain would be a barren desert island. There is a considerable body of evidence that the level of water in underground aquifers is steadily declining. In limited areas of the east coast of the island and particularly on Sitrah it is evident that the head of fresh water is no longer sufficient to exclude the salt sea water from intruding, killing the palms and rendering the land useless. Abstraction of water from wells has been estimated by Wright and Ayub (1975) as $155.4m^3 \times 10^6$ of which $104.3m^3 \times 10^6$ is used for irrigation.

Mean monthly temperatures and mean monthly rainfall can be plotted against each other (Fig. II.7) to illustrate the annual characteristics of the climate. Comparison with other areas, as is done in Figure II.7 indicates the high temperature and low (but seasonal) rainfall experienced in Bahrain, as compared with other places.

II.4.3 Humidity

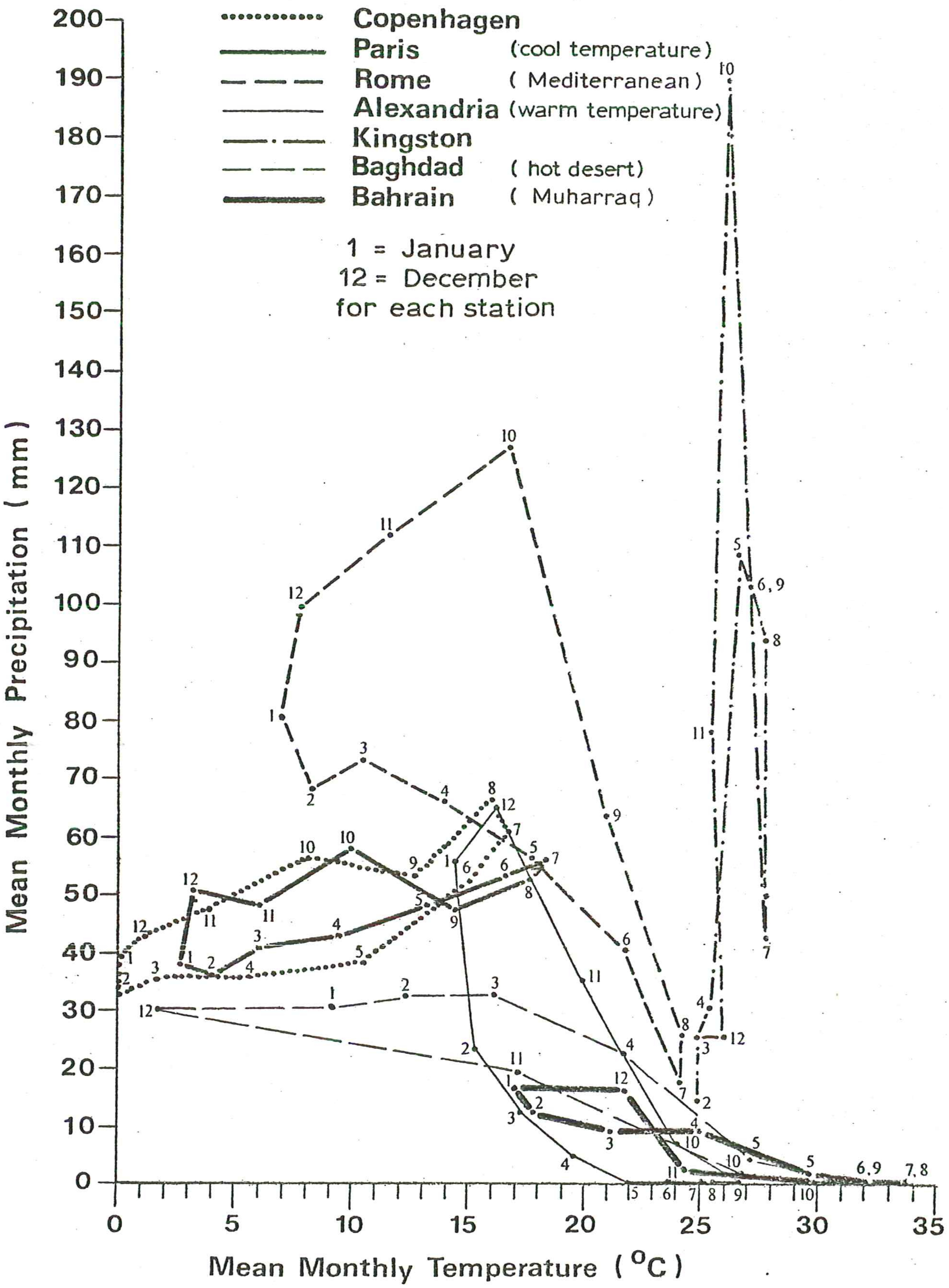
Although the maximum humidity of the atmosphere in Bahrain is at or approaching 100 per cent, there are considerable variations from this figure in spite of the maritime location. The mean daily maximum humidity is about 85 per cent throughout the year but mean daily minimum amounts respond more obviously to the higher summer temperatures dropping to 39 and 40 per cent in May and June. The absolute minimum relative humidity recorded occurs in the month of May, but the period April to October can have months with low minimum relative humidities. The figures are given in Table II.6.

Humidity is very important in considering irrigation needs and excessively low humidities can result in the desiccation of plants or crops. The use of palms as shade trees and the extensive use of palm-leaf fences helps to reduce the losses of moisture from the soil and is to be encouraged. Potential evapotranspiration given by Wright and Ayub (1975) indicate that the amounts vary from approximately 75mm in January to 250mm in June. However, because of the moister conditions beneath the trees of Budayyi (the oasis effect) evaporation figures from Budayyi are 15-30 per cent lower than those of Muharraq.

II.4.4 Surface Winds

In Bahrain many of the relief and soil characteristics, their nature and distributions, are related to the direction and velocities of the surface winds.

FIGURE II.7 Comparison of the Climate of Bahrain with other selected climates



The predominant wind directions have a northwesterly component, and this is also the direction from which the strongest winds blow (Table II.7). Over the whole year 46% of the winds come either from the west-northwest, northwest, or north-northwest. The next two most frequent directions are the adjacent compass bearings of north and west (Fig. II.6). The other directions are almsot equally represented with individual frequencies of 5% or less on average throughout the year.

Mean wind speeds tend to be of the order of 6-8 knots (Table II.7); but the winds from the west-northwest, northwest and north-northwest have mean speeds of 10, 12 and 12 knots respectively. This confirms the overall dominance both in speed and direction of winds with a northwesterly component. Such winds tend to originate over the Saudi Arabian mainland.

II.4.5 Summary

The climate of Bahrain consists of high temperatures, high relative humidities, low but seasonal rainfall, and a predominantly northwesterly wind direction from which also the strongest winds blow. These characteristics either singly or in combination provide strong influences on the processes which sculpture the landscape, determine its soil properties and affect crop growth. To these climatic characteristics can also be linked the hazards of flash floods and salt weathering, the latter being of particular engineering significance.

II.5 AVAILABLE GEOLOGICAL, GEOMORPHOLOGICAL AND PEDOLOGICAL INFORMATION AT THE BEGINNING OF THE SURVEY

The published or otherwise available studies of the geology and geomorphology of Bahrain compiled during the period 1908-1974 have been reported to the Bahrain Government by Messrs. Sandberg (1975) and need only to be summarily reviewed here. Further reference to these is incorporated, as is relevant, in later parts of this report.

The earliest work on the geology of Bahrain is that of Pilgrim (1908) whose brief visit to the Sheikdom included some shrewd observations. Further work was carried out for the Gulf Oil Corporation by Rhoades and drilling work continued after the discovery of the oil field. Drilling was also carried out by the Bahrain Petroleum Company (BAPCO) as a service in the location of productive fresh water wells. The cores from these 670 or so boreholes were recorded and the records filed.

A short account of the geology of Bahrain was published by Willis (1967) as part of the United States Geological Survey's work in the Arabian Peninsula (see also Powers et al. 1966). Also Geophoto Services (?1971) of Denver, Colorado, produced a photogeological study of the Bahrain Islands for BAPCO, with a series of maps at a scale of 1:20,000. Unfortunately this latter study was not available to the present survey team until late in its fieldwork programme.

In 1971 a firm of Italian Consultants were retained by the Government of Saudi Arabia, and as part of their work they included a study of the geology and hydrogeology of Bahrain. In addition they investigated the soils of 27 auger holes, to a maximum of 3m, on 15 farms. This is incorporated in the Italconsult Report (1971). A further section of their report deals with land use and agriculture. In 1974 BAPCO produced geological maps of the islands. In the same year Messrs. Sandberg produced their photogeological study (Messrs. Sandberg, 1974). Only the latter was available to this survey team from the outset.

In the meantime the borehole data available from the water well exploration work had been collected together by Mr. A. Mohanna of the Ministry of Agriculture in Bahrain, and a series of structural contour maps were produced by hand for selected horizons separately identified in the borehole logs. (These maps are reproduced in the review report of Messrs. Sandberg, 1975, Vol. 2).

In brief, therefore, there was a dearth of pertinent published information between the very early work of Pilgrim in 1908 and the short general review by Willis in 1967. Since 1967 there has been a more vigorous interest in the near-surface geology, but none of this has been at a sufficiently detailed scale to enable an effective and comprehensive assessment to be made of the available near-surface natural resources of Bahrain. In addition to which there has been no geomorphological investigation to provide information on the combined conditions of surface form, materials and processes across Bahrain.

The two reports that were available to the team at the outset of their work, and which are partial exceptions to this general statement, are the photogeological report by Messrs. Sandberg (1974) and a very detailed account based on intensive field study, by Engineering and Resources Consultants (1971), whose study of soils for agriculture along some of the northern and western margins of the mainland of Bahrain, also provide information concerning the superficial geological materials. This includes field evidence from 277 auger holes and 32 trial pits, and laboratory analyses of the physical and chemical properties of 800 soil samples.

The photogeological report (Messrs. Sandberg 1974) was carried out as a preliminary to the detailed fieldwork reported here (see Appendix II.VI). It presented a clear summary statement of the existing state of knowledge and of the information which could be derived from the available 1:20,000 air photographs. Two of the maps from the photogeological report are reproduced in Map Volume A. More importantly it enabled Messrs. Sandberg and subsequently, the Bahrain Surface Materials Resources Survey, to establish where gaps existed in our knowledge of the island and how best to design a field survey programme. The photogeological survey clearly drew attention to the need for detailed field mapping, measurement of type sections, examination of geological structures including joint directions, exact descriptions of lithology, superficial soil materials, landforms and processes. This preliminary study must therefore be seen as a useful attempt to define some of the problems to be tackled by the ground survey team and although much of the information contained in the photogeological report is superceded, corrected and updated by the present report it retains its place as a valuable initial statement.

II.6 AVAILABLE BASE MAPS AND AERIAL PHOTOGRAPHS AT THE BEGINNING OF THE SURVEY

II.6.1 Base maps

Maps were required by the Survey team for three purposes:

(i) to act as locational guides,

(ii) to provide background information useful in the analysis of the topography of Bahrain,

(iii) as base maps on which field information could be recorded.

The maps listed in Table II.8 were available to the Survey team at the beginning of their work (see also Fig. II.8). Of these neither the map at 1:63,360 nor the one at 1:1,200 were very much used. The 1:50,000 map (in 2 sheets) was useful as a general-purpose map and, in a photographically enlarged form, as a base-map (see Section II.10). These two map sheets also provided useful altitudinal information (with contours at 10m intervals). In addition they were used as base maps for the synoptic maps at 1:50,000 (Map Volume A). Data abstracted from the 1:50,000 map has also been digitized and stored for computer retrieval and automatic map drawing at the Department of Geography, University of Nottingham, England. As such it provides the base maps to several of the map sheets in Map Volume D.

The 1:2,400 maps were useful in the soil survey for agriculture both as a locational guide and as a means of recording field information. In addition the close contouring intervals on these maps aided in some of the geomorphological interpretations, mapping and pit locations of the north coastal areas.

In general, however, adequate base maps were not available to the team. Improvisation and time-consuming base-map production (including the construction of air-photo mosaics) was a necessary pre-requisite of much of the work done. The manner in which this was achieved is described in Section II.10.

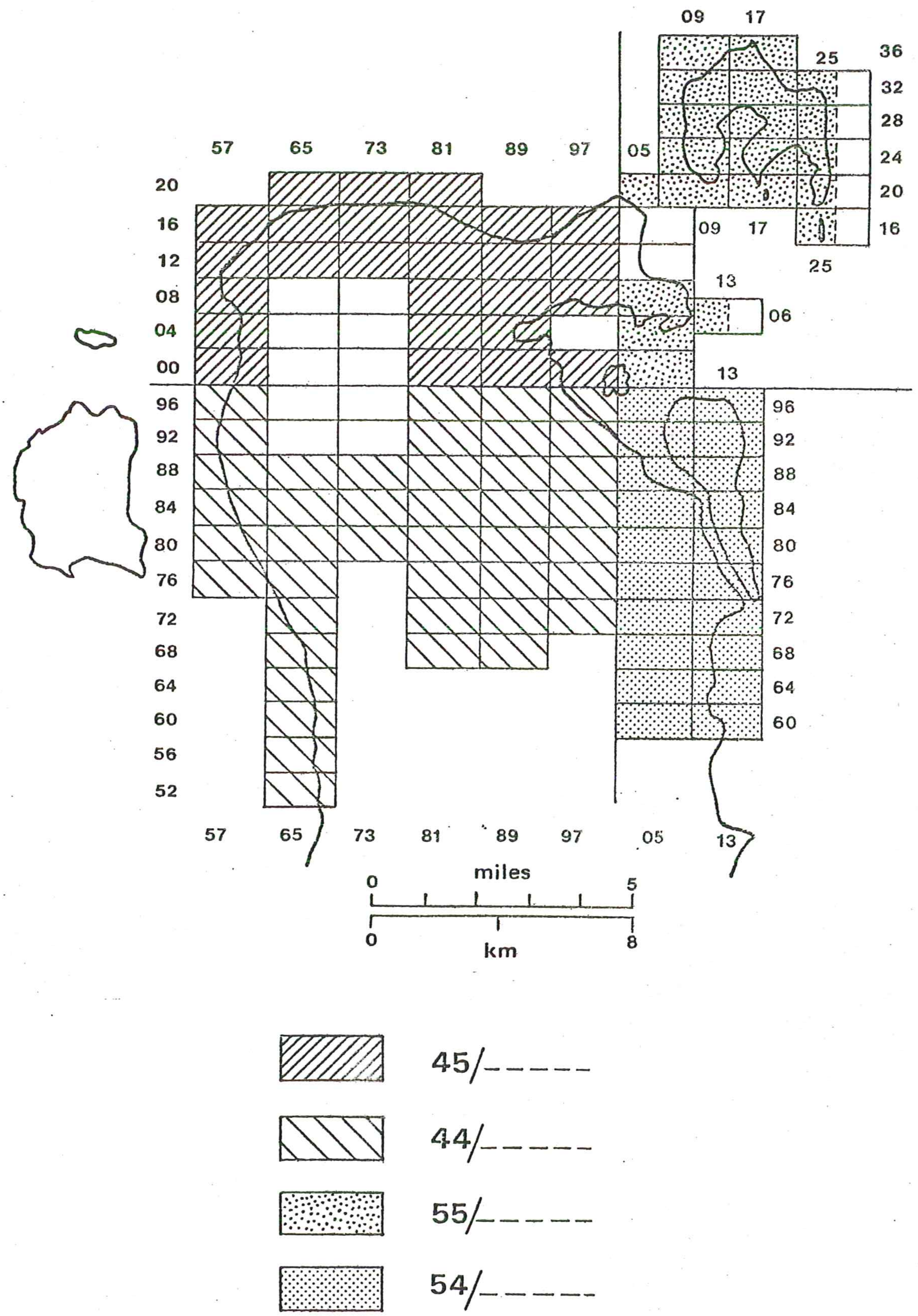
TABLE II.8

TOPOGRAPHIC MAPS AVAILABLE TO THE SURVEY NOVEMBER 1974

Scale	Publisher	Area covered
1:63,360	Revised and printed by Fairey Surveys Ltd. 1967	Whole of Bahrain
1:50,000	Director of Military Survey, Ministry of Defence, U.K. 1973	Bahrain, except Hawar Islands
1:2,400 1:1,200	Fairey Surveys Ltd. Fairey Surveys Ltd.	See distribution shown in Fig. II.8

FIGURE II.8

INDEX TO COVER OF 1:2,400 SCALE TOPOGRAPHIC MAPS AVAILABLE TO THE SURVEY IN NOVEMBER 1974



II.6.2 Aerial Photographs

The aerial photographic cover of Bahrain included a range of scales from a satellite image to panchromatic aerial photography at 1:6,000. The photo cover used by the Survey is illustrated in Figure II.9 and listed in Table II.9.

Of these the 1:10,000 photography was generally the most useful. It provided a more or less consistent scale of photography across the whole island (but see Section II.9; Section II.10 and Appendix II.V); and it was chosen as both the mapping scale and the reproduction scale for the detailed systematic maps of geology (Map Volume B), geomorphology and surface materials (Map Volume C).

The aerial photographs at a scale of 1:6,000 show with great clarity many of the significant surface details of the geology and geomorphology of Bahrain. These would have been used extensively as base maps in the field mapping programme if they had been available for the whole territory (see Fig. II.9).

The 1:20,000 scale photography was not used at all. The 1:30,000 scale photography had to be used for the Hawar Island group as this was the only photography available.

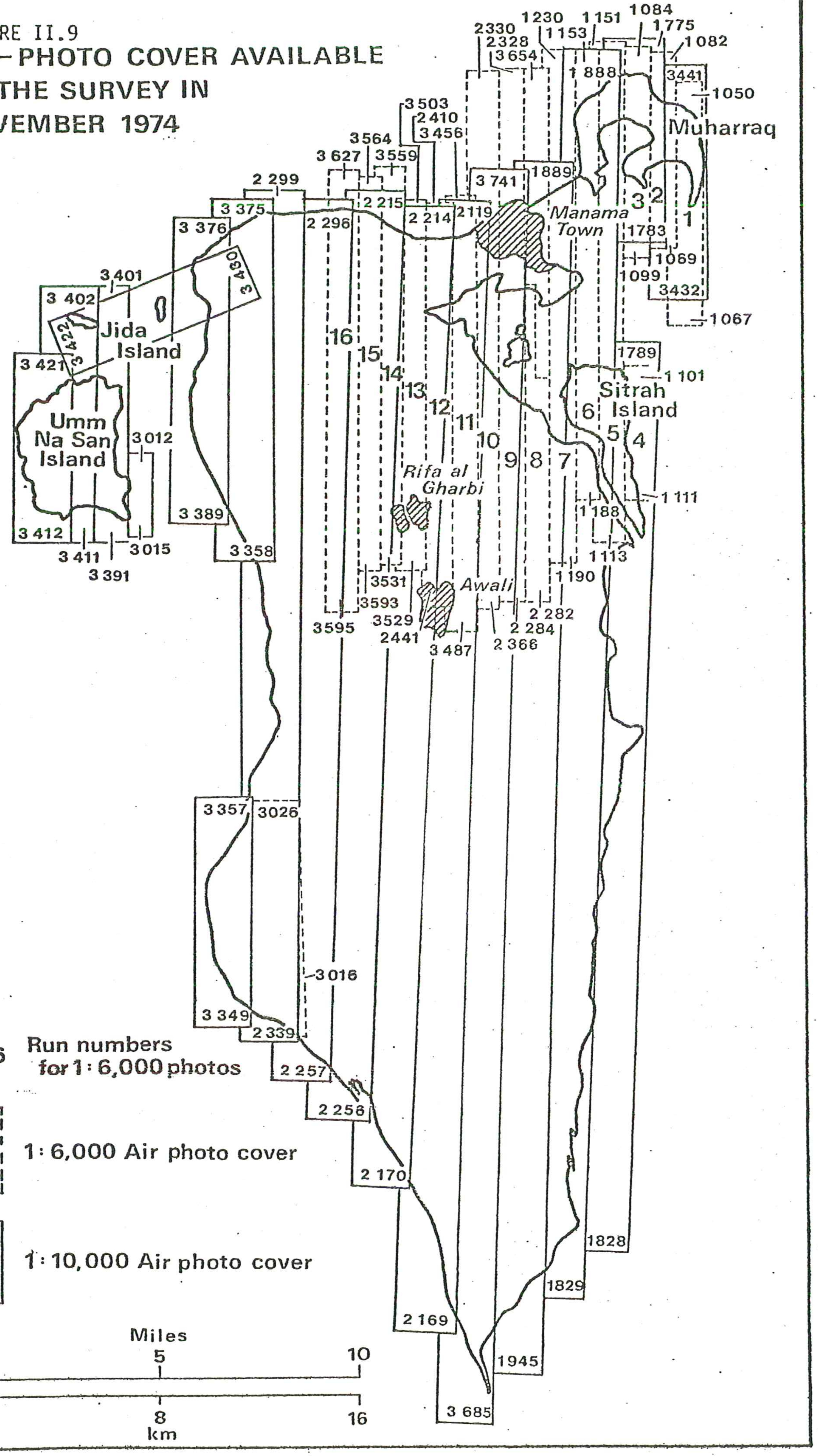
TABLE II.9

AERIAL PHOTOGRAPHS AVAILABLE TO THE SURVEY

Scale	Date	Flown by	Ref. Nos.	Area covered
A On 1st November 1974				
1:80,800	Unknown	Satellite imagery		Bahrain, except Hawar Islands
1:20,000	21 June 1969	R.A.F.		Bahrain, except Hawar Islands
1:10,000	9 May 1964	Fairey Surveys Ltd.		Bahrain, except Hawar Islands
1:6,000	3 Dec. 1966	Fairey Surveys Ltd.		Northern parts of Bahrain (see Fig.II.9)
B On 1st September 1975				
1:30,000	Dec. 1970	R.A.F.	Sortie No. 13D/1862	Hawar Islands

FIGURE II.9

AIR-PHOTO COVER AVAILABLE TO THE SURVEY IN NOVEMBER 1974



II.7 THE TIME CONSTRAINT

The Ministry of Development and Engineering Services, Government of Bahrain, required that the Survey team should present its findings as quickly as possible, and this introduced certain constraints on the work that could be done. The time-table allowed for only two periods of fieldwork, the timing and length of which were both governed by the dates of English university vacations (since nearly all of the team members have university teaching commitments in term time). The whole programme from conception to completion lasted only 19 months, and ran as follows:

1974	July-August	Programme devised and agreed with MODES.
	August-November	Team members chosen and briefed.
	November 27 - December 21	Fieldwork.
1975	January-March	Laboratory analysis of samples, air photo analysis, synthesis of ideas and facts obtained in fieldwork, base map production.
	March 28 - May 8	Fieldwork.
	May - February 1976	Laboratory analysis, map compilation and report writing.
1976	February	Report completed in manuscript.

Some of the consequences of this very tight schedule inevitably are reflected in the results as presented in this report. Notably, for example, more horizons of superficial deposits were sampled than have been analysed in the laboratory. Time was not available to carry out an analysis of all samples, and hence a judgement based on the field evidence was made as to which of the samples most warranted laboratory analysis.

There was not enough time to produce more than three 1:10,000 map sheets to show the distribution of agricultural soils. However, it was important that this scale of mapping should be applied to the northern part of Bahrain where most of the active agriculture is taking place and where the urban expansion of Manama is fast encroaching on to agricultural lands. The pedologists (who only took part in the second period of fieldwork) thus concentrated their efforts in the north, while at the same time producing a reconnaissance soil map at 1:50,000 for the whole of the mainland area of Bahrain and some of the islands. Tentative soil boundaries at a scale of 1:10,000 can be derived for other parts of the country from the geomorphological maps.

Because of the time constraints upon the team, and indeed for other reasons as well, this report and maps must be considered as a reconnaissance survey that presents the regional framework within which subsequent site-specific investigations can be set. Such more detailed studies will make necessary modifications to the ideas as well as perhaps to some of the facts presented in this report.in the same way that this Survey has updated the photogeological report.

II.8 METHOD OF APPROACH

The listing of the team members (p.ix-x) shows that most of these are not only from differing disciplines but they are also from several different universities, and other organisations. They were brought together for this one survey, with each member chosen for the specific contribution which he (or she) could make to the task in hand. Nevertheless, the work as a whole demanded much inter-disciplinary effort and co-operation as well as individual initiative.

The team's prime method of gaining information was through mapping landforms in the field, the recording of the nature of bedrock and superficial materials, and through observations on processes whenever these could be made. No field instrumentation of processes was carried out. This fieldwork was backed up by some air-photo interpretation, and by selected laboratory tests on some of the samples of water, bedrock and superficial materials (including soils). An attempt was made to obtain bore-hole and other pertinent data from files, publications, reports and records. Where this was successful and proved to be useful it has been incorporated in the appropriate section of the report. All of this study is Bahrain specific, no attempt is made to include a comprehensive study of the implications of the findings either on adjacent territories or on the Gulf area as a whole.

Much of the fieldwork has revolved around the geomorphological assessment of the terrain, and in particular the geomorphological mapping which provided the regional mapping framework, especially for the distribution of surface materials and relief features. This is illustrated, for example, in the coastal areas where geomorphological mapping (in this case leaning heavily on air-photo interpretation to provide a primary map for field-checking) formed the basis for:

(i) identifying the separate components of the coastal areas.

(ii) providing the optimum location of transect lines along which trial pits could be dug, and for ensuring that each major component of the area was sampled at least once.

Similarly, in the inland basin the marginal fans and playa basins appeared to be one of the more important features worthy of further examination. These areas were separately identified in location and extent by the geomorphological mapping, and then the soil properties of some of them were described by the engineering geologist.

The geomorphological mapping formed the basis for identifying remote or isolated bedrock outcrops, especially in the coastal and southern playa areas and was used to establish the boundaries of the superficial deposits. Since the classification of the soils on the 1:50,000 reconnaissance soil map is largely in terms of soil site and physical conditions it is, in part at least, a derivative of the geomorphological mapping.

In a sense, therefore, the systematic mapping of the geomorphology provides the main backbone of the survey, and from the distributive framework which it provides stem many of the separate specialist studies. Each part of the report indicates the extent to which specialist skills have been used. These are many and varied, and chosen as was most pertinent to the problem in hand.

II.8.1 Geomorphological Mapping

(a) Introduction

Separate mapping teams were selected to map different, and morphologically distinct, parts of Bahrain. Responsibilities were shared as follows. The Interior Basin (plus Central Plateau and Jabals, and Multiple Escarpment Zone) was mapped by Dr. Brunsden, Mr. Jones and Dr. Doornkamp, who were joined by Dr. Townshend for the second fieldwork period and who had special responsibility for the southern playa basins. The main backslope around the Interior Basin (Upper Dammam Backslope) was mapped by Drs. Cooke and Goudie. The coastal areas were assigned to Prof. P. H. Temple, Drs. Bush and Evans, and they were joined by Mr. Gibbons for the second fieldwork period. Help was also provided in the coastal areas by Prof. Pugh and Dr. Townshend. The northern coastal lowland area was investigated by

Drs. Townshend and Doornkamp, with information also drawn from both the pedological survey (see below) and from the mapping done by team members whose work over-lapped onto this area.

Systematic mapping was generally preceded by an air-photo interpretation on either the 1:10,000 or the 1:6,000 photography. Field mapping consisted of very intense field-checking of the air-photo interpretation (e.g. by additional mapping and a heavy pitting programme on the coast; by systematically mapping as much of the ground as possible (usually on foot) in the non-coastal areas and sinking confirmatory pits as was possible). The pits dug are all marked on the final 1:10,000 geomorphological maps, and their descriptions are recorded in the Appendix to Volume IV.

(b) The Coastal Lowlands (including the main islands)

Special planning was required in the coastal areas for here variations in materials were less clearly betrayed by variations in surface form. Indeed, much of the coastal zone has very little relief, making normal geomorphological mapping very difficult. As a result the work programme was devised as follows: the design and completion of a systematic programme of pitting and field description of surface materials based in part on preliminary morphological and photogeological map drafts; the checking of morphological and mapping boundaries in the field; the compilation of finished maps based on all available data. These included topographical maps, photogeological draft maps, field maps, surveyed sections, pit logs, laboratory analyses of sampled materials for grain size and mineralogy, and the analysis of water samples. In all less than 200 man-days were available for field work within the coastal zone during the two periods in Bahrain.

During the first field work period, and in the absence of 1:10,000 maps or photomosaics, the main effort was concentrated on a reconnaissance and particularly with the identification of type-sites and areas of particular interest and importance. The feasibility of a systematic pitting programme was tested in the field and a start made on surface material sampling. This first fieldwork period was also used to field check the significance of tones and patterns on the 1:10,000 air photographs so that the photo-interpretation and the preparation of some provisional morphological maps could proceed in the U.K. before the final more extended field survey of 1975. The data which were only available in Bahrain were collated and analysed during this period.

The experience gained during the reconnaissance period proved invaluable in devising efficient methods of investigation for the enlarged coastal team during the second field study. Photo-interpretation of the morphology of the two largest coastal areas were prepared in the U.K. and these were used as a guide for the location of the sampling of the surface materials. Maps of the remaining coastal areas were compiled in Bahrain in conjunction with the field investigation and were completed later in the U.K. These maps were checked by standard field methods in Bahrain, by reference to the pit information and laboratory analysis and from the air by helicopter. For the northern part of the island, photographic enlargements of the 1:50,000 sheet were used as the map plotting base, whilst for the south, a specially prepared photomosaic was used.

(c) Interior Basin (Central Plateau and Jabals, Multiple Escarpment Zone)

The complexity of the relief within the central area of Bahrain, and the comparative smallness of many significantly different features (and materials) in this area, made it necessary to employ a mapping scale of at least 1:10,000. The first field work period was used:

(i) to test the appropriateness of this mapping scale on a range of the features in the area.

(ii) to establish the mapping legend to be employed.

(iii) to test air-photo interpretations made prior to work in the field.

Once this had been done a mapping programme was worked out which generally included:

(i) preliminary air-photo interpretation.

(ii) field mapping directly on to the 1:10,000 aerial photographs.

(iii) soil pitting to include several sites within each of the geomorphological units defined by the mapping.

The Interior Basin was sub-divided for mapping purposes between Dr. Brunsden, Dr. Doornkamp, and Mr. Jones, with the playa in its southeastern corner being mapped by Dr. Townshend. Assistance in identifying materials was provided by Drs. Bush, Evans, Cooke and Goudie. Surveying was carried out by Prof. Pugh.

(d) Dammam Backslope

This very large area of Bahrain is generally monotonous, though variations in its surface and material composition do occur. Interest is added by the several cross valleys that occur particularly on its western side, areas of Dilmun mounds and wind abraded topography. Large parts of this area, especially in the northeast have been stripped and the materials taken away as 'desert fill'. The two-man team of Drs. Cooke and Goudie ranged extensively across the whole of the area, paying special attention to those localities which appeared from air-photo analysis to carry features of interest.

The field survey was directed towards:

(i) field checking of geological structures and lithological variations derived from air-photo analysis.

(ii) preparation of a reconnaissance geological map for the northern part of the Upper Dammam Backslope to assist Dr. Barber.

(iii) field checking of landforms mapped from aerial photographs with special reference to scarp features, drainage lines, karstic and wind-erosion phenomena. (Relatively little attention was paid to the areas of extensively worked ground but areas of Dilmun mounds were recorded).

(iv) systematic mapping and sampling of surface materials with special emphasis on:

a) the debris mantle

b) the 'blue askar' (which posed the problem as to whether or not it was a surface-related duricrust)

c) the hardness of surface rocks

d) the occurrence of sand or silt deposits

e) the investigation of daya and playa deposits.

f) a study of rock weathering.

(e) Northern Lowlands

The most extensively occupied area of Bahrain, namely the lowlands west of Manama, are also the most difficult to map. They are in part densely covered by palm trees, making intervisibility and precise location difficult; and are everywhere much modified by long occupance of the land, making geomorphological interpretation of specific features difficult.

Mapping by Drs. Doornkamp and Townshend thus consisted very largely of identifying recognisable geomorphological forms (e.g. dunes), surface materials, and man-made features. Aerial photographs at a scale of 1:10,000 were used as base maps, with variations in grey tones frequently assisting in boundary identification. Cross-checks were made with the soil maps being prepared by Drs. Bridges and Burnham.

Field mapping in the Northern Lowlands was left until the last stages of the fieldwork period. This enabled the accumulated experience of mapping and data gathering in other parts of the Island to be used in tackling this intrinsically difficult mapping area.

(f) Hawar Islands

The mapping of the Hawar Islands was done on the basis of a one-day visit by three team members, and air-photo interpretation by Prof. Temple. Time did not permit more field work to be done on this part of Bahrain.

II.8.2 Geological Mapping

The approach adopted during the geological mapping was to establish 'type-sections' for each of the rock units encountered on the island. These type-sections were carefully measured and described in the field. Specimens of all the rock types encountered were collected with a view to later petrographic study, chemical analysis and the determination of physical properties. This programme of field work was initiated by Drs. Evans and Bush at the commencement of the first field work period. The study was started in the north-western part of the Interior Basin. Here a series of vertical sections around the rim escarpment were measured using ranging rods, measuring tape and Abney level. At an early stage in the first period of fieldwork a set of detailed measured stratigraphic sections was available for the northern part of the rim escarpment. Later on the measured sections were accurately surveyed by Mr. Fielding so that they could be fitted onto topographic profiles.

The programme of section measuring was continued during the second period of field work by Drs. Hancock and Hubbard who extended this study to cover the southern part of the island. In the second part of the programme in addition to the parameters already determined, the petrographic, lithological and fossiliferous characteristics of the rocks were used to determine the environments of deposition for each rock unit. Similar studies were also carried out on all the other rock units in the island, in addition to those exposed in the rim scarp. Sections of rocks in the Interior Basin were studied, including a special study by Dr. Hubbard of the rocks forming the cap of Jabal ad Dukhan and the other hills in the same region. Outside the rim scarp specially designated type sections were studied at the Refinery escarpment and Sitrah on the east, and Hamala Camp on the west.

As soon as the stratigraphy of the rocks forming the rim scarp was well established, geological mapping was commenced in the northwestern part of the Interior Basin by Dr. Barber. Geomorphological mapping of the superficial deposits was already in progress in the same area. Mapping was carried out on the ground using aerial photographs on the scale of 1:10,000. Data was recorded on transparent plastic overlays mounted on alternate aerial photographs.

Mapping commenced in the area where the boundaries between the rock units had already been established. The location of boundaries identified on the ground was marked at the corresponding point on the overlay. The excellent degree of exposure made the tracing of the geological boundaries on the ground a relatively straightforward process. When the boundaries were plotted the areas occupied by particular rock groups were coloured on the overlay to correspond with their distribution on the ground. During the course of the field mapping any marked changes in the inclination of the beds were measured by compass and clinometer and recorded in the appropriate position on the overlay. Changes in lithology, fossil content or the relationship between rock units were also recorded.

Once field mapping was under way it was possible by using a mirror stereoscope to study the aerial photographs in three dimensions and to extrapolate the geological boundaries into areas which had not yet been visited. Again the excellent degree of rock exposure and the very close relationship between the topography and the rock units made the tracing of boundaries a comparatively straightforward process. The process of interpretation was continued in the period between the two field visits.

By the time of the second field visit in April 1975 base maps on the scale of 1:10,000 were available for the northern part of the island and a ground controlled aerial photographic mosaic was available for the southern half. It was not possible to transfer data which had been accumulated on individual photographs onto these bases and to compile a geological map. As the map was completed, areas in which the interpretation was doubtful became apparent. As these problem areas were encountered, it was possible to go into the field and to check the interpretation on the ground and to amend the developing geological map wherever this was necessary. Field checking was carried out by Drs. Barber, Hancock and Hubbard.

To complete the map the boundaries between the solid formations and the overlying superficial drift deposits were added. These boundaries were mapped by the geomorphological team using the same techniques as those already described for mapping the solid geology. The boundaries within the Interior Basin were mapped by Drs. Brunsden, Doornkamp, Jones and Townshend and Drs. Cooke and Goudie were responsible for mapping patches of drift on the dipslope of the Al Buhayr and West Rifa Flint Formations. They also mapped the lower boundary of the dipslope where the solid rocks pass beneath the recent deposits of the coastal plains.

In the northern lowlands outcrops were mapped by Drs. Doornkamp and Townshend as part of their geomorphological mapping programme. Once located the rocks were then identified by the geologists.

II.8.3 Mapping Engineering Hazards

The engineering hazards discussed in Volume V concentrates upon the attack of building and other materials by salts (salt weathering).

This study was undertaken by Drs. Cooke and Goudie with special attention being devoted to the northern part of the Bahrain mainland. Field work consisted of the collection of over 200 water samples whose electrical conductivity was measured, and upon some of which chemical analyses were later carried out. The sampling scheme enabled automatic-contouring to be carried out by computer analysis, and areas of relative intensity of the hazard thus to be defined (Map Volume A).

II.8.4 Pedological (Soils for Agriculture) Mapping

Drs. Bridges and Brunham joined the team for the second period in the field to carry out a mapping programme designed to provide detailed (1:10,000) soil maps for the northern part of Bahrain, and a general (reconnaissance 1:50,000) soil map for the whole of the mainland and some of the adjacent islands. The approach used is described in Volume VI.6.1.

II.8.5 Laboratory Analysis

At various stages in the Survey it was necessary to carry out laboratory analysis of rock, soil and water samples. The majority of the work was carried out on samples shipped to the United Kingdom at regular intervals. Other tests were carried out in the field especially for rock hardness and electrical conductivity. Many samples were tested by the Bahrain counterpart to the soil survey, Mr. J. H. Ahmed, and with the generous co-operation of the Department of Agriculture. The majority of the samples were tested by team members or with the assistance of colleagues and technicans of many university departments. The remainder of the work was carried out commercially by Messrs. Sandberg Ltd.

The most important tests used included:

- Particle Size Analysis
- Chemical Analysis for Acid soluble sulphate and for chloride
- Thermogravimetric analysis
- X-ray diffraction
- Petrographic analysis including thin sectioning
- Acid Insoluble residue
- Electron Microscope photography
- Salt Weathering tests
- Water absorption tests
- Schmidt Hammer tests
- Electrical Conductivity
- Ionic concentrations

Wherever possible these tests were carried out with procedures recommended by British Standards or by manufacturers of equipment, or which are widely recognised as standard laboratory procedures. Where these tests were varied to suit the specific requirements of the Survey details are given in the appropriate section of the report.

II.9 TOPOGRAPHIC SURVEYING

The Survey team included two land surveyors, Mr. H. M. Fielding and Prof. J. C. Pugh, whose primary task was to provide back-up information and support to the rest of the team's programme. Their tasks mainly involved a control survey (including the erection of marker beacons), and levelling.

II.9.1 Control Survey

The aim of the survey was to provide a network of points positioned such that at least two, and preferably three points, when beaconed, were visible from any point on the southern half of the island. These points were for the use of the geologists and geomorphologists for positioning by prismatic compass resection, and were also used as a control for the production of an air-photo mosaic (see below). This survey was carried out by Mr. Fielding.

Ten days were available for the surveying. This was split, approximately as follows:

Reconnaissance and beaconing	3 days
Digging holes for ground marks	2 days
Concreting in ground marks	2 days
Observing	3 days

The area covered was some 18 x 12 kilometres and was exclusively in the southern half of the Island (Fig. II.10), for it is here that least control exists by way of recognisable cultural features in the landscape. Thirty one (31) stations were eventually fixed. The points were marked by metal rods set in concrete blocks at ground level, with beacons about three metres high erected over them. (The designs of the beacons and ground marks are shown in Appendix II.I).

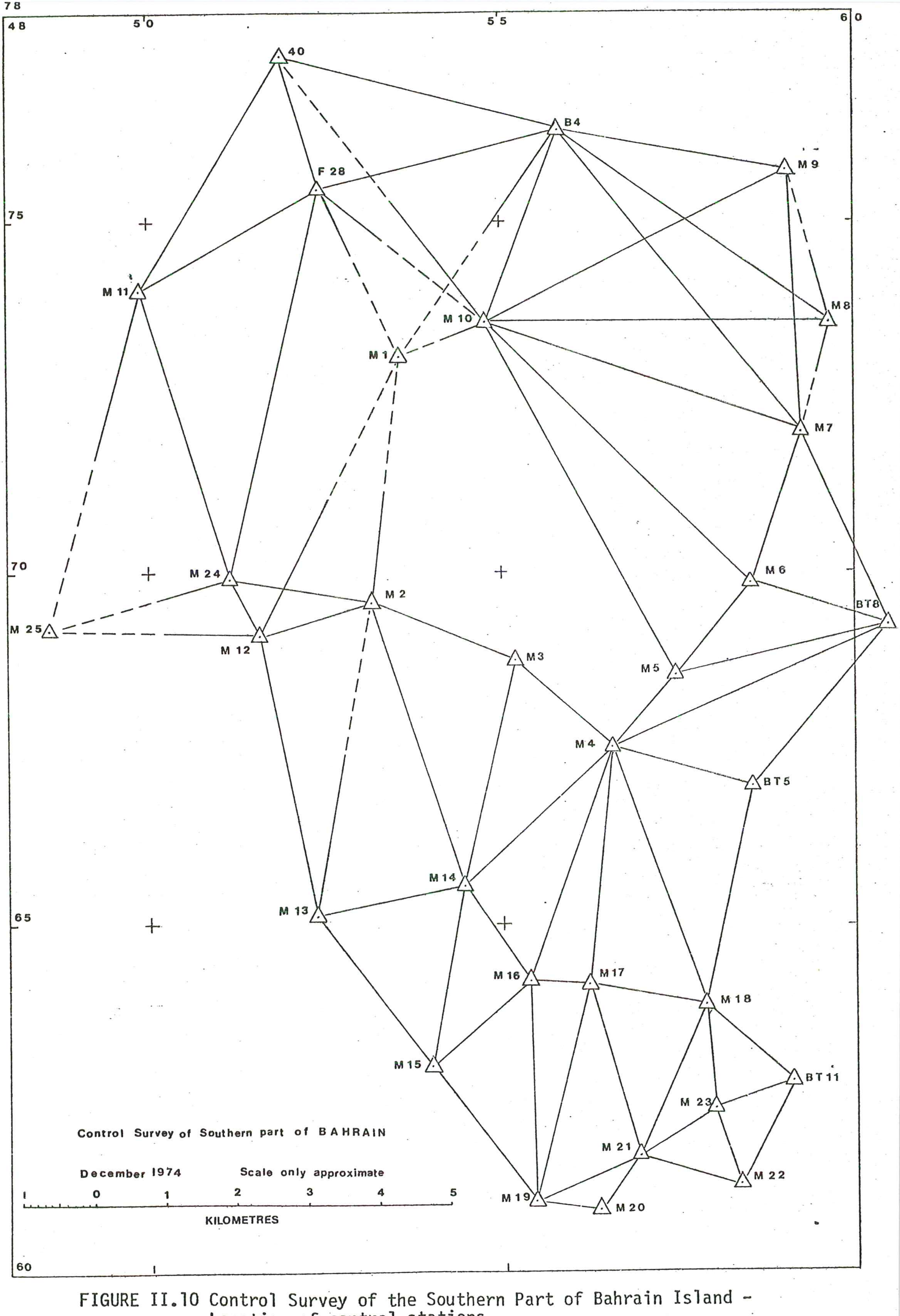


FIGURE II.10 Control Survey of the Southern Part of Bahrain Island - Location of control stations.

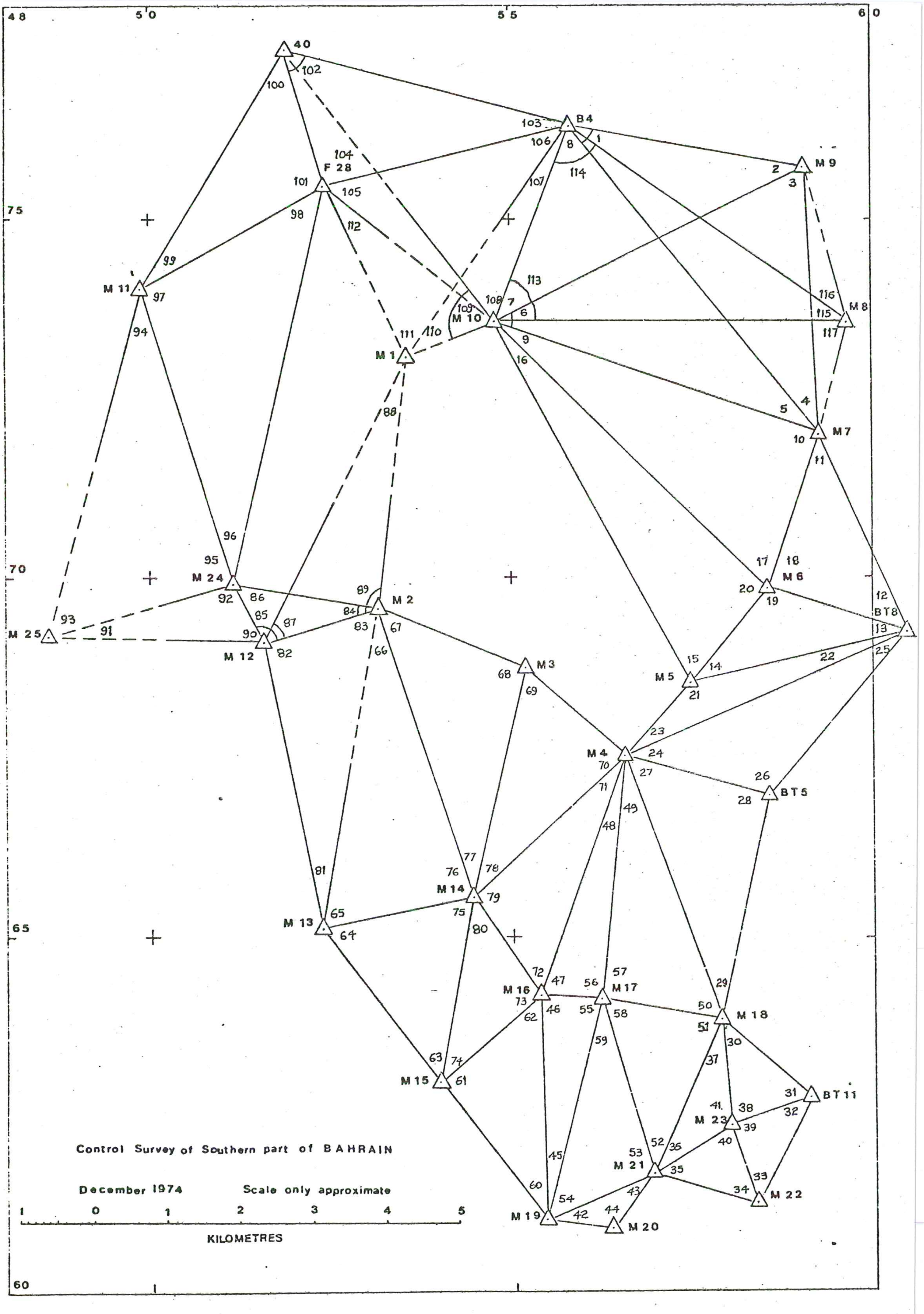


FIGURE II.11 Control Survey of Southern part of Bahrain Island - angular measurements

It was decided that an overall accuracy of ±0.5 metres would be ample for this work, and hence various parts of the survey were relaxed to increase speed. In actual fact the computed accuracy was in the region of ±0.2 metres which falls well within the requirement.

The work was carried out by one man, drivers and up to eight labourers. Progress, although possible, was very difficult and slow, especially for the truck carrying the concreting party. Over a number of rough roads and tracks, 10-15mph was possible, but over the remainder of the area, which was strewn with large rocks, speeds were down to between 0 and 5mph.

The main intervisibility problem in this area was caused by the convex cross-section of slopes in all directions, especially east-west, which meant some of the lines had to be quite short. Although this fact is no detriment to the scheme, it means that other areas are rather sparsely covered because of lack of time. An attempt was made whenever possible to position stations on the largest rises in the area so as to make them as prominent as possible on the low-profile landscape (see Fig. II.12).

In the northern part of the area a ring of ten stations was positioned round the top of the perimeter scarp, with three stations on rises in the Interior Basin. Four points were chosen by the side of the road between the Southwest Sabkha and the backslope, and one point was chosen on an isolated sand dune in the centre of the Southwestern Sabkha.

(a) Design of Scheme

Much of the survey work previously done in Bahrain has been carried out, and computed, on a piecemeal basis, so that different co-ordinate systems tend to cause confusion. It was therefore decided to observe the present scheme as a pure triangulation, and to obtain scale and azimuth by joining the work to one of the existing schemes.

This survey is therefore in sympathy with:

(i) Survey by BAPCO (taken from a manuscript file).

(ii) Survey by Compagnie General Geophysique of France in 1970.

The design of the triangulation caused problems in two areas. First, on the eastern side opposite the southern tip of the scarp a thin triangle M4, M5, BT8 had to be used as the line M5, BT5 was not visible. Secondly around the northwestern corner, where all figures are plain triangles.

The main cause of these two problems was lack of time. Another day on reconnaissance would have enabled better planning, and two extra stations, one in each area, would probably have rectified the situation.

In actual fact, lack of time also prevented observation of two stations in the northwestern area which further weakened the system.

Analysis of the observed angles (see Appendix II.II) showed these areas to be the weakest parts of the scheme, but also indicated that errors were well within the ±0.5 metres required.

As only three days were left at the end of the scheme to observe the 33 stations (about 45 minutes per station, including travelling) it was impossible to observe more than one round of angles at over half the stations. Fifteen (15) stations were observed on two rounds and 18 stations were observed on one round. At the 15 stations where two rounds were observed vertical angles were also observed. In general the angular measurement in the figures is good (see the list of residuals in Appendix II.II) except for the area around BT5 and BT8 where it is thought a beacon could have been out of plumb for some of the observations.

Mis-identification of beacons in three cases caused little problem, as did the lack of observations at M1. M25 is poorly fixed (max. and min. standard errors are 0.845 and 0.494 metres respectively) as:-

(a) observations were not taken from this station,

(b) observations from M11 to M25 are not too reliable owing to haze,

(c) triangle M25, M12, M25 gives a weak fix.

All co-ordinates have been calculated on the Universal Transverse Mercator projection on Clark's 1880 spheroid. Three points, 40, BT8 and BT11 from the previous surveys were accepted as fixed stations, and the observed angles adjusted to produce the best fit.

Computations and adjustment were carried out simultaneously by variation of co-ordinates, using initial co-ordinates scaled from a 1:25,000 plot. As the initial co-ordinates were in some cases in error by quite large amounts, two iterations were made, the largest movement from initial to final co-ordinates in the second iteration being 3.009 metres.

The computer programme used gives standard errors for both Eastings and Northings at each point, as well as for Azimuth and Distance for selected lines. Lists of observed angles and residuals are given in Appendix II.II. Final adjusted co-ordinates and standard errors of co-ordinates in Appendix II.III and standard error in Azimuth and Distance for selected lines in Appendix II.IV.

(b) Photo-mosaic Production

From the data obtained during the control survey it was hoped to produce a semi-controlled photo-mosaic of the 1:10,000 aerial photography for use as base maps for the mapping team during the second fieldwork period, and later as a ready means for data compilation. Owing to many difficulties the final mosaic had to be left uncontrolled, but information as to its scale is supplied for each sheet. (This is listed in Appendix II.V). The final mosaic was photographed and transparencies produced (as a 1:1 reproduction) on a stable film base. (One set of these mosaics, with the identifiable control points marked on them has been lodged with the Ministry of Works, Power and Water in Bahrain.)

The work fell into two parts:

1. Extension of control by slotted templet assembly (S.T.A.)
2. Preparation of mosaic.

The slotted templet assembly method makes the assumption that all height and tilt distortions on the aerial photograph are radial from the plumb point. This is only valid for truly vertical photography. However, for photographs with small tilts, when the ground is relatively flat, the errors introduced are small. Bearing in mind these points, and the fact that the S.T.A. is by far the fastest means of increasing control, it was decided that a laydown would be produced, involving 185 photographs. The laydown was controlled by 17 of the ground control points, 16 of these being taken from the new triangulation scheme and 1 being taken from earlier work.

This was extended to give a final plot on plastic film at the scale of about 1:10,000 of:

35 ground control points

185 principal points

225 pass-points.

The completion of this laydown brought out two things. First that the overall scale of the photography was considerably smaller than 1:10,000, and secondly that the scale of individual photographs varied. While it was reasonably constant for one run, the variation between runs was large.

Alternate photographs were used, working firstly in strips and then building up the strips from the centre outwards to form one complete mosaic for the whole area. As work progressed, discrepancies at joins were removed as far as possible by introducing very small errors into each overlap to obtain a best mean fit. Where possible areas of high detail were joined exactly, and errors 'lost' in plain areas. In a few areas, the scale of one photograph was out by such a large amount that the discrepancy is still very obvious. This was unavoidable, and only rectification of the prints concerned could have helped.

The completed mosaic was cut into 9 sheets, keeping to a regular grid line pattern. (The sheet layout is shown in Fig. II.13.)

A 1:1 negative was produced with a process camera, and contact film diapositives were made from these for use in the field.

Comparisons between principal points and pass points on the 1:10,000 plot and on the diapositives of the mosaic, to give scale for the mosaic, are tabulated in Appendix II.V. The mean scale is in the region of 1:10,480.

II.9.2 Levelling

The levelling was carried out mainly by Prof. J. C. Pugh in locations requested by the geomorphologists and geologists. The purpose being either to establish the elevation of selected sites, or to provide relief (topographic) profiles and cross-sections. All the short cross-sections, and the detail work on the long cross-section were surveyed using the Wild R.D.S. self reducing tacheometer - an instrument which gives a direct readout of the horizontal distance and difference in height between instrument and staff position.

During this work the geologists acted as staff men, this being considered the only way to guarantee the positioning of the points. The information concerning point numbers, layer numbers, surface types etc. was passed to the surveyor over a 'walkie talkie' radio. In some cases additional (or supplementary) data was gathered in a Deodimeter and 1" Theodolite, or by using an automatic level. Overall accuracy in position is estimated to be about 1:250, and in height 1:500. For short sights (i.e. levels on scarp faces) the internal accuracy in height is of the order of ±0.010 metres.

Individual cross-sections are incorporated in the appropriate parts of the geomorphological and geological reports.

No reliable spot heights existed in the southern part of the island, nor were there any consistent height data for the northern quarter of Bahrain. For various surveys in the past individual datum levels have been adopted.

For purposes of the survey, a spot height near the Aluminium Works was accepted as the starting point. This spot height was shown on the most southerly of the 1:2,400 sheets on the east coast. Levelling was carried southwards from this point along the Jaww road, using a CTS Self-adjusting level. Forward and back sights were taken to Sopwith staves, the sight lengths being set out approximately equal by pacing, and corrected if the lengths calculated from stadia readings differed by more than 2 metres, the sight lengths being approximately 35 metres. Stadia readings as well as readings of the horizontal cross wire were taken throughout the six weeks in the field whenever a level was used, as a check on centrality between staves and as a check on instrumental readings. In the later stages, particularly on the flat areas of the southern sabkhas, line of sight was increased to 50-60 metres if heat shimmer was not too pronounced, with an allowable difference of sight length of 4 metres. Length of sight was constricted by topography (being obviously reduced on steeper slopes), by heat shimmer and by wind, which was the greatest problem: on a few days the wind strength and variability were such that the self-adjusting mechanism became a liability through over-rapid correction resulting in image vibration which made reading impossible.

The first stage of the levelling programme, from the initial spot height to Askar village, was levelled in both directions. The difference in the calculated heights for the two lines was 0.023 metres over a total line length of 2825.3 metres. This two-directional levelling procedure was intended first as a training run for the locally recruited labour, and secondly, as a check on accuracy likely to be attained. In view of the results quoted, obtained with labour at that stage still inexperienced, it was thought that one-way levelling would give results of acceptable accuracy provided that stadia intercepts were always read as a check and provided that sight lengths were kept within the limits stated.

Heights were continued southwards by levelling along the road to Jaww and Ad Dur with a diversion to the point of the Ra's Hayyan; thence along the track through the Qurayn adh Dhirbān close to the coast to the tarred road running south-southeast from Hafirah and the artillery range; thence by track to the southeast sabkha and the Ra's al Jamal. Rate of work averaged 5 kilometres per day. Temporary bench marks, consisting of wooden pegs and/or painted marks on the ground, were placed at approximate intervals of 1 kilometre, for later use as required.

From the Ra's al Jamal a levelled profile (line F) was run along the line of soil pits extending on a magnetic bearing of 295°. Levels were continued southwards on the sand track to the point at which profile E left the coast on a magnetic bearing of 315°, and an interconnected system of profiles formed lines A, B, C and D. (Line designations refer to field map originals).

All the profiles in the Southeast sabkha were thus interconnected and related to the East Coast levels. All profiles included points at approximate H.W.M., as judged from beach features of drift material. Some slight variation would be expected at different points around the island, and also as a result of the differences between drift material positions on the beaches. Values obtained from H.W.M. were as follows: (Pits are located on the 1:10,000 geomorphology map sheets (Map Volume C)).

1.850 metres	near Pit 17/19
1.894	near Pit 18/11
1.910	near Pit 18/4
1.921	Pit 17/52
2.004	Ra's al Jamal Pit 17/36
2.045	above Pit 17/37
2.100	on the N. side, Ra's al Jamal
2.182	S. of Askar
2.302	near Ra's al Qurayn

H.W.M. is at approximately 2.00 metres on the original datum.

The range of 0.452 metres may appear large, but it is believed that error in datum for any one profile is small, for reasons stated above. The largest difference of 0.120 metres, between the two highest figures, was over a distance of 12543 metres, giving a variation rate of 0.095 metres per kilometre, which is an acceptable order of change.

Profiles were levelled similarly on the Southwest sabkha, forming an interconnecting system. In the light of the small rate of change of H.W.M. down the East Coast lines, it was decided to save time by referring the Southwest sabkha profiles to approximate H.W.M. datum assessed from beach features in the same manner. The same technique was used to fix heights for the line of soil pits on Umm na'San Island.

Levels from the East coast system were carried up the tarred road to the artillery range and the profiles across the southern playa. Heights given on these profiles are therefore referable to the same East Coast datum.

II.9.3 Tacheometer Surveys

These were carried out by Prof. J. C. Pugh in the area north east of the Jabal ad Dukhan to map the erosion surface profiles and the gully profile in the geomorphological study SSE of Awali (see Vol. IV). A 1" theodolite was used, with vertical circle readings made to a Sopwith staff at a height above base equal to the height of the trunnion axis above the station mark, and stadia readings taken for calculation of vertical difference and horizontal distance.

Tacheometer surveys were also used for the calculation of low angle dips across the Jabal ad Dukhan. A closed traverse was run round the main hill mass, and adjusted for co-ordinate calculation, and branch lines were extended into the valleys and on both sides of the southern Jabal. From co-ordinated points observations were taken to Sopwith staff positions on relevant geological formations and co-ordinates and altitudes calculated across the entire hill mass. All altitudes were related to spot height of 107 metres on the southern Jabal.

II.9.4 Yardang Surveys

Measurements were made to profile both large and small yardangs. On long and cross profiles, readings were taken with the self-adjusting level to staff positions set out by tape at every metre. Plans were drawn by offset measurements from a taped line (see Volume IV).

II.10 MAP PRODUCTION

A map is no more accurate than the base map upon which it is compiled. This Survey was dependent upon the base map material already available at the commencement of its work. It had no brief to produce a new topographic survey in order to provide an improved base for its own specialist mapping programme.

Once it had been decided that the geology and geomorphology of Bahrain was to be mapped at a scale of 1:10,000 there then remained the problem of finding both a suitable mapping base and a convenient method of map compilation. These remained two quite different problems. The 1:10,000 air photo cover of 1964 provided a complete cover of Bahrain (except for the Hawar Islands) on which the field information could be plotted directly. There was no 1:10,000 base map, however, to which the data could be transferred. As a result such a base map had to be made out of the available maps and air-photos, and within the short time period available. The northern half of the mainland of Bahrain, including Muharraq and Sitrah, carries many roads and cultural features which are shown on the 1974, 1:50,000 topographic map of Bahrain. These occur in sufficient density to allow a transfer of information from the aerial photographs using the cultural features as locational controls. The 1:10,000 base map for the north was thus obtained by photographically enlarging the 1:50,000 map. The transfer of information was not always easy in that the aerial photographs display not only the usual distortion and scale changes towards the photo margin, but scale also varied from photograph to photograph and none were at precisely 1:10,000. However, with the aid of a Zeiss Sketchmaster, it was possible to complete a transfer of information from the air-photos to the 1:10,000 map by this method.

The southern half of the Bahrain mainland presented quite a different problem. Here there are few cultural features to provide a locational control, and consequently a photographic enlargement of the 1:50,000 topographic map would have served no useful purpose. Instead it was necessary to build up a partially-controlled air-photo mosaic. This is a very time-consuming procedure and involved first of all a field triangulation survey to establish precisely the relative positions of selected control points (see Section II.9.1). The triangulation stations were identified on the aerial photographs so that they could be laid down on a firm base at their correct relative positions and true to scale. The other photographs for the south were then keyed-in to these fixed points so as to provide a mosaic of photographs for the whole area. This mosaic was then photographed to provide base maps on which the field data could be plotted, there being little difficulty in recognising the same physical features on both the air-photos used for field mapping and the air-photo mosaic used for final map compilation.

Because of the intense pressure of time both at the field triangulation stage and in the air-photo mosaic preparation stage it was not possible to do the same for the northern part of the country. Nor was it possible to match each photo boundary exactly with that of adjacent photos. Variations in photo scale are partly responsible for this and these variations are indicated by the data in Appendix II.V .Since the air-photo mosaics were used as base maps for map compilation these scale variations naturally carry through to the final maps. This produces considerable difficulty in establishing the correct position of the grid lines, and they have been drawn as a best estimate of their actual coincidence with the information on the published 1:50,000 topographic map. In order to bring the maps based on the air-photo mosaic to (approx.) the same scale as those based on the enlargement of the 1:50,000 sheets, the former have been photographically enlarged by a small amount. The distribution of the final map sheets is shown in Figure II.1 .

An unusual feature of the maps is that they have been reproduced at field mapping and compilation scales. Normally they would have been photographically reduced to 1:20,000 for reproduction. This was not done for two reasons. The first is that the complexity of landforms in the Interior Basin is such that a reduction would have involved the loss of mapping detail. The second is that subsequent users of these maps may well require to plot additional information, or make corrections, that will require the space provided by a 1:10,000 reproduction. An inherent consequence of this decision is that some areas thus appear to be devoid of detailed information. This is usually a reflection of a real difference in physical complexity. Areas which appear as uniform on the maps (e.g. parts of the Dammam Backslope, parts of the coastal and northern areas) are in fact uniform in their characteristics displaying very little surface indication of changes in materials. However, it must be recognised that more fine detail could have been recorded in some of these areas. There would probably have been little point in doing so. Indeed, it was a conscious decision, for example, not to map low-amplitude, random, and small variations in the character of the main backslope around the rim of the Interior Basin because these were judged to have no bearing on the fundamental terms of reference under which the work was being carried out. The team did not have the time to pause over the finest details where no economic justification could be made for doing so.

For the Hawar Islands it was only possible to obtain air-photo cover at a nominal scale of 1:30,000. It was only possible to make a one-day visit to this part of Bahrain. The map of the area is thus only a tentative photo reconnaissance map with a minimum of field checking. The same is partly true for the Umm na'San map for the actual field checking was kept to a minimum at the request of the Government.

The 1:50,000 maps (Map Volume A) of Geology, Geomorphology and Superficial Materials, Soils and Land Capability for Agriculture, have been produced by optical (non-photographic) reduction methods by more than one operator from the 1:10,000 map sheets. The compilation was done on a 1:50,000 base which provided very weak locational control for much of Bahrain. As a result some errors in location have crept in, and the various maps do not always match each other precisely in detail.

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APPENDICES II.I-V

DETAILS OF THE LAND SURVEYING

Bahrain Surface Materials Resources Survey, 1976

APPENDIX II.I

DESIGN OF BEACONS AND GROUND MARKS

Beacons

These were of a tripod design made out of 3" x 3" timber. Two legs $3\frac{1}{2}$ metres long were joined $\frac{1}{2}$ metre from the top by a bolt, and a third leg 3 metres long was fastened to one of the long legs with a hinge. Three 1 metre x 4" x $\frac{1}{2}$" boards were provided with each beacon, and these were nailed, each to two legs, at ground level. A half metre strip of "Dayglo" orange cloth was then fastened round the top for a target.

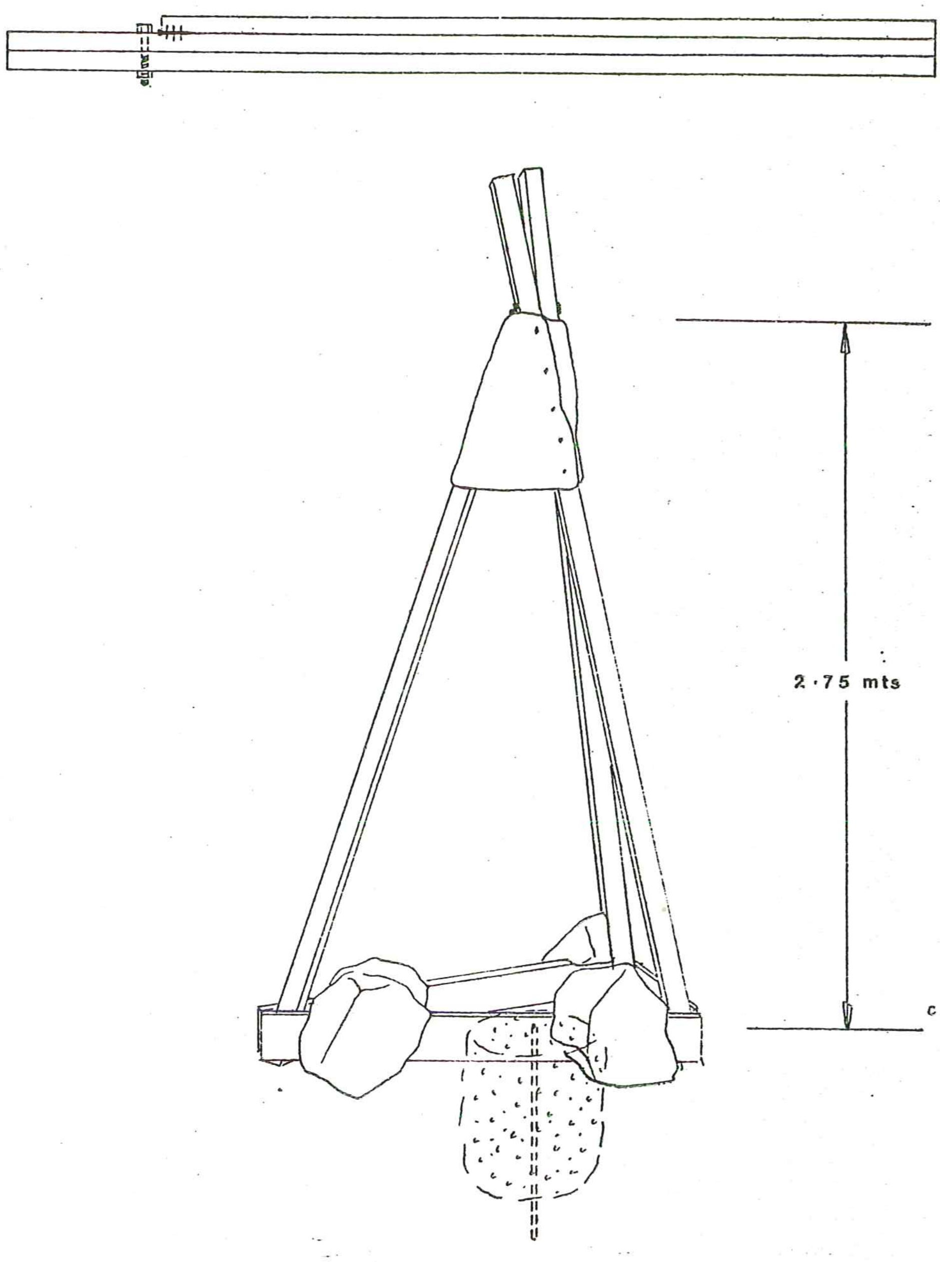
The beacons were held in position by piling rocks round the base on these horizontal boards. In two cases (M11 & M25) the area was sand. The beacons at these stations were dug about $\frac{1}{2}$ metre into the sand, and appeared to be quite stable.

All the wood for these beacons was prepared locally prior to the survey, the three legs being connected together at this stage. One beacon could be erected in approximately five minutes.

Ground Marks

These were blocks of approximately 30 centimetres diameter and 30 to 40 centimetres deep (depending on ground conditions) made with sulphate resistant cement. The points were marked with a $\frac{1}{2}$" diameter length of reinforcement rod, which were at least the depth of the concrete, and hammered into the ground where possible. In a number of cases where the concrete went down to bedrock (at M15, bedrock was about 10 centimetres below the surface) the rods were bent at the bottom to make them secure.

The beacon at M11 is on deep sand, and therefore, at this point a cylinder about 70 centimetres long was made. M25 has no ground mark, as this station was not decided upon until late in the scheme after all the concreting had been finished.



BEACON CONSTRUCTION

FIGURE II.12

APPENDIX II.II

OBSERVED ANGLES AND THEIR RESIDUALS

No.	At	Between		Angle	Residual	No.
1	B4	M9	M7	41° 10' 10"	-1.16	1
2	M9	M10	B4	36 50 24	0	2
3	M9	M7	M10	66 18 18	0	3
4	M7	B4	M9	35 41 08	1.16	4
5	M7	M10	B4	31 54 44	-2.96	5
6	M10	M9	M7	46 05 46	5.80	6
7	M10	B4	M9	42 47 28	3.93	7
8	B4	M7	M10	59 11 51	4.22	8
9	M10	M7	M6	25 37 38	5.48	9
10	M7	M6	M10	90 16 05	-18.34	10
11	M7	BT8	M6	42 47 15	6.43	11
12	BT8	M6	M7	48 54 04	-13.86	12
13	BT8	M5	M6	30 38 25	17.54	13
14	M5	M6	BT8	37 59 33	17.68	14
15	M5	M10	M6	66 33 17	-15.91	15
16	M10	M6	M5	17 13 50	-6.01	16
17	M6	M10	M7	64 06 44	-14.14	17
18	M6	M7	BT8	88 18 46	2.23	18
19	M6	BT8	M5	111 21 00	26.78	19
20	M6	M5	M10	96 13 30	-15.08	20
21	M5	BT8	M4	145 03 06	-13.49	21
22	BT8	M4	M5	10 48 20	-3.41	22
23	M4	M5	BT8	24 09 16	-25.10	23
24	M4	BT8	BT5	40 41 52	15.58	24
25	BT8	BT5	M4	24 35 53	2.64	25
26	BT5	M4	BT8	114 41 57	-0.23	26
27	M4	BT5	M18	55 00 54	16.66	27
28	BT5	M18	M4	93 39 10	-0.02	28
29	M18	M4	BT5	31 19 42	-2.65	29
30	M18	BT11	M23	43 07 32	0.08	30
31	BT11	M23	M18	60 29 41	8.04	31
32	BT11	M22	M23	45 02 04	-1.81	32
33	M22	M23	BT11	43 47 37	1.21	33
34	M22	M21	M23	55 02 56	-7.75	34
35	M21	M23	M22	49 53 58	-5.47	35

Appendix II.II (cont.)

No.	At	Between		Angle	Residual	No.
36	M21	M18	M23	33° 54' 45"	5.84	36
37	M18	M23	M21	28 41 21	5.87	37
38	M23	M18	BT11	76 22 34	4.88	38
39	M23	BT11	M22	91 10 22	-2.40	39
40	M23	M22	M21	75 03 28	-8.78	40
41	M23	M21	M18	117 23 36	6.29	41
42	M19	M21	M20	32 16 41	-4.67	42
43	M21	M20	M19	29 10 56	-4.67	43
44	M20	M19	M21	118 32 37	-4.67	44
45	M19	M16	M17	15 26 19	3.85	45
46	M16	M7	M19	89 58 20	-1.50	46
47	M16	M4	M17	69 37 58	0.94	47
48	M4	M17	M16	14 05 35	-2.77	48
49	M4	M18	M17	25 53 48	1.85	49
50	M18	M17	M4	60 44 09	-2.25	50
51	M18	M21	M17	76 18 06	-4.83	51
52	M21	M17	M18	40 16 29	2.16	52
53	M21	M19	M17	97 49 48	3.47	53
54	M19	M17	M21	49 49 23	4.09	54
55	M17	M19	M16	74 35 21	-2.35	55
56	M17	M16	M4	96 16 29	-0.17	56
57	M17	M4	M18	93 22 01	2.41	57
58	M17	M18	M21	63 25 29	-1.33	58
59	M17	M21	M19	32 20 40	1.44	59
60	M19	M15	M16	35 05 38	-1.24	60
61	M15	M16	M19	94 12 39	1.34	61
62	M16	M19	M15	50 41 43	-0.10	62
63	M15	M13	M14	50 06 20	-1.54	63
64	M13	M14	M15	64 09 19	0.12	64
65	M13	M2	M14	66 46 13	-0.99	65
67	M2	M3	M14	50 33 24	3.19	67
68	M3	M14	M2	98 38 26	1.90	68
69	M3	M4	M14	61 20 52	5.35	69
70	M4	M14	M3	82 37 08	4.05	70
71	M4	M16	M14	27 31 27	-0.81	71
72	M16	M14	M4	53 50 51	-5.01	72

Appendix II.II (cont.)

No.	At	Between		Angle	Residual	No.
73	M16	M15	M14	95^{o} 51' 11"	2.67	73
74	M15	M14	M16	39 45 08	3.35	74
75	M14	M15	M13	65 44 18	-1.59	75
76	M14	M13	M2	84 24 28	-2.72	76
77	M14	M2	M3	30 48 05	-0.09	77
78	M14	M3	M4	36 01 48	2.50	78
79	M14	M4	M16	98 37 51	-3.18	79
80	M14	M16	M15	44 23 30	4.98	80
81	M13	M12	M2	21 51 09	-4.66	81
82	M12	M2	M13	94 41 27	0.66	82
66& 83	M2	M14	M12	91 16 50	0.70	66& 83
84	M2	M12	M24	25 56 48	-12.63	84
85	M12	M24	M2	100 54 10	-12.71	85
86	M24	M2	M12	53 09 40	-12.66	86
87	M12	M1	M2	45 51 57	-5.32	87
89	M2	M12	M1	114 00 33	-4.34	89
90	M12	M25	M24	60 58 58	0	90
92	M24	M12	M25	101 32 03	-0.38	92
95	M24	M25	M11	89 22 29	-0.38	95
96	M24	M11	F28	30 04 57	8.58	96
97	M11	F28	M24	102 47 50	11.71	97
98	F28	M24	M11	47 06 43	9.72	98
99	M11	40	F28	29 20 36	-8.61	99
100	40	F28	M11	47 02 52	-3.63	100
101	F28	M11	40	103 36 52	-7.75	101
102	40	B4	F28	59 23 04	3.40	102
103	B4	F28	40	28 30 16	1.60	103
104	F28	40	B4	92 06 37	-2.00	104
105	F28	B4	M10	51 23 57	4.58	105
106	B4	M1	F28	41 10 45	1.09	106
107	B4	M10	M1	14 55 33	0.50	107
108	M10	40	B4	58 25 36	6.46	108
109	M10	M1	40	73 30 20	-0.56	109
112	F28	M10	M1	26 15 13	-0.59	112

Appendix II.II (cont.)

No.	At	Between		Angle	Residual	No.
113	M10	B4	M8	69^{o} 32' 58"	4.00	113
114	B4	M6	M10	75 22 01	5.03	114
115	M8	M10	B4	35 04 52	-0.02	115
116	M8	B4	M9	38 26 00	-0.18	116
117	M8	M7	M10	74 23 51	1.12	117

APPENDIX II.III

CONTROL SURVEY, BAHRAIN

FINAL ADJUSTED CO-ORDINATES

	Eastings	Northings
M1	453619.321	2873025.120
M2	453179.472	2869525.423
M3	455193.224	2868740.513
M4	456645.283	2867463.549
M5	457581.968	2868528.768
M6	458631.538	2869858.662
M7	459355.878	2872009.741
M8	459779.699	2873576.593
M9	459127.188	2875717.286
M10	454888.886	2873536.787
M11	449888.104	2873962.827
M12	451561.266	2869036.551
M13	452340.242	2865084.841
M14	454477.711	2865559.888
M15	453955.462	2863045.105
M16	455368.747	2864169.883
M17	456233.924	2864157.529
M18	467874.147	2863854.707
M19	455325.556	2861036.902
M20	456289.479	2860895.758
M21	456929.716	2861749.321
M22	458328.776	2861295.494
M23	457988.698	2862489.143
M24	451131.044	2869854.556
M25	448547.696	2869103.652
M26	452440.494	2875414.758
M27	455881.730	2876267.107
M28	458552.833	2866910.225
BT8	460589.100	2869263.030
BT11	459070.983	2862764.004
40	451897.913	2877304.327
102	456276.794	2853418.023

STANDARD ERRORS OF CO-ORDINATES

	Std. Error in Eastings	Std. Error in Northings
M1	0.176	0.170
M2	0.183	0.361
M3	0.183	0.281
M4	0.156	0.201
M5	0.157	0.118
M6	0.111	0.068
M7	0.134	0.152
M8	0.172	0.305
M9	0.195	0.206
M10	0.151	0.155
M11	0.195	0.235
M12	0.205	0.401
M13	0.273	0.304
M14	0.177	0.238
M15	0.262	0.237
M16	0.180	0.188
M17	0.147	0.163
M18	0.102	0.115
M19	0.254	0.227
M20	0.220	0.211
M21	0.158	0.153
M22	0.130	0.123
M23	0.087	0.075
M24	0.217	0.423
M25	0.835	0.511
F28	0.084	0.127
B4	0.162	0.167
BT5	0.135	0.165
BT8	FIXED	
BT11	FIXED	
40	FIXED	

APPENDIX II.IV

STANDARD ERROR IN AZIMUTH & DISTANCE
FOR SELECTED LINES

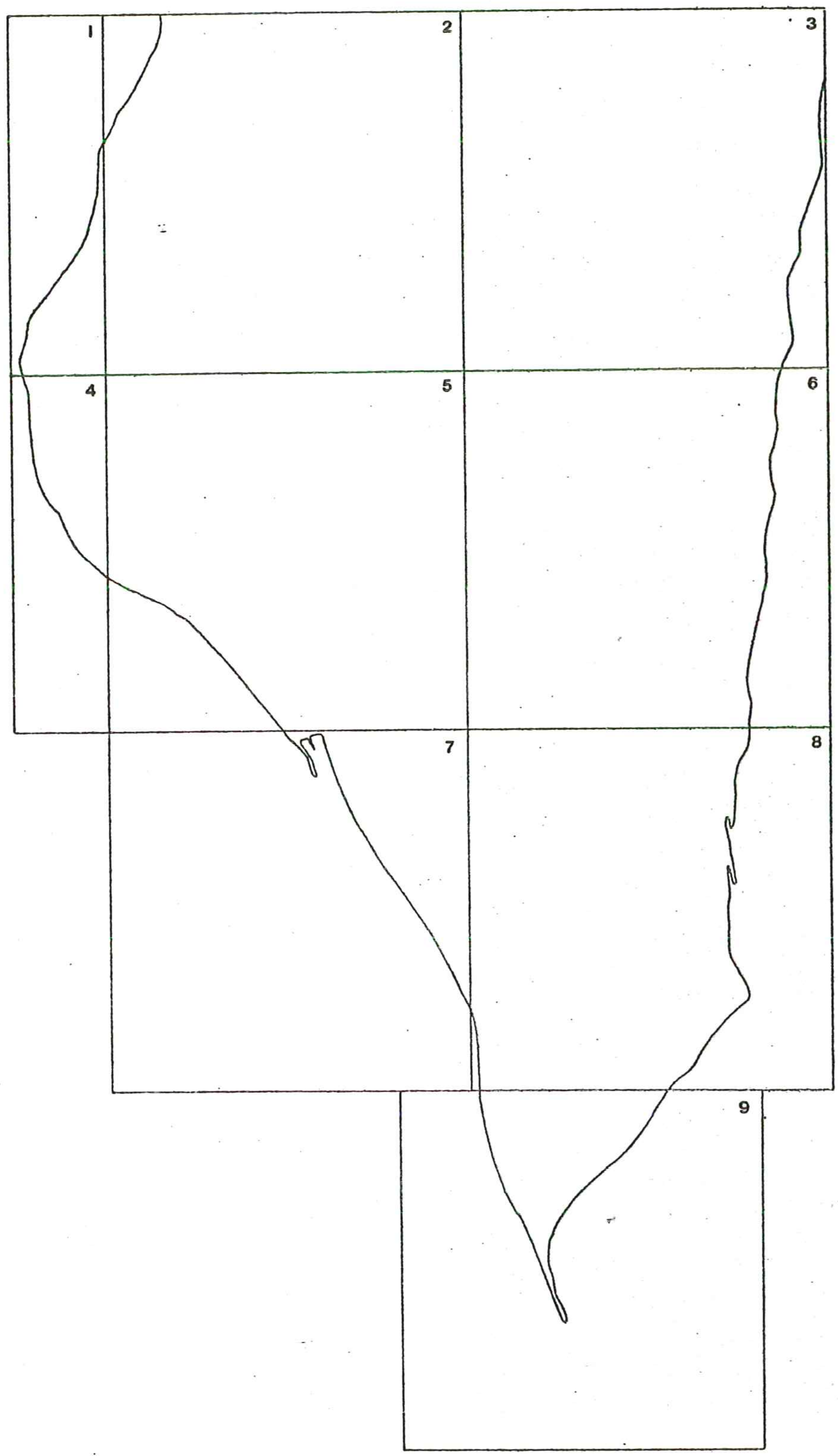
Line	S.E. in Azimuth	S.E. in Distance	P.P.M.
M1 - M2	10.13 sec	0.3497M	99
M3 - M4	12.21	.1356	70
M5 - M6	6.47	.1369	81
M7 - M8	14.53	.2743	169
M9 - M10	7.29	.1494	31
M11 - M12	7.95	.3341	64
M13 - M14	10.54	.1400	64
M15 - M16	10.54	.1165	64
M17 - M18	8.74	.0919	55
M19 - M20	14.99	.1091	112
M21 - M22	15.31	.1225	83
M23 - M24	6.65	.3510	35
M25 - F28	18.85	.6578	89
B4 - BT5	4.57	.1836	19
BT8 - BT11	FIXED		
M1 - M10	11.67	.1391	102
M1 - M20	5.02	.2633	21
M1 - BT8	4.75	.1623	20
M1 - BT11	3.30	.1587	14
M1 - 40	8.24	.1602	35
M10 - M20	4.39	.2604	20
M10 - BT8	4.37	.1549	22
M10 - BT11	2.68	.1560	14
M10 - 40	6.44	.1558	32
M20 - BT8	4.40	.2294	24
M20 - BT11	11.92	.2354	70
M20 - 40	2.78	.2010	12

APPENDIX II.V

MOSAIC SCALE FOR ALL SHEETS TAKEN

N-S, E-W, NW-SE & NE-SW

Sheet No.	Line	Between Point No.	Photo^{mm} Distance	Plot^{mm} Distance	Scale
1	N S	2 327 2 332	405.8	423.3	1:10,431
E	W E	2 332 002	219.0	231.4	10,566
2	N S	063 071	574.1	607.9	10,589
	W E	024 088	508.9	541.8	10,646
	NW SE	020 2 151	874.0	918.3	10,507
J	NE SW	083 029	798.2	842.2	10,672
3	N S	172 179	601.5	629.4	10,464
	W E	110 202	492.1	511.3	10,390
	NW SE	107 207	774.8	815.7	10,528
B	NE SW	199 113	781.7	811.2	10,377
4	N S	2 333 2 338	415.9	436.0	10,483
E	W E	2 333 003	199.3	210.7	10,572
5	N S	2 247 2 254	617.8	652.5	10,562
	W E	035 2 155	615.9	645.6	10,482
	NW SE	030 2 159	857.7	904.7	10,548
C	NE SW	2 152 2 258	724.4	763.3	10,537
6	N S	1 926 1 933	648.2	684.1	10,554
	W E	118 212	493.6	512.0	10,373
	NW SE	114 216	853.7	891.9	10,447
D	NE SW	209 3 700	778.9	815.0	10,463



M O S A I C   S H E E T   I N D E X

FIGURE II.13

Appendix II.V (cont.)

Sheet No.	Line	Between Point No.	Photo mm Distance	Plot mm Distance	Scale
7	N S	2 160 131	617.9	641.2	1:10,377
G	W E	2 255 2 160	348.2	370.3	10,634
8	N S	1 934 1 941	650.1	669.3	10,297
	W E	3 797 220	421.2	429.1	10,188
	NW SE	3 699 1 832	700.6	719.9	10,275
A	NE SW	1 840 3 692	694.3	714.2	10,287
9	N S	166 171	503.3	536.1	10,652
	W E	3 689 225	388.9	416.1	10,699
H	NE SW	224 Δ 102	494.2	518.3	10,488

APPENDIX II.VI

REVIEW OF THE PHOTOGEOLOGICAL STUDY MADE BEFORE THE CONCEPTION OF THE PRESENT SURVEY

During part of 1973 and 1974, a photointerpretative study of Bahrain, its adjacent islands and near shore areas was carried out for the Ministry of Development and Engineering Services of the State of Bahrain. This work was performed by Leigh A. Readdy and John W. Norman of the Photogeology and Remote Sensing Laboratory, Geology Department, Imperial College, London, under sub-contract to Messrs. Sandberg Consulting Engineers.

This initial study resulted in a set of four photointerpretative maps, accompanied by a report on the techniques used and the findings obtained. The initial photointerpretation resulted in an inexpensive preliminary set of materials maps that required field checking. The resulting data, however, indicated areas with potential engineering problems as well as probable sources of engineering construction materials.

The initial photointerpretative study resulted in a basic set of four map sheets. These were:

Sheet 1 - Bahrain Main Island, Terrestrial Superficial Deposits including playas and Sabkhas

Sheet 2 - Bahrain Main Island, bedrock deposits

Sheet 3 - Western offshore and Island areas, terrestrial and submarine superficial deposits and bedrock

Sheet 4 - Eastern offshore and Island areas, terrestrial and submarine superficial deposits and bedrock.

Sheets 1 and 2 are reproduced in Map Volume A of the present report. They indicate the starting point for the work of the Survey team.

The aerial photography utilized in the photo-interpretation consisted of 201 panchromatic black-and-white photographs, having a scale of 1:20,000.

This photography was collected by the British Royal Air Force during 1969 and 1970. Most of the photography was taken on 21 June 1969, but additional photographs required to meet photogrammetric standards were obtained on 24 February 1970.

The quality of the photographs was graded by Dr. J. W. Norman into three grades of quality, the percentage in each category being:

good	79%
poor, but mainly adequate	15%
poor, with defects seriously affecting interpretation	6%

The main defects within those photographs classed as "poor" were hot spots, which reduced tonal contrasts in inland areas, and back scatter glare from the marine surface, which obscured the submarine geology. These resulted in some of the breaks in boundaries seen on the original photointerpretative maps.

Other defects included "crab" (an angular misorientation between the photo axis and the flight path of the aircraft), "tilt" (deviation of the camera optic axis from the vertical), and scale variations resulting from the lack of maintaining a constant elevation above the terrain. On the whole these defects did not adversly affect the interpretation. Tilt and scale changes did however, cause local problems during compilation.

The main problem faced during the photointerpretation was the scale of photography used. The use of 1:20,000 scale photography limited the amount of data that could be interpreted and plotted. Some of the smaller features, that may have been important to an engineering geology study could not be plotted.

There is an interesting trade off regarding photographic scale and photo interpretation. The initial cost of obtaining lower altitude (e.g. 1:10,000 scale) photography rather than 1:20,000 scale is only slightly higher per unit area. The main difference in acquisition cost is the additional flying hours required. The additional costs of film and processing are relatively insignificant by comparison. However, when it comes to interpretation the cost of interpretation of 1:10,000 scale photography is roughly four times (4X) that for interpretation of 1:20,000 scale photography. This results from the fact that approximately four times as many photographs must be interpreted. This additional cost is usually more than offset by the increase in the amount of data that may be derived from interpretation of the lower altitude photography and the higher degree of confidence achieved. From experience gained during the field study and examination of the 1:10,000 panchromatic photography, it is estimated that the additional information available and plottable at the 1:10,000 scale would have resulted in a more meaningful initial interpretation with at least four times the detail obtained in the original study.

The photogeological criteria used to interpret the materials included combinations of land forms, photographic tone, texture and pattern, vegetation, and drainage characteristics. These criteria were exploited on the basis of past interpretative experience with similar materials and environments. Correlation was made with known local geology, and with local spot ground identifications provided by Messrs. Sandberg.

The final interpretation assigned to each unit was based on the significance of converging photo derived evidence. The choice between possible alternative interpretations was often based on subjective decisions. This is the only way that a non-field checked photo interpretation could proceed.

For purposes of map compilation the engineering geological data was annotated on working overlay sheets of the same 1:20,000 scale as the photographs. The 1:24,000 scale base map provided was photographically enlarged to this scale. Data from the overlays was then plotted on the enlarged map, using roads and similar cultural features as controls.

Positional errors due to tilt and scale variations were partially corrected by fitting the geological features to the base. In several places the coastline shown on the base map was modified to fit the photography.

Every effort was made to maintain positional accuracy during compilation. However, positional accuracy will be found to vary slightly over the maps, as a result of the combination of plotting errors in the original base map, normal distortions on the photographs, errors in fitting to the base, and other unavoidable plotting errors.

The amount of detail shown on the photointerpretative maps stretches the reliability limit of the type and scale of the photography used. However, it was considered preferable to show as much detail as possible, rather than the generalized boundaries conventionally depicted on this type of map.

The grid used on the original photointerpretative map sheets was that shown on the BAPCO base map provided. This is the BAPCO grid, having its origin near the centre of the Island. The north south grid lines match those shown on the 1:63,000 photogrammetric mapping prepared by Fairey Aerial Surveys for the Bahrain Government. Latitude and longitude reference marks are shown at the margin of the maps.

In future work of this kind in the Arabian Gulf area, it is strongly recommended that a different approach is utilised. The initial study of the very gross features should be done with high altitude photography, e.g. 1:40,000-1:50,000 at the same time initiating interpretation of 1:10,000 scale panchromatic or colour aerial photography. This would allow both continuity and detailed analysis to be quickly developed. Early in the interpretative phase a short, but intense, period of field work should be possible. A slightly longer period of field checking should be allowed prior to completion of the final map. The resulting maps would have a much higher degree of confidence, and would provide more data to the user than the non-field checked photointerpretative maps made from

1:20,000 scale photography. Such 1:10,000 scale photointerpretative sheets would form an ideal data base for use by a multi-disciplinary team studying surface materials.