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ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF RE-INJECTING OIL-FIELD WATER INTO THE MIOCENE CLASTIC SEDIMENTS ON THE SHALLOW AQUIFER IN THE BU HASA OIL FIELD, UNITED ARAB EMIRATES

By
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B. Sc. in Geology 1982

A Thesis Submitted to the Faculty of Science of the United Arab Emirates
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for the Degree of Master of Science
in
ENVIRONMENTAL SCIENCE

Faculty of Science
U. A. E. University
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The thesis of Khalid Ali Al-Amari for the degree of Master of Science in Environmental Sciences is approved .

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United Arab Emirates University
1997

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ABSTRACT

The Bu Hasa oil field is located about 200 km southwest of Abu Dhabi City in the U.A.E. Oil production from the field started in 1965 and a water injection program was initiated in 1970. This research is focused on the assessment of the environmental hazards to the Quaternary Liwa aquifer from either the re-injection of oil-field water into the Miocene Clastic aquifer or surface dumping into unlined pits.

Well logs, core samples, structure and isopach contour maps, stratigraphic cross sections, and water chemistry analyses were utilized in this study. Moreover, a detailed hydrogeological aquifer assessment was conducted and a classification scheme for the various brines was established.

Iso-salinity contour maps over the Bu Hasa field area indicate a general increase in salinity from 2,000-3,000 mg/l in 1964 to 5,500 mg/l in 1996.

Stable isotopic analysis of water samples from the Liwa and Bu Hasa areas suggests that the oil-field water and water of the Quaternary Liwa aquifer have different signatures. This result implies the lack of fluid communication between the Miocene Calstic and the Liwa aquifer. This observation is further supported by the presence of an effective sealing interval represented by the Miocene evaporites that isolate the two aquifers.

Integrated geologic, hydrogeologic, hydrochemical and stable isotope analyses, indicate that the disposal of oil-field waste water into the Miocene Clastic aquifer in the Bu Hasa area does not contaminate the shallow Quaternary aquifer. In contrast, the same analyses demonstrate that the disposal of brines in unlined pits is the practice that has a definite adverse effect on the Quaternary Liwa aquifer in the Bu Hasa area.

TABLE OF CONTENTS

Page

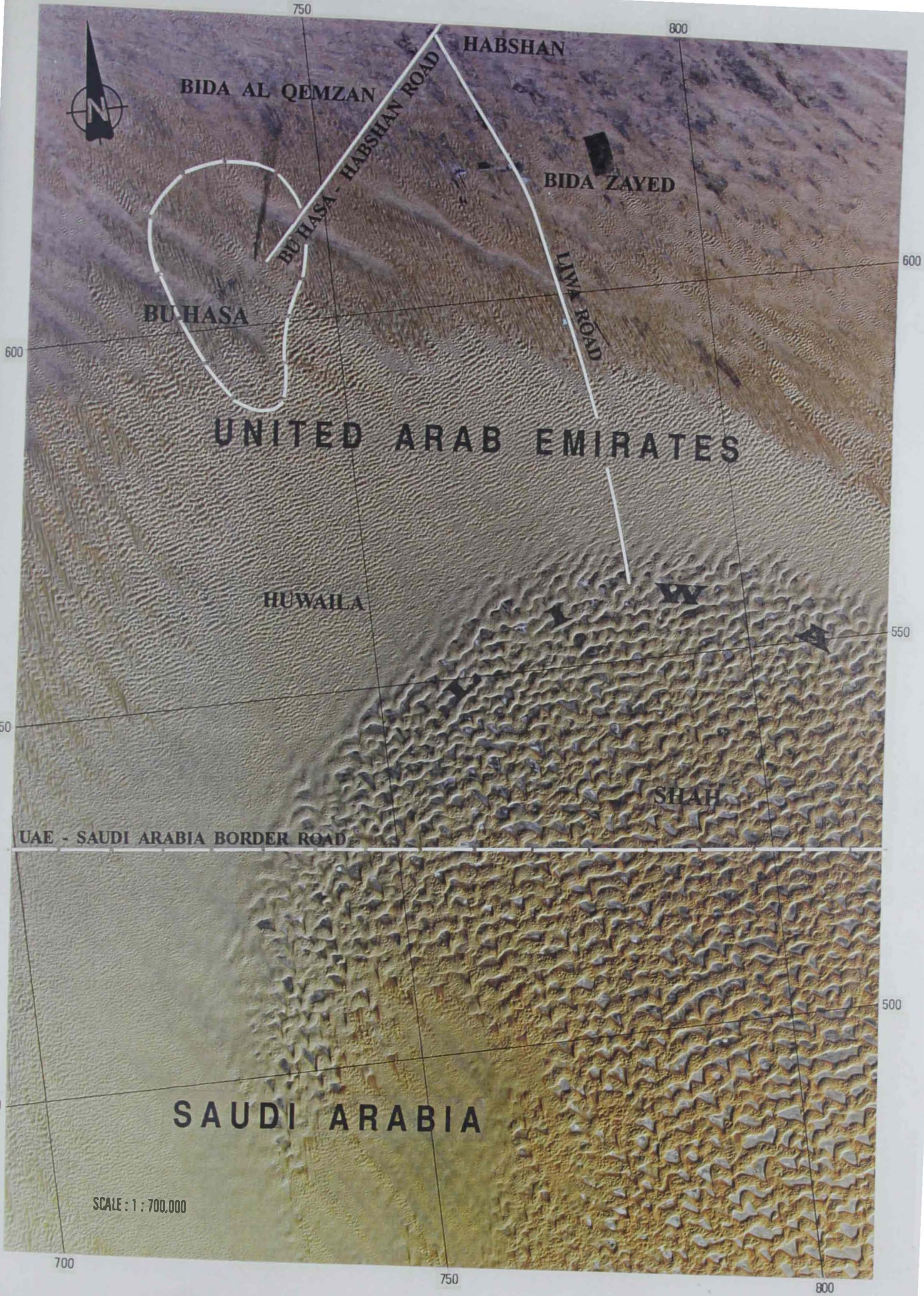
LIST OF FIGURES

Figure **Page**

Figure Page

Figure **Page**

LIST OF TABLES



Landsat image of the Bu Hasa Field and surrounding vicinity.

Chapter I

Introduction

CHAPTER I

INTRODUCTION

Bu Hasa oil field, the subject of this study, was discovered in 1962 on a seismic anomaly (Figure 1). Oil production started in 1965 from the Lower Cretaceous Shuaiba Formation as the principal productive horizon, with some production coming from the Upper Kharaib Formation (Thamama zone B). The total daily production from the field in the year 1996 was nearly 450,000 barrels (bbls). In the 1970's, there was a significant drop in the reservoir pressure that necessitated the introduction of a secondary recovery method. A water injection program was therefore initiated to maintain the reservoir pressure. About 5,500 billion barrels of water supplied from the Simsima, Umm Er Radhuma (UER) and Dammam aquifers, were injected into the field, during the period 1970-1996 (Figure 2).

After oil is produced. entrained water (produced water cut) is separated from the oil in surface facilities. Although water and oil are separated, some hydrocarbons, especially fatty acids. will always remain in emulsion.

The produced water cut, with an average concentration of 280 (ppm) oil and Total Suspended Solids (TSS) of 90 mg/l. was

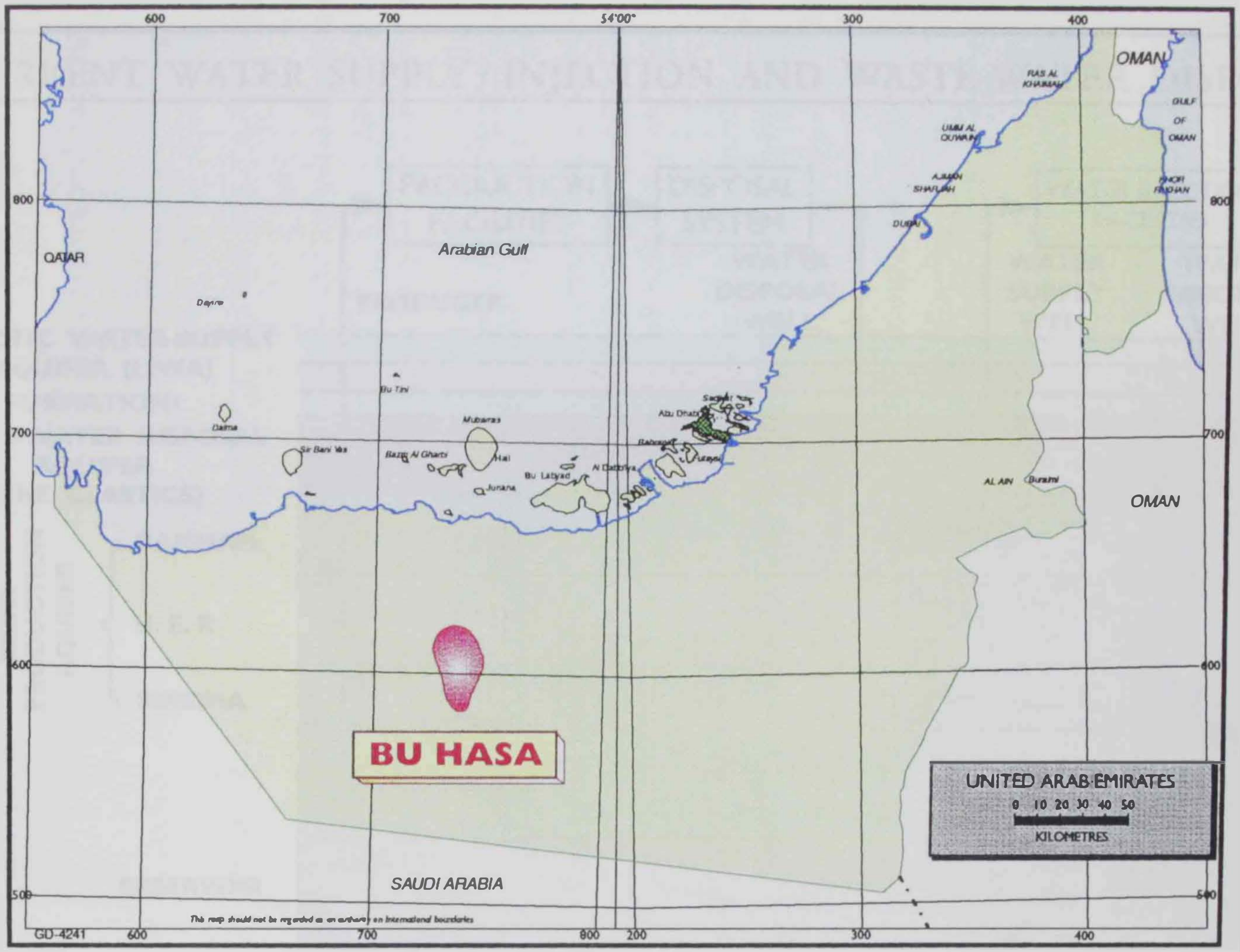


Figure 1. Location map of Bu Hasa oil field

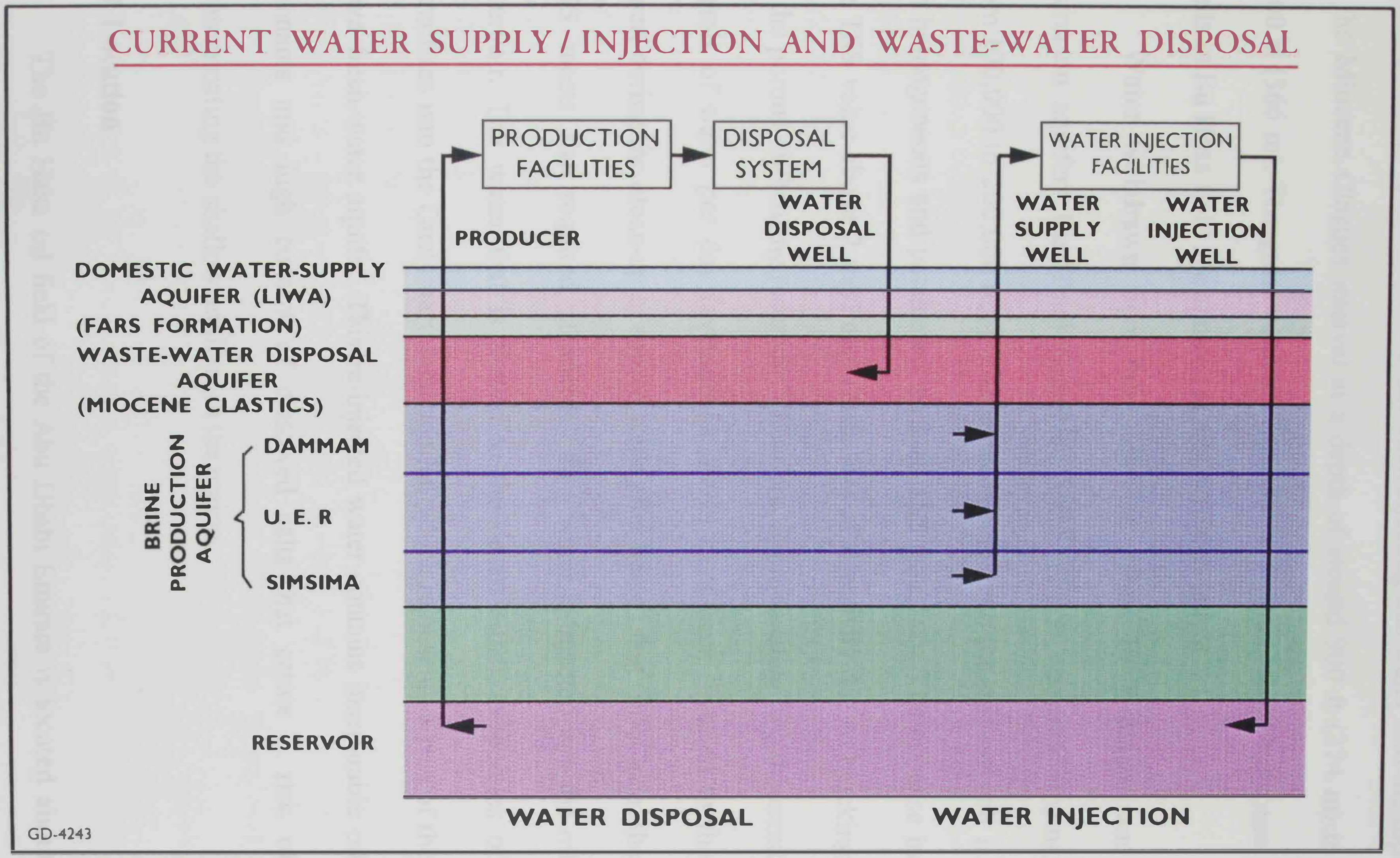


Figure 2. Schematic diagram showing the brine production, injection and waste-water disposal in the Bu Hasa oil field.

disposed off by injection. ADCO has been injecting this water into the top of the Miocene Clastics interval at a depth of around 900 ft (274 m) to 1200 ft (366 m). The gross volume of the injected water into the disposal wells in Bu Hasa field is estimated at 5,000-10,000 bbls/d.

Water withdrawn from the Simsima, Umm Er Radhuma and Dammam aquifers has Total Dissolved Solids (TDS) contents ranging from 100,000 to 200,000 mg/l. The water injected into the oil reservoir is not homogeneous and parameters such as TSS may vary. The increase in the TSS value above 2 mg/l may cause loss of injectivity due to blocking of the porous oil-bearing reservoir. Therefore, approximately two thousand barrels of water per day (average for 1996) have been diverted to the desert during the clean-up of source wells after being shut in. Once the TSS meets the required standards, the water is injected into the oil reservoir. The water that is flowed to the desert either evaporates or percolates into the Quaternary sand aquifer. which represents a part of the Liwa fresh-water aquifer. This re-injected water contains inseparable oil remnants and high content of dissolved salts that create a risk of contaminating the shallow aquifers in the region.

1.1 Location

The Bu Hasa oil field of the Abu Dhabi Emirate is located about 124 mi, 200 kilometers (km), southwest of Abu Dhabi City, 37 mi (60 km) south of the Arabian Gulf coastline and 40 mi (65 km) northwest of the Liwa Crescent. It is 22 mi (35 km) long from north to south, approximately 15.5 mi (25 km) wide and covers a surface area of about 243 mi^2 (639 km^2) .

1.2 Objectives

The main objectives of this study are: a) to evaluate the possible contamination of the Quaternary Liwa aquifer in the Bu Hasa oil field by highly saline, metal and oil bearing effluent generated in association with produced oil, b) to determine the factors that may control contamination such as stratigraphic setting, geologic structure, groundwater-flow direction and water chemistry will be taken into consideration, and c) to assess the environmental hazards due to contamination of the Quaternary aquifer by oil-field waste water.

1.3 Methods of Study

1.3.1 Field Work

a. Field visits were paid to the Hasa field in April and September 1996. Investigations included the domestic water wells, water supply wells and waste-water injection wells.

b. In April 1996, 17 water samples were collected from the domestic water-well field, 12 samples were obtained from shallow rig wells, close to selected water-supply wells, 2 samples were collected from

Al Daafra and Bin Thani camps and 1 sample was obtained from the waste-water injection plant.

c. In September 1996, 13 water samples were collected from the domestic water-well field, 1 samples was obtained from shallow rig wells, close to selected water-supply wells, 2 samples were collected from Al Daafra and Bin Thani camps and 1 sample was obtained from the waste-water injection plant.

d. Examination of 105 ft (32 m) core recovered from the Miocene Lower Fars Formation.

1.3.2 Laboratory Work

a. Chemical analysis of the major and minor constituents of groundwater samples collected for this study were performed by Atomic Absorption Spectrometer (AAS) and Inductively Coupled Plasma (ICP) and Ion Chromatography. The main physical parameters of water such as Electrical Conductivity (EC) in microsiemens per centimeter (μS/cm), temperature (°C) and pH were directly measured in the field.

b. Measurement of hydrocarbon content in some water samples derived from the Liwa Formation was performed by solid-phase extraction (SPE) and gas chromatography-mass spectrometry (GC-MS).

c. Petrographic examination of core samples recovered from the evaporitic sediments of the Fars Formation.

1.3.3 Office Work

a. Literature search on the thesis subject, including water re-injection procedure, legislation, standards, hazards and case studies.

b. Collection of previous geologic, hydrogeologic, geophysical and hydrogeochemical data on the study area.

c. Use of available geologic data for construction of isopach maps for the Miocene clastic aquifer, the Lower Fars evaporites and the Quaternary aquifer within the study area.

d. Use of the available hydrogeologic data for construction of longitudinal and transverse hydrogeologic cross sections for the study area.

e. Preparation of iso-salinity maps and iso-concentration maps for major ions and trace chemical constituents in water samples collected from the Quaternary aquifer within the study area in April 1996.

f. Use of geologic, hydrogeologic, hydrogeochemical and isotope data in assessment of the impact of injecting oil-field water in the Miocene clastics on groundwater in the Quaternary Liwa aquifer within the Bu Hasa field.

e. Preparation of the final draft and writing the thesis.

1.4 Previous Studies

A number of geological and hydrogeological studies have been carried out on the Bu Hasa field. The geology and water chemistry of the Quaternary Liwa aquifer, as well as the Miocene, Dammam, UER and Simsima aquifers have been investigated for water injection purposes.

Light and Halse (1964) studied groundwater development and exploration in the vicinity of Bu Hasa and Bab oil fields, formerly called Murban. Their report is subdivided into three parts: part one is concerned primarily with the history of water-well drilling for rig supply from 1958, together with completion and production methods, and includes a detailed tabulation of mechanical data and costs. Part two covers detailed groundwater information from the Murban area including partial and complete analyses, water levels and general occurrence. The report includes general comments on these data and a detailed list of all the wells drilled in the Murban field up till April 1964. Part three is concerned in general terms with the total dissolved solids content found in groundwater over the entire Abu Dhabi area. On a base map, scale 1:500,000, the TDS contents of groundwater in the Abu Dhabi area were illustrated based on the information obtained from drilling, geophysical survey, Bedu wells and other sources gathered in the course of Company's operations in the area.

Gosling (1973) carried out a geological review of the deep aquifers which include the Miocene clastics, Eocene Dammam, Paleocene-Eocene UER and Upper Cretaceous Simsima formations.

Budd (1973) conducted a feasibility study for a proposed scheme designed to remove salt from the produced crude at Bu Hasa. This scheme involves the use of 10,000 barrels of water per day to wash the crude and its subsequent disposal. It was suggested that the near-surface ‘dune sand’ aquifer may be able to produce this fresh water.

In 1981, Goudain studied the Tertiary and Upper Cretaceous aquifers of onshore Abu Dhabi. The main purpose of the study was to describe the four water-bearing formations, which include the Tertiary Sahil (Miocene clastics), Dammam, UER and the Upper Cretaceous Simsima, within the regional pattern of the recent data obtained from Bab-129 well drilled between Bab and Bu Hasa. Geological data were reviewed in order to investigate the potential of the studied aquifers for sustained water production. Isopach and structure contour maps were constructed to show the pattern, structural setting and evolution of these formations. Porosity maps were made for each formation and for each sub-unit. Aquifer characteristics, such as porosity and permeability, were compiled and summarized in tables and plots. Lithologically, the Sahil (Miocene clastics) Formation was described.

Hassan and Al Aidarous (1985) compiled a report on the regional geology of aquifers in onshore Abu Dhabi. Most of the data in this report were derived from water well data and from the ADCO report on the Tertiary and Upper Cretaceous aquifers of onshore Abu Dhabi (Gouadain, 1981). The report contains isopach maps of the three main aquifers; Simsima, UER and Dammam formations in Abu Dhabi. Each formation was subdivided into 3 subunits, and it happens that Unit 2 of each formation has the highest porosity and permeability; the so called clean zone.

De Matos (1986) published a study on the UER and Simsima aquifers in the Bu Hasa field. In this study, he defined the facies, reservoir characteristics, facies/reservoir relationships, diagenesis and depositional history of these two aquifers. Twenty-two cores from five wells in the Simsima Formation and 40 cores and 107 sidewall cores from four wells in the UER Formation were examined and studied. De Matos (1986) prepared a total of 466 thin sections of UER Formation and 137 thin sections of Simsima Formation and used it for detailed microfacies and petrographic investigations. In addition to the cored wells, 54 wells were used in the correlation of the study.

Where sufficient core recovery was obtained, porosity versus permeability cross plots for the various units and subunits of the UER and

Simsima formations were constructed. Nine reservoir appraisal sections, five data summary charts, seven cross sections and twelve isopach and structural maps were constructed.

In 1995, the Arab Center for Engineering Studies prepared a study on the impact of leakage from unlined pits in Bu Hasa field on the Quaternary Liwa aquifer. Eight boreholes were drilled to a depth of 130 ft (40 m) and 20 lithologic samples were obtained from each borehole at different depths using a split-spoon sampler. The notable results of this study came from one borehole drilled adjacent to a seepage pit in the base camp area, two boreholes at BU-40, one near the discharge pipeline outfall and the other in an area not affected by disposal operations, and finally two boreholes drilled at BU-68; one near the discharge pipeline outfall and the other in an area not affected by disposal operations (NDC--USGS, 1996). The results suggest downward seepage from several locations occupied by disposal pits within the central area of the field. Waste water has been diverted to seepage pits by a closed drain system at a rate of 1,000 to 1,500 bbls/d (AEA, 1994). The highest concentration of oil sampled near the seep pit, about 9,600 mg/l, came from a depth of 115 ft (35 m) below land surface. Soil samples collected near discharge pipeline out falls from BU40 and BU68 also suggest downward movement of disposed fluids. A chloride concentration of 1,240 mg/l was observed at depth of 130 ft (40 m) at Bu-40. These results indicate that the saline water from unlined pits has infiltrated to a depth of at least 130 ft (40 m).

The latest study was conducted by National Drilling Company (NDC) and United States Geological Survey (NDC-USGS) Groundwater Research Project (GWRP) in 1996, to examine the potential for contamination of the Quaternary Liwa aquifer by disposal of brine in Bu Hasa and Asab fields. The project drilled two water wells (GWP-188A and GWP-188B, Figure 3) and recovered two cores in the Lower Fars Formation in one of the two wells. Production test, water quality and wireline logs were obtained. The conclusion of this study is that the groundwater mound and associated saline plume, derived from the infiltration of wasted brine diverted and pooled in an unlined pit, has seeped into Liwa aquifer to a depth of 300 ft (91 m) near Bu-303. The presence of this plume indicates that groundwater degradation has occurred in the Bu Hasa field due to oil-field activities.

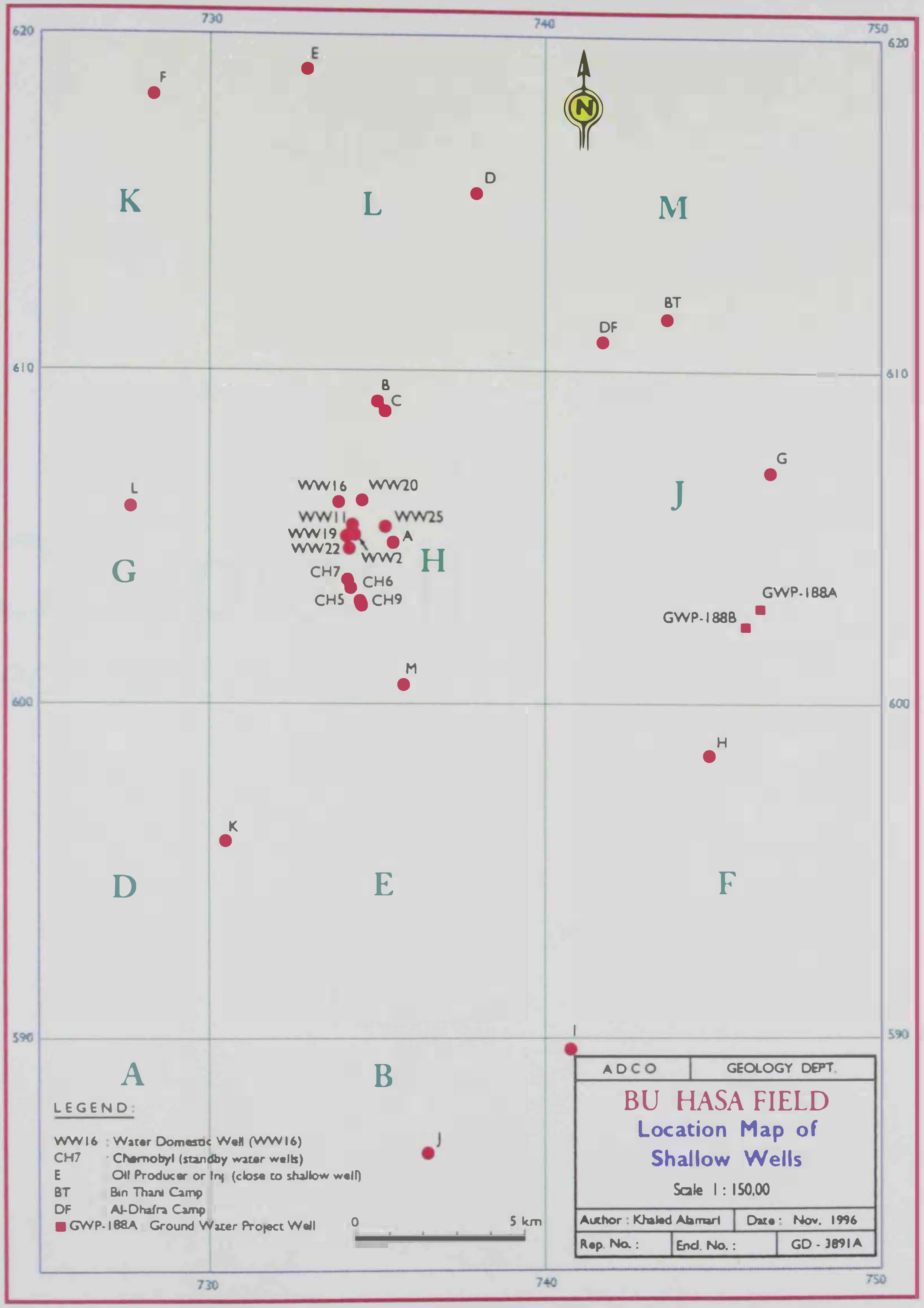


Figure 3. Location map Bu Hasa area showing the shallow water wells used in the study.

Chapter II

Geologic Setting

CHAPTER II

GEOLOGIC SETTING

2.1 Stratigraphy

The Miocene rocks in the Abu Dhabi Emirate are either exposed as scattered outcrops (e.g. at the various diapiric islands) or buried under a thin cover of surficial sediments (Figure 4). Precise chrono-stratigraphic assignment of these rocks is not available due to the lack of stratigraphically significant fossils (Peebles, 1995). However, isotope dating methods have been utilized by several workers to delineate the stratigraphic position of these rocks.

Conventionally, the Miocene sediments of Abu Dhabi are classified into Miocene clastics and Miocene evaporites. The Miocene clastics are considered of Early Miocene age (Peebles, 1995). These clastics are also known as the Baynunah Formation in western Abu Dhabi. This unit is predominantly composed of friable sandstones, siltstones and marls interbedded with thin beds of limestone and anhydrite. Regionally, this formation exhibits considerable lateral variation in lithology and thickness. This variation is generally observed from western to eastern Abu Dhabi. On the other hand, the Miocene evaporites, also known as the Gachsaran Formation (Peebles 1995; Alsharhan 1989; and Whybrow 1989), are believed to be of Late Miocene age. This unit is considered equivalent to

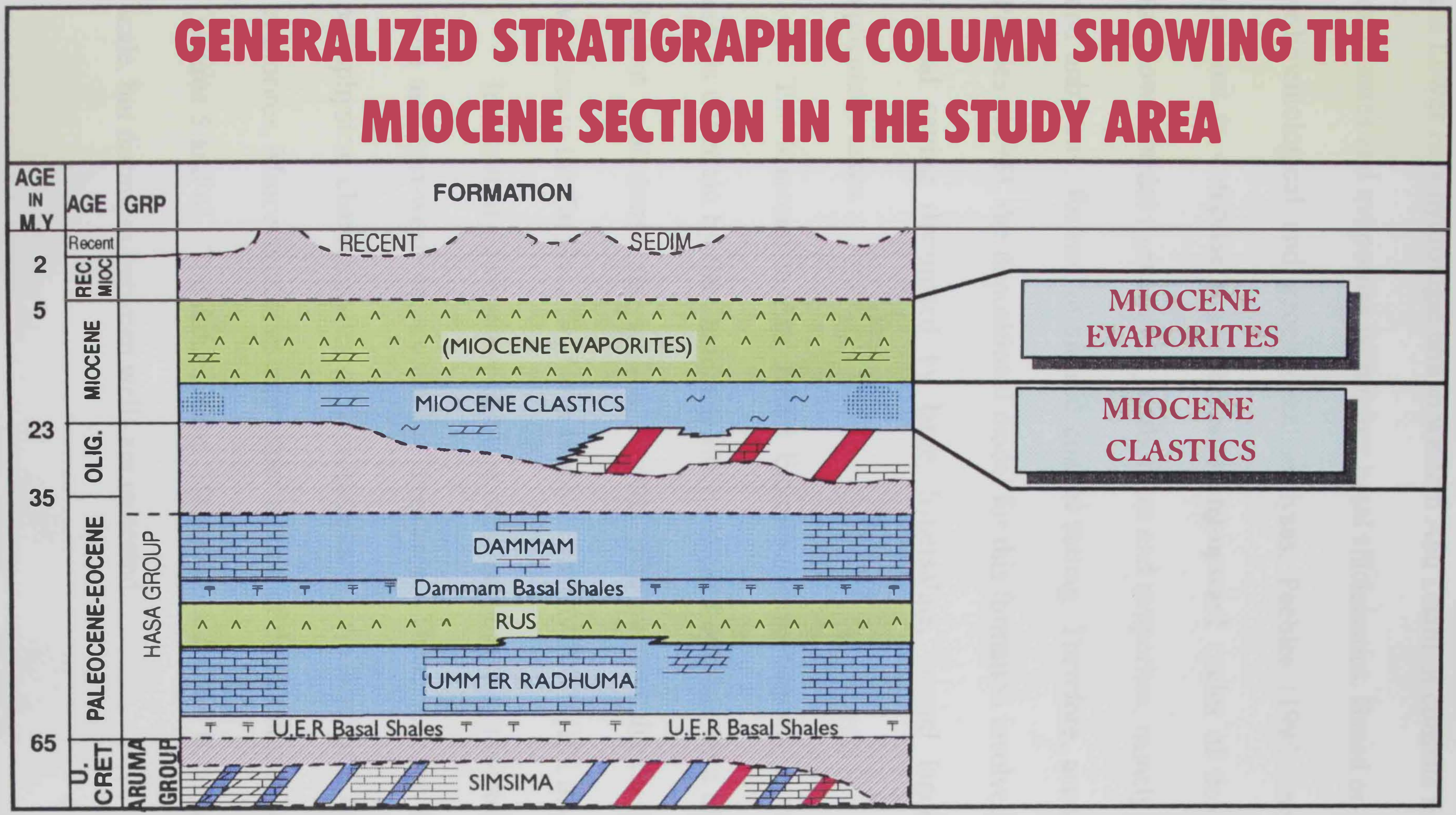


Figure 4. Generalized stratigraphic column showing the Miocene section in the study area.

the Lower Fars hydrologic unit in western Abu Dhabi. It consists mainly of carbonates and evaporites with minor basal siliciclastics. Based on detailed sedimentological and geochemical analyses, Peebles (1995) interpreted this unit to comprise multiple shallowing-upward cycles of dolomitized (shallow subtidal to supratidal) carbonates and evaporites, namely gypsum and anhydrite, formed in an arid coastal setting. Therefore, according to Peebles (1995), the depositional model for this formation involved an arid coastal setting dominated by large, hypersaline, coastal lagoons and ephemeral lakes.

The Miocene in Abu Dhabi Emirate and particularly in the study area is underlain by the Dammam limestones and overlain by a blanket of Recent sand dunes and sabkha deposits. The average thickness of the Miocene in the Bu Hasa field area is approximately 500 ft (152 m).

In this study, two log correlation cross sections are presented, north-south and east-west, across the Bu Hasa area. These sections show the petrophysical characteristics of the Quaternary Liwa Aquifer, Lower Fars evaporites, Miocene clastics and upper section of the Dammam Formation (Figures 5 and 6). The datum is top Dammam and there is no horizontal scale, but distances between wells are indicated.

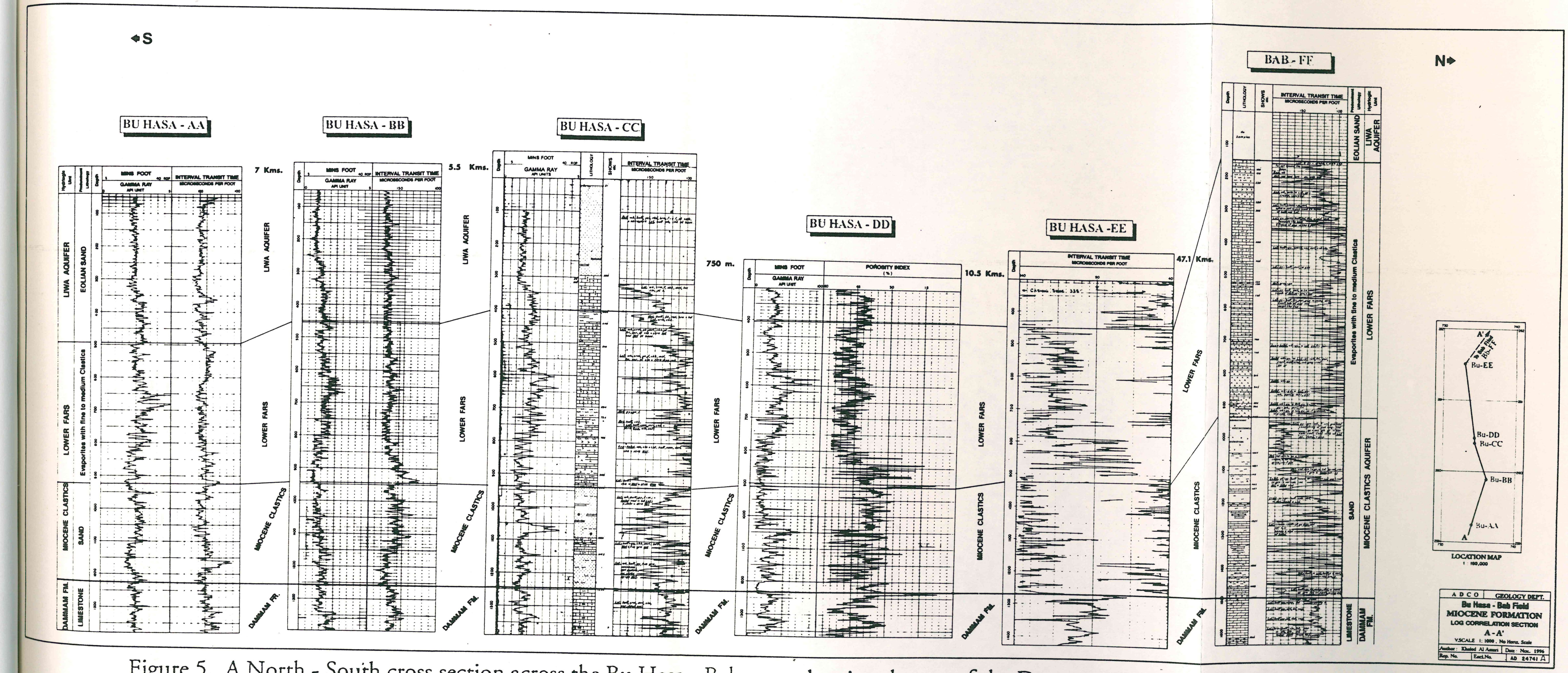


Figure 5. A North - South cross section across the Bu Hasa - Bab area, showing the top of the Dammam Formation, the Miocene clastic aquifer, Fars Formation and the Quaternary Liwa aquifer.

2.1.1 North-South Cross Section

Log correlation section A-A' (Figure 5) contains five Bu Hasa wells. Well No. FF in the Bab field in the north is added to show thinning of the Liwa aquifer towards the coast. Five of the wells have the interval transit time sonic log for porosity indication and Bu-DD has a neutron porosity index curve. The two Tertiary units, the Miocene clastics and Lower Fars, are thicker in Bab-FF to the north. These same units may become thicker north of Bab Field into the Arabian Gulf and then into the Iranian geosyncline. The Lower Fars unit in Bab-FF, in addition to being thicker, contains a higher percentage of gypsum in the upper subunit.

2.1.2 East-West Cross Section

Five wells are arranged along this line covering 20 km in an east-west direction (Figure 6). All wells have gamma ray curves for lithology and radioactivity differentiation. One well, Bu-CC, has a sonic log for porosity measurement and the other wells have neutron curves for the same measurement. The Well BU-303 (188A), drilled by the NDC-USGS Groundwater Research Project (GWRP), has a bulk density log and a neutron porosity curve. That combination gives the best definition of

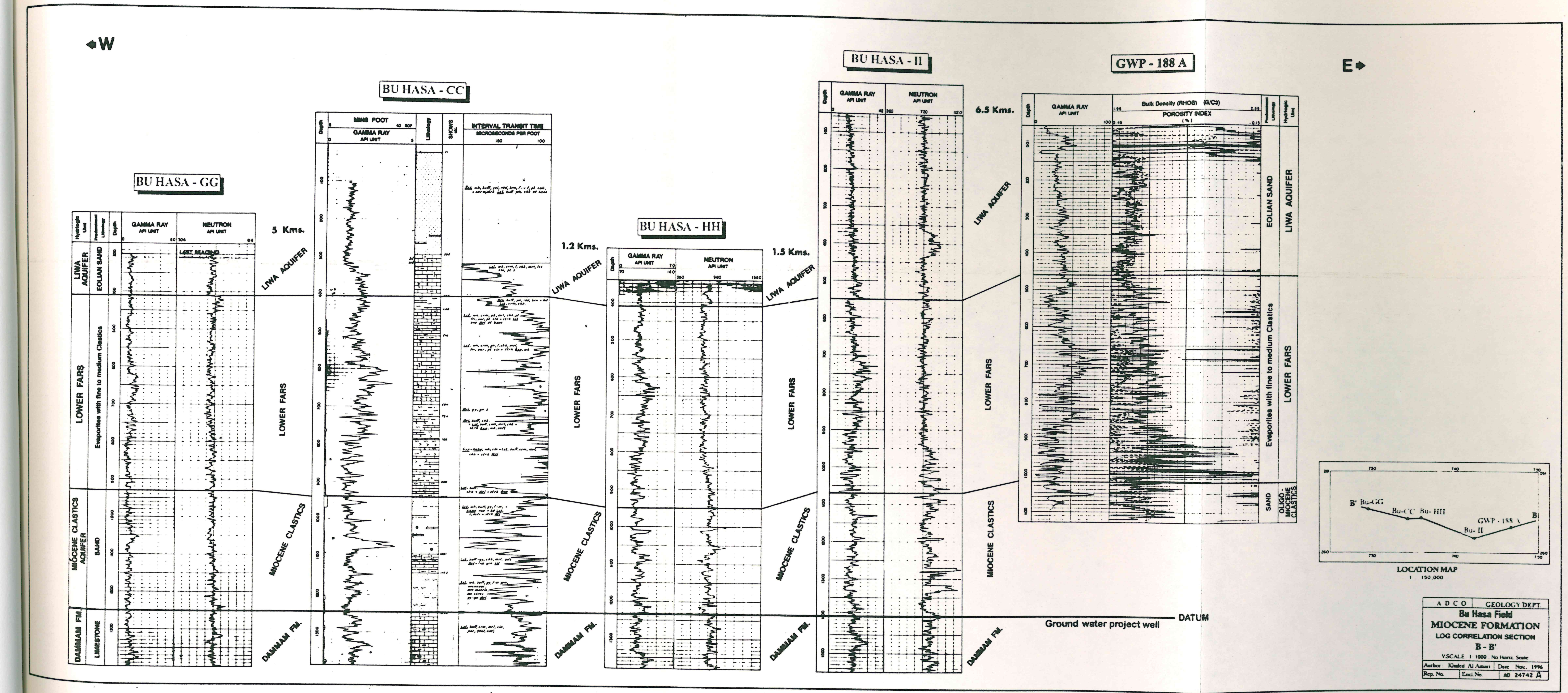


Figure 6. An East - west cross section across the Bu Hasa area, showing the top of the Dammam Formation, the Miocene clastic aquifer, Fars Formation and the Quaternary Liwa aquifer.

lithology together with the gamma ray. The Miocene clastics have a fairly consistent log character and thickness east-west across Bu Hasa. They appear fairly clean on the logs with only a few shaly or limy streaks. According to logs, the Lower Fars has two subdivisions; a predominant upper portion of slightly marly limestone with some gypsum, and a lower portion of interbedded thin anhydrite and thicker marls. The overall unit is thinner in the middle of the correlation section over the crest of the Bu Hasa structure. The Liwa aquifer is fairly massive across the area but the lower portion has a slightly higher level of radioactivity in Bu-303 (GWP-188A) and could be slightly marly or argillaceous.

2.2 Lithological Description

In general, the upper part of the higher beds in the Miocene succession is substantially composed of sandstone facies underlain by limestones, marls and gypsum beds. In the west, the Miocene Clastics of the Baynunah Formation form the mesas and jebels (hills) frequently encountered along the coast. In the east, the Lower-Middle Miocene carbonates and evaporites of the Gachsaran Formation form inland buttes and small isolated outcrops or lie just meters below surface sabkhas. The Miocene sediments are also exposed on many of Abu Dhabi's islands, brought to the surface by salt diapirism. Along the coastal strip, the sandstones crop out in mesas and surface deposits, and also occur as the dominant aquifer towards the south in thick dune areas. The drilling of a sufficiently thick porous interval below the water table usually results in water production from a variety of lithologies in all parts of the Bab (Murban) area. With the exception of the evaporite and marl horizons, all near-surface beds appear to be porous and water-bearing.

2.2.1 Miocene Clastics

These clastics consist of friable sandstones, siltstones with marl and thin limestone and anhydrite intercalations (Figure 7). According to Gosling (1964), this formation exhibits considerable lateral variation in lithology and thickenss on a regional scale from western to eastern Abu Dhabi. The Gamma ray correlation of Bab and Bu Hasa fields indicates remarkable changes in lithology and thickness.

The Lower Fars Formation unconformably overlies an eroded, channelled and weathered surface of the Hormuz Group at Dalma Island and can be subdivided into three lithostratigraphic units from top to base (Figure 8):

a. Unit A lies conformably over Unit B and consists of interbedded white, slightly hard limestone, buff to reddish brown siltstone and reddish gray marl. Translucent selenite-fills veins and fractures in the upper part of this unit. Iron staining is notable. Units A and C are believed

BU HASA FIELD
MIOCENE CLASTICS . LOWER FARS & LIWA AQUIFER
TYPICAL SECTION

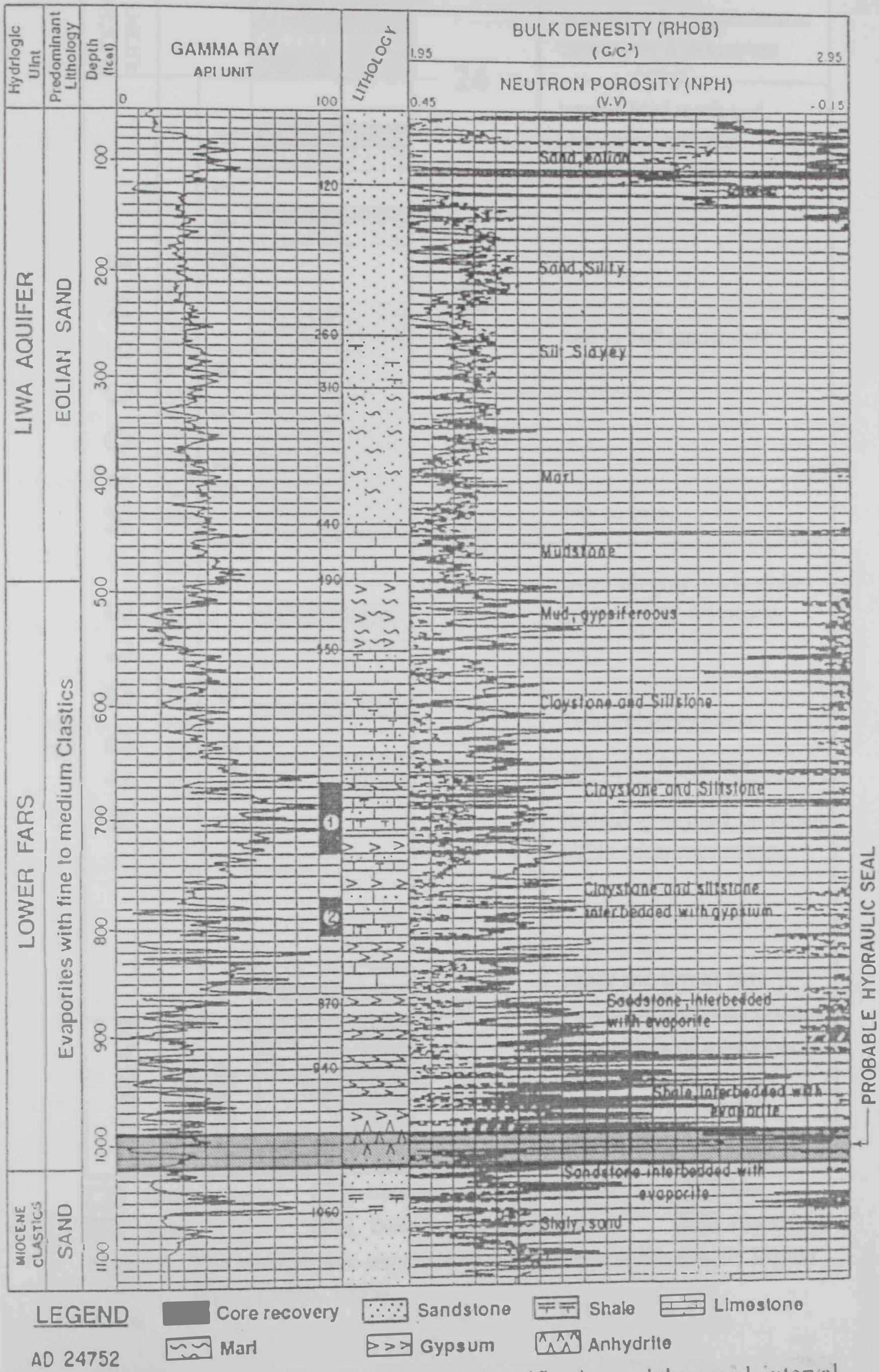


Figure 7. Well log illustrating the Miocene Classification and the cored interval studied for the study.

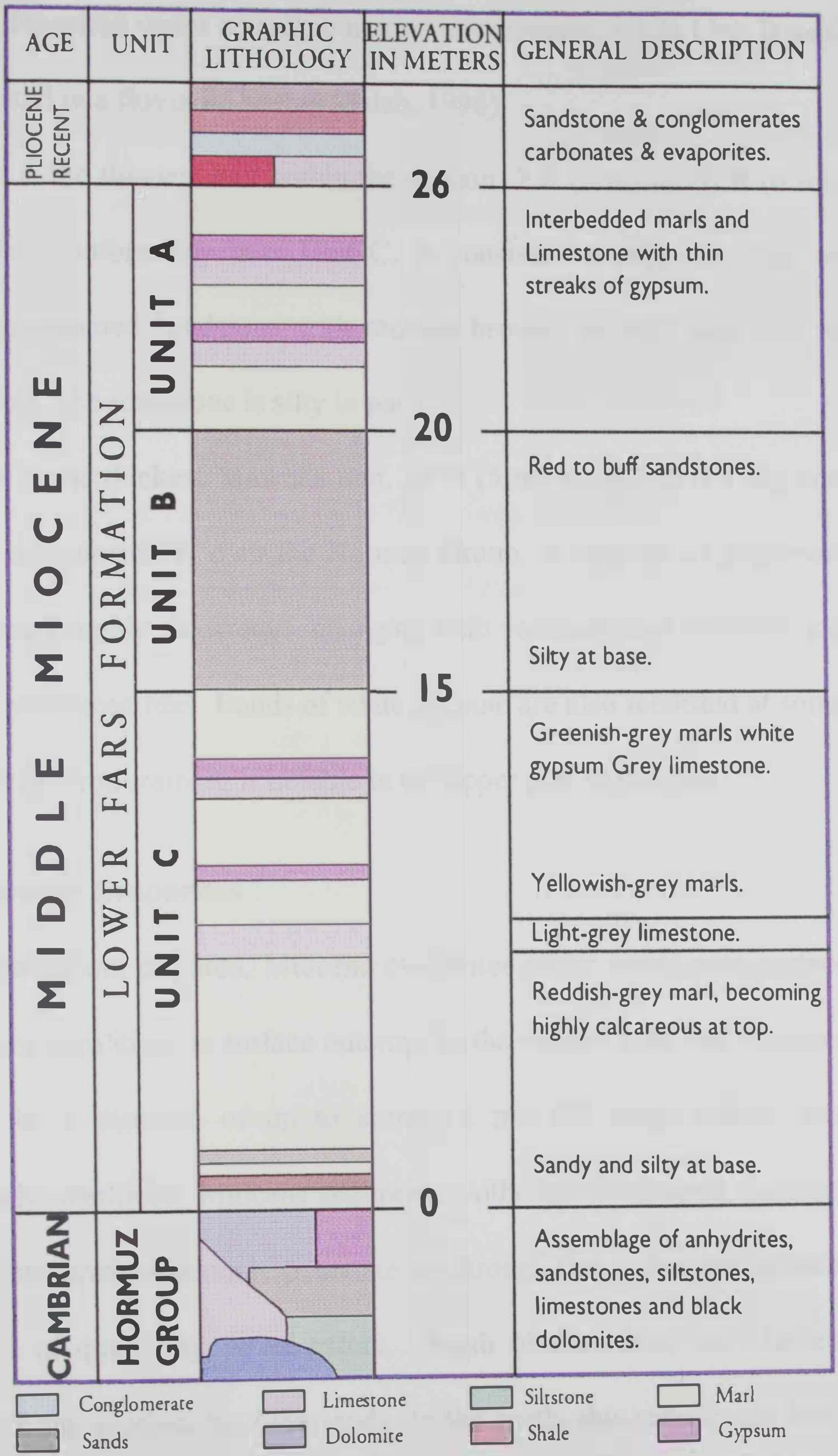


Figure 8. The stratigraphic sequence of the Miocene sediments on Dalma Island (Salah, 1995).

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to be deposited under a shallow marine environment, while Unit B was deposited in a fluviatile setting (Salah, 1996).

b. Unit B is the thinnest unit within the section, 7 ft (2 m) to 20 ft (6 m), and lies conformably over Unit C. It consists mainly of fine to medium-grained sandstone with reddish brown to buff hues due to staining. The sandstone is silty in parts.

c. Unit C is the thickest Miocene unit, 16 ft (5 m) to 49.2 ft (15 m), and rests unconformably over the Hormuz Group. It consists of gray marl becoming highly calcareous, changing both vertically and laterally into hard gray limestone. Bands of white gypsum are also recorded at some localities. Iron staining is notable in the upper part of this unit.

2.2.2 Miocene Evaporites

Throughout the area, Miocene evaporites occur either near surface or, in some localities, as surface outcrop. In the coastal area and tonguing inlands for a distance of up to some 15 mi. (24 km), sabkha flats extensively overlie the Miocene sediments. Although flat topped, outcrops of Miocene strata commonly penetrate up through this cover and in some cases are of quite large areal extent. South of this zone, the Miocene sediments are overlain by dune sands. In the north, this sand cover has a patchy distribution and relatively thin. Southwards, it becomes progressively more extensive and thick.

In the Bu Hasa region, at the southern end of the field, the sand cover exceeds 200 ft (61 m) in thickness, masking almost completely the underlying strata. However, in isolated locations, small windows and deep hollows in the sand cover do allow the Miocene strata to be exposed at the surface.

The confining unit belonging to the Lower Fars Miocene evaporites is 525 ft (160 m) thick and consists mainly of mudstone, siltstone and marl with interbeds of evaporite. The thickness of the evaporite reaches about 49 ft (15 m), great enough that it would appear to be an effective seal against vertical flow of water at the base of the Liwa aquifer. Southwards across the Bab Field towards Bu Hasa, a gradual topographical rise occurs and similarly, but to a lesser degree, an increase in structural elevation within the Miocene strata is evident, if one refers to the depths at which the Miocene Clastics are encountered in the various development wells. For instance, from the coast south to Mb-13, there is a topographical rise of some 350 ft (107 m) and an increase in structural elevation within the Miocene of roughly 150 ft (46 m). The depth of the water table below the ground level is as little as 2 ft (0.6 m) in the sabkha areas, but it gradually becomes deeper to the south (Bu-J) where it reaches 80 ft (24 m) to 140 ft (43 m).

Within the Murban area, the formations encountered in various water wells are largely determined by how far the particular well is from the coast. Near the coast, the Miocene aquifer can be reached at surface or after penetrating a small thickness of sabkha cover. Further south, but still in the area of the Bab dome, the Miocene section crops out at the surface or lies below a thin cover of dune sands.

Surface outcrops, where visible, consist of Miocene sediments varying lithologically from friable sandstones to limestones, marls and gypsum, which are all generally evaporitic in nature. On the coastal strip, these outcrops commonly rise above the sabkha cover to form a mesa-type topography. Over the Bab dome area, the Miocene sediments occur as extensive, weathered outcrops, or are masked by a shallow sand cover. On the Bu Hasa dome, Miocene outcrops are mainly confined to small local hollows of limited aerial extent, being otherwise Miocene sediments are buried beneath thick dune sand.

2.2.3 Petrography

In conjunction with the drilling of the borehole GWA-188A (Figure 3), 105 ft (32 m) of core within the Lower Fars Formation (675-735 ft and 765-810 ft) were recovered. The core samples were brought to the Abu

Dhabi Company for Onshore Oil Operations (ADCO) for analysis of lithology and hydraulic conductivity (Figure 7). The author has described core samples for ADCO and the NDC-USGS GWRP. Description of selected core samples is illustrated in Figures 9 to 19.

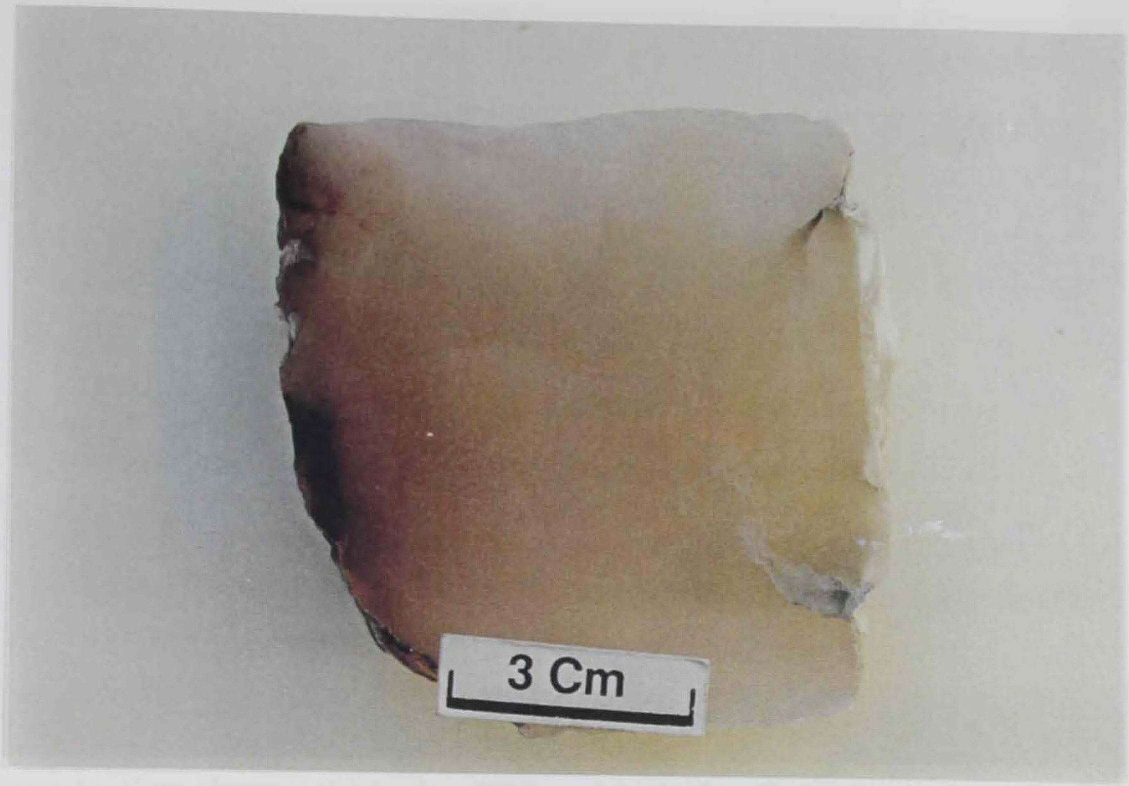

Figure 9.Core photograph (depth=675ft.) showing transparent to light-reddish gypsum.

Figure 10 Core photograph (depth = 683ft.and 5 in) of light siltstone-claystone, with nodules of anhydrite (arrow) ranging in size from 2 to 5 Cm. Notice the iron staining and horizontal burrowing.

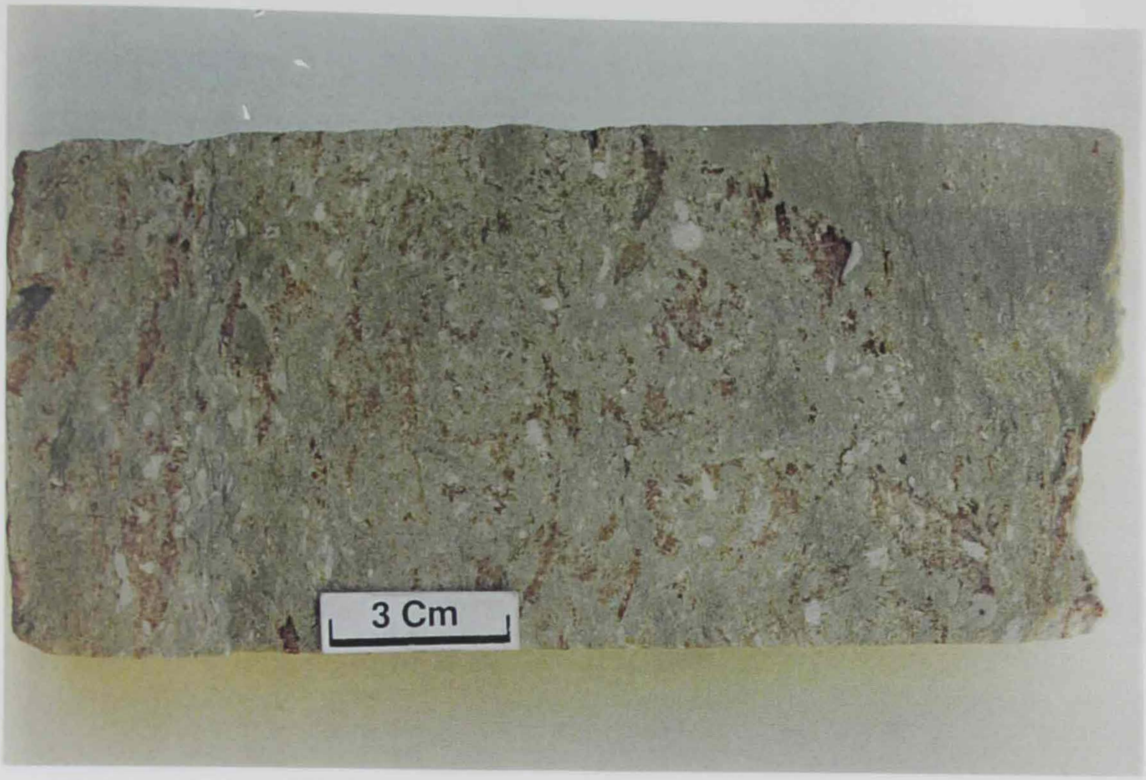

Figure 11. Core photograph (depth = 693ft. and 6 in) of buff, light gray, brownish and yellowish claystone-limestone, with iron-oxide staining. Porosity is vuggy and partially filled with gypsum.

Figure 12. Core photograph (depth = 696ft. and 7 in) of laminated and finely-bedded claystone-limestone showing light to dark gray color. Notice the presence of shell debris and oxidation (arrow).

Figure 13. Core photograph (depth = 709ft. and 7 in) of gray, whitish gray limestone (wackestone-packstone) with clay clasts and large well-preserved echinoids fragments (arrows). Notice the relatively high porosity due to leaching.

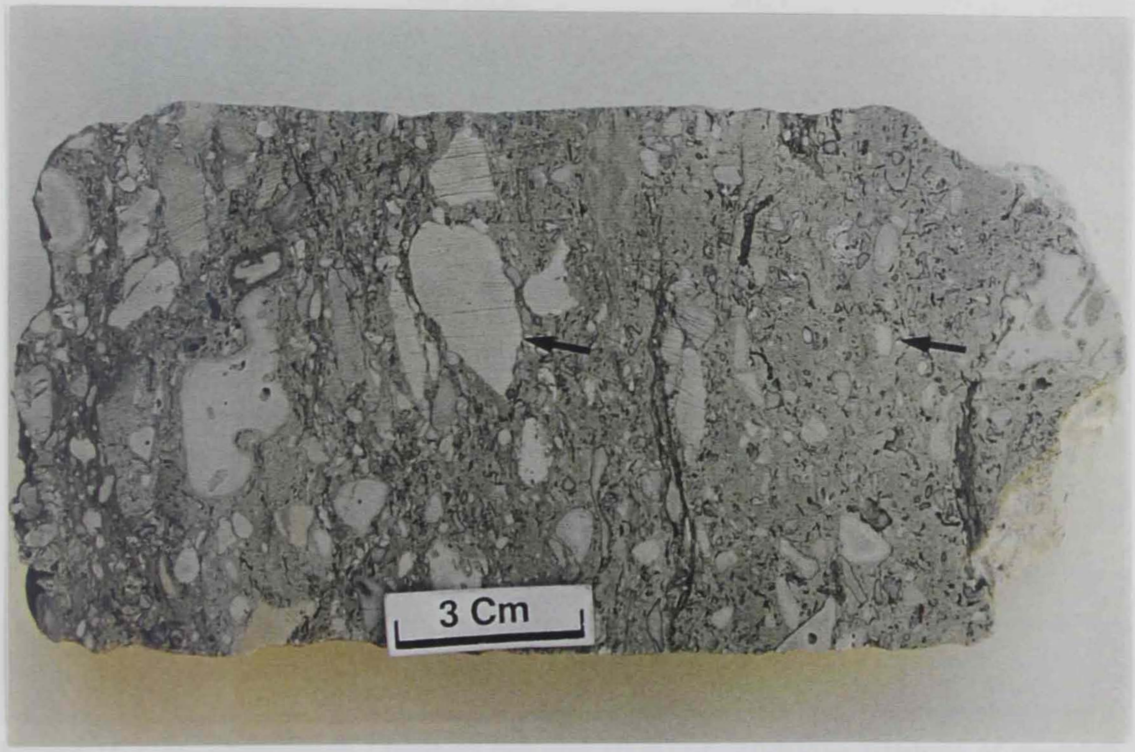

Figure 14 Core photograph (depth= 715ft.) of light to whitish gray coarse lithoclastic limestone (packstone), locally argillaceous with angular to subangular lithoclasts ranging in size from a few to 1.5Cm.(arrows). Notice the partial replacement of some shell fragments by anhydrite.

Figure 15.Core photograph (depth= 771ft.) of light gray to light brown, black spotted bioclastic limestone (wackestone-packstone), with some gypsum nodules (arrow).

Figure 16.Core photograph (depth=778ft.and 10 in) of mudstone-siltstone of greenish to light gray color. The rock is locally nodular with fine dark clayey material (arrow).

Figure 17. Core photograph (depth = 781ft. and 4 in) showing an interval of dark gray gypsum with cloudy appearance.

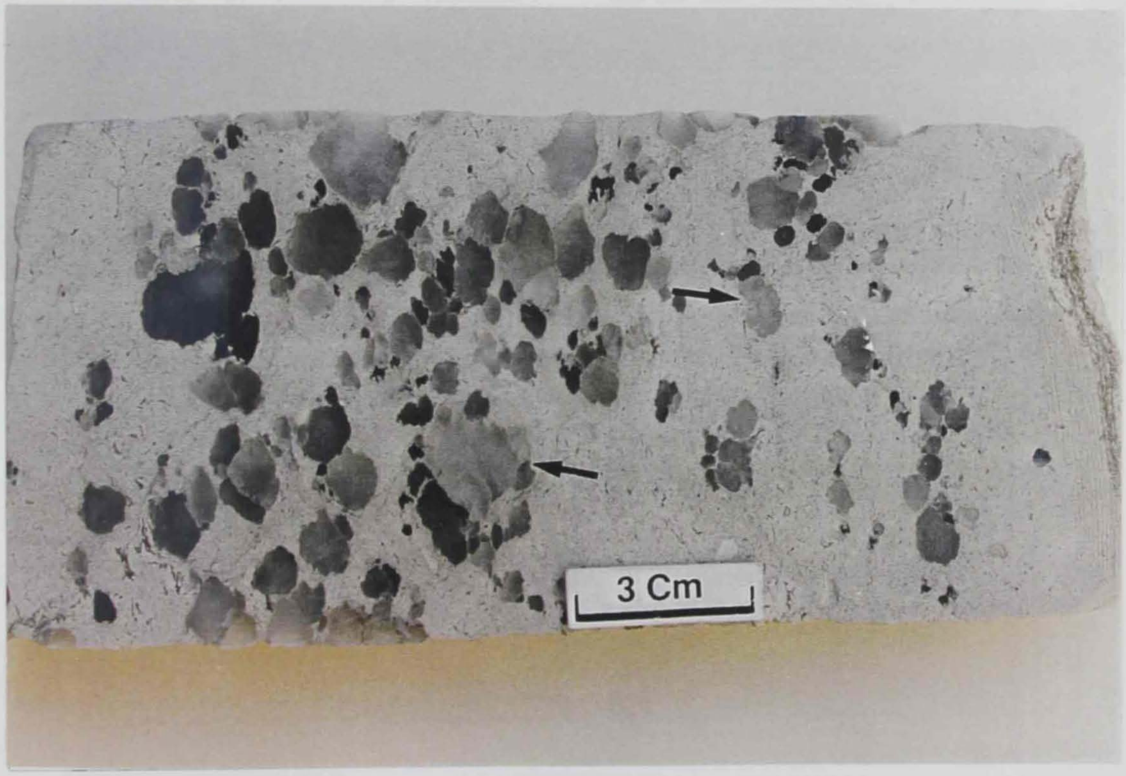

Figure 18 Core photograph (depth = 785ft. and 10 in) of light to dark gray siltstone with scattered gypsum nodules (arrow) and cloudy appearance.

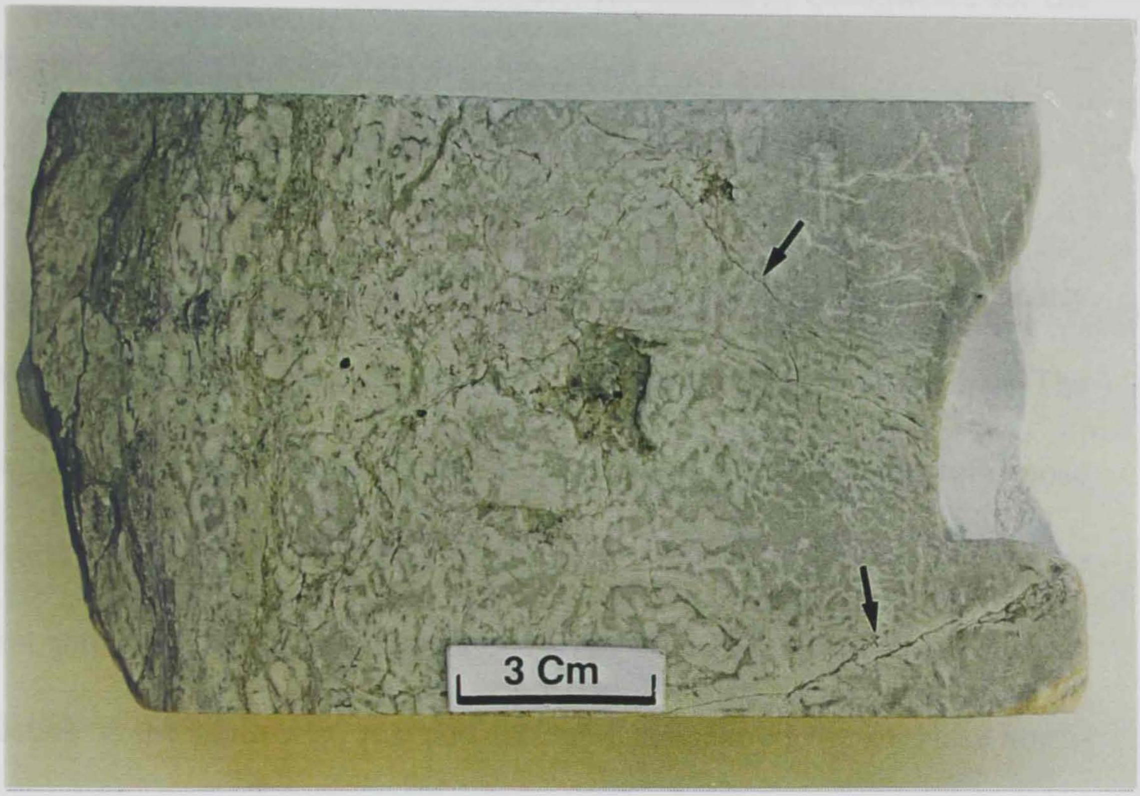

Figure 19. Core photograph (depth = 790ft.and 6 in) showing light to dark gray burrowed siltstone with gypsum nodules. Notice the presence of fractures (arrows) that are locally enlarged and irregular.

2.3 Geologic Structure

In western Abu Dhabi, gentle and simple folds are common features. Folds are aligned north-south, probably related to deep seated basement tectonics (Hassan and Al Aidarous, 1985).

The structural configuration in the study area is interpreted, in this section, based on structural and isopach contour maps constructed for the Miocene clastics, Lower Fars evaporites and Liwa aquifer.

2.3.1 Structure Contour Map of the Miocene Clastic Aquifer

The structure map on top of the Miocene clastic aquifer clearly shows the local and regional structural configuration of the study area. The Bu Hasa field is shown as a north to northwest plunging structural nose with dips on the east into the Falaha syncline and less obvious dips on the west into the Ras Gharib syncline (Figure 20). The top of the Miocene clastics is the shallowest mapped surface which shows the Bu Hasa north-south structural trend. Geophysical studies using gravity and magnetic records have indicated that the north-south trend is basement-block related. Subsurface mapping deeper in the section has revealed the southern dip which makes Bu Hasa a dome.

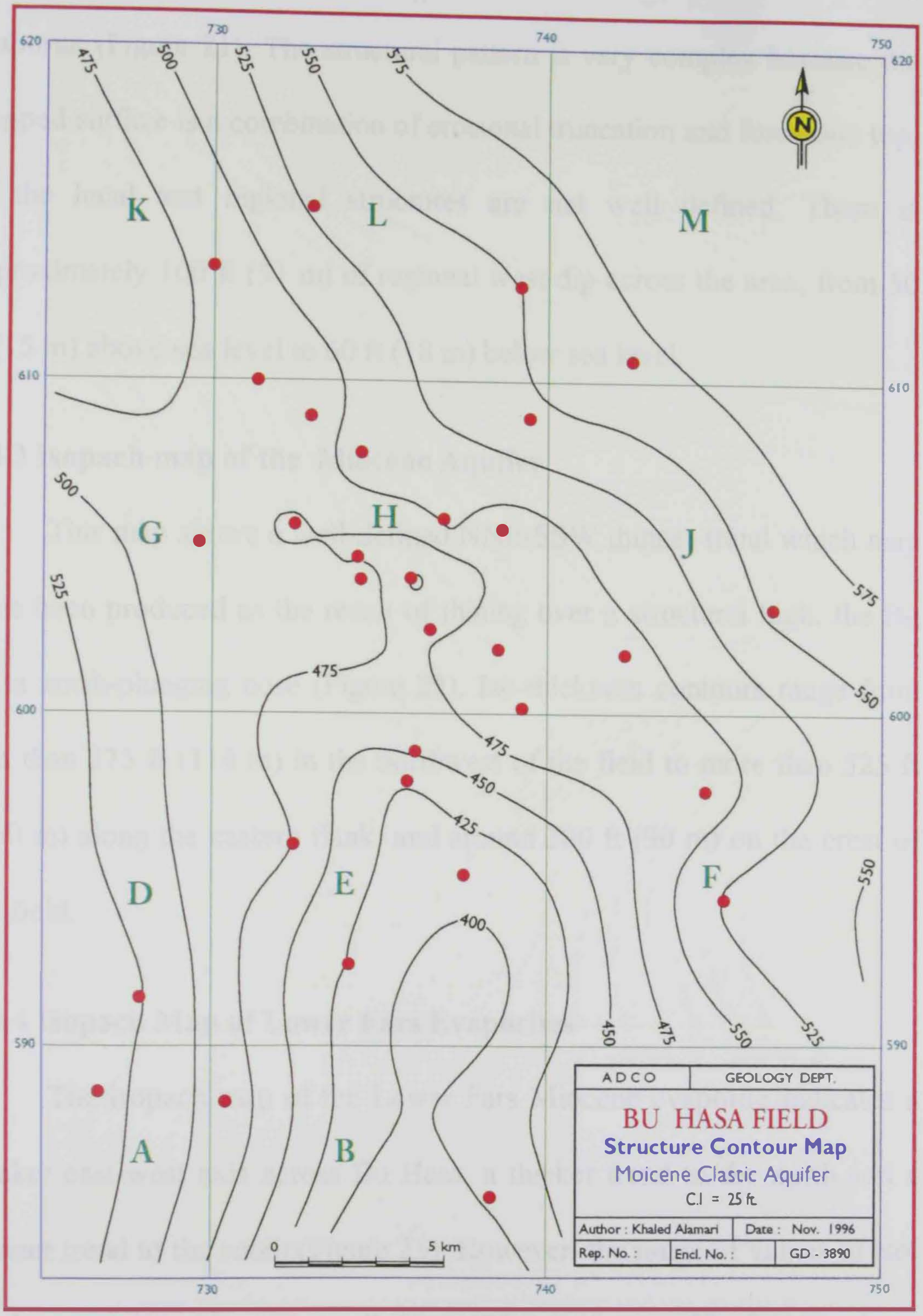

Figure 20. Structure contour map of the Miocene clastic aquifer in the Bu Hasa area. Contour interval = 25 ft.

2.3.2 Structure Contour Map of Lower Fars Evaporites

The shallowest structural map is on top of the Lower Fars Miocene evaporite (Figure 21). The structural pattern is very complex because the mapped surface is a combination of erosional truncation and formation top, so the local and regional structures are not well defined. There is approximately 100 ft (31 m) of regional west dip across the area, from 50 ft (15 m) above sea level to 60 ft (18 m) below sea level.

2.3.3 Isopach map of the Miocene Aquifer

This map shows a well-defined NNE-SSW thinner trend which may have been produced as the result of thining over a structural high, the Bu Hasa north-plunging nose (Figure 22). Iso-thickness contours range from less than 375 ft (114 m) in the northwest of the field to more than 525 ft (160 m) along the eastern flank, and around 300 ft (90 m) on the crest of the field.

2.3.4 Isopach Map of Lower Fars Evaporites

The isopach map of the Lower Fars Miocene evaporite indicates a thicker east-west axis across Bu Hasa, a thicker trend to the north and a thinner trend to the south (Figure 23). However, the range of values of iso-thickness contours is quite small, from 475 ft (145 m) to 526 ft (160 m).

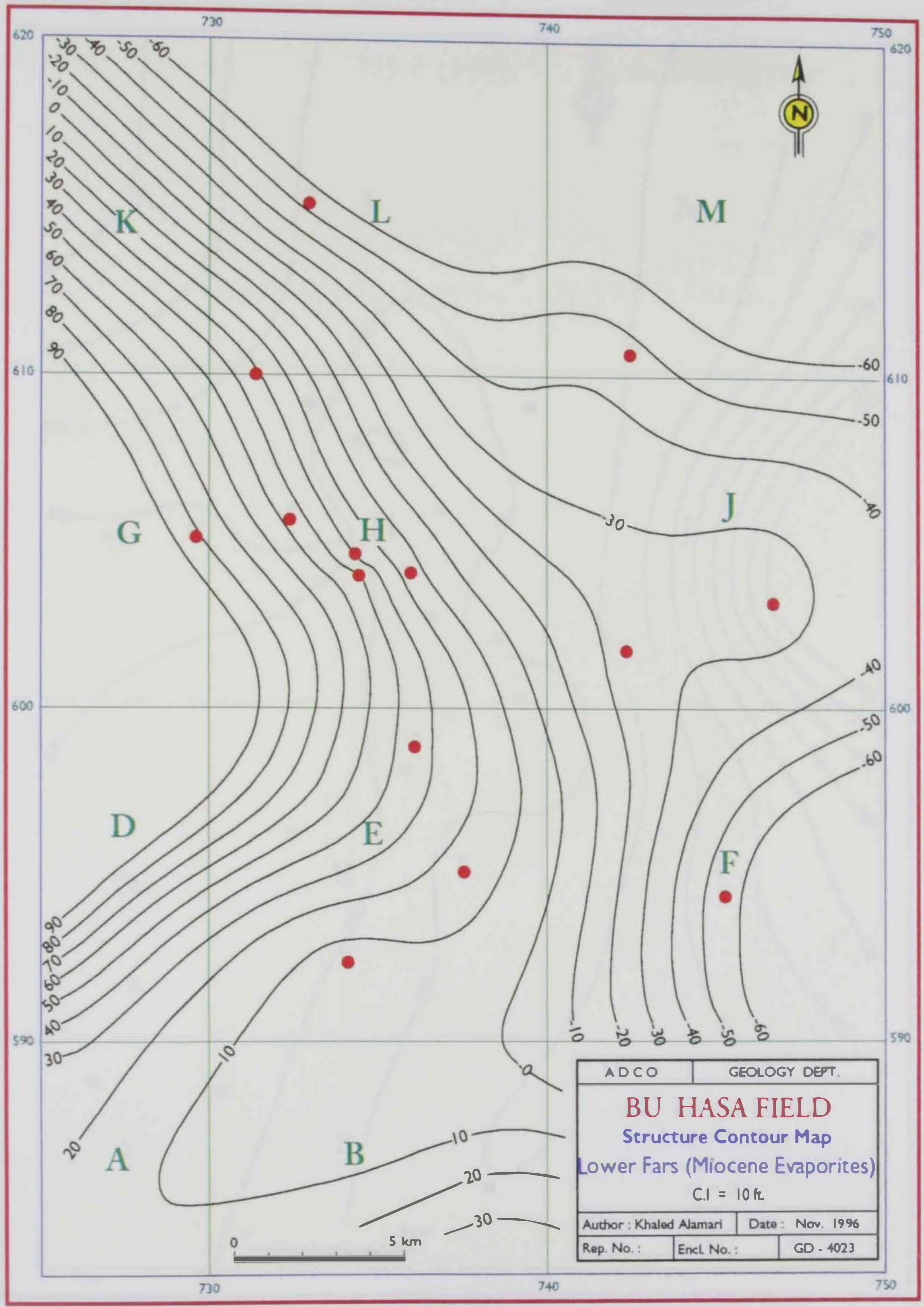

Figure 21. Structure contour map of the Lower Fars Formation (Miocene Evaporites). Contour interval = 10 ft.

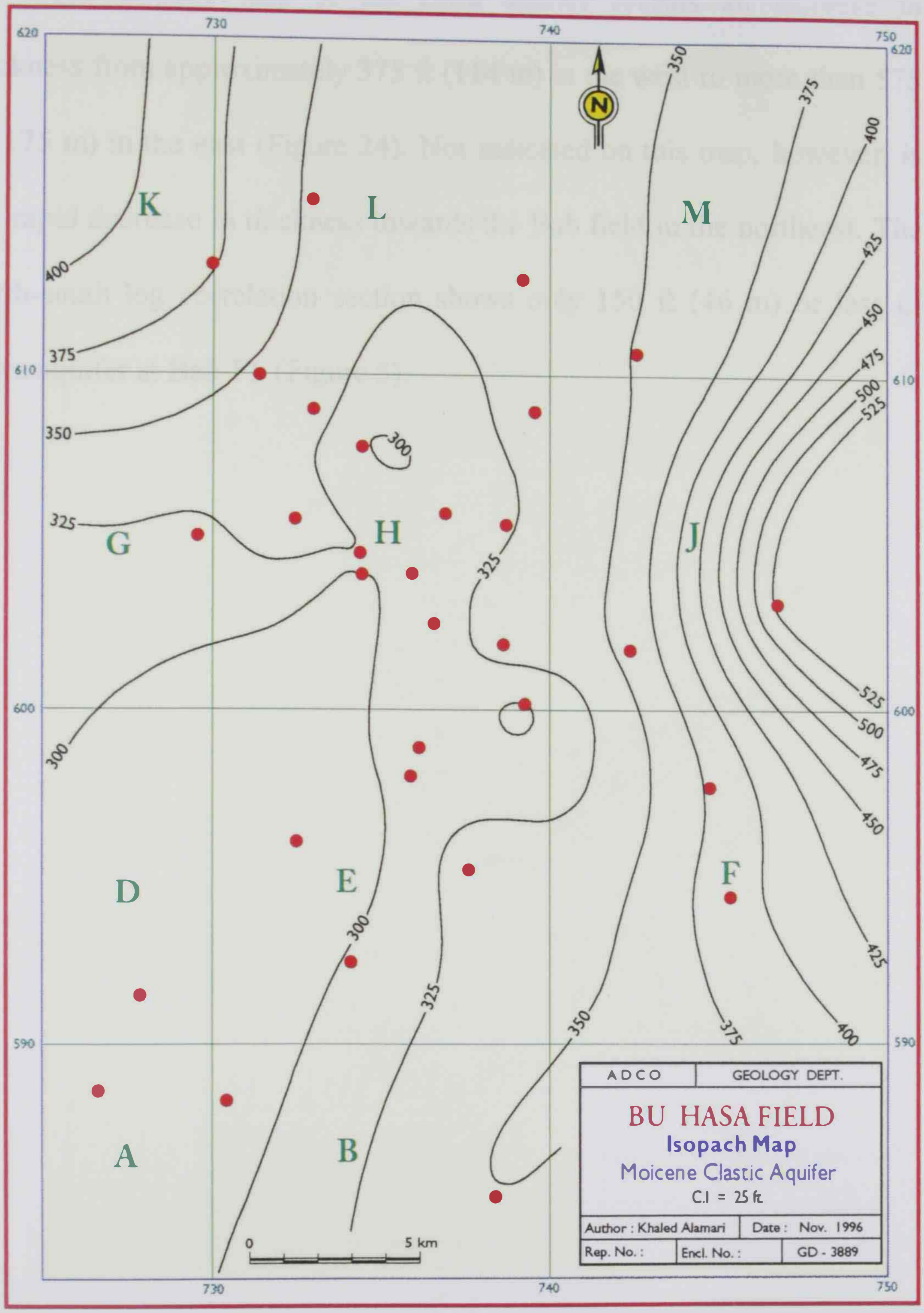

Figure 22. Isopach map of the Miocene clastic aquifer at the Bu Hasa area. Contour interval = 25 ft.

2.3.5 Isopach Map of the Liwa Aquifer

The isopach map of the Liwa aquifer reveals an increase in thickness from approximately 375 ft (114 m) in the west to more than 575 ft (175 m) in the east (Figure 24). Not indicated on this map, however, is the rapid decrease in thickness towards the Bab field in the northeast. The north-south log correlation section shows only 150 ft (46 m) or less of Liwa aquifer at Bab-FF (Figure 5).

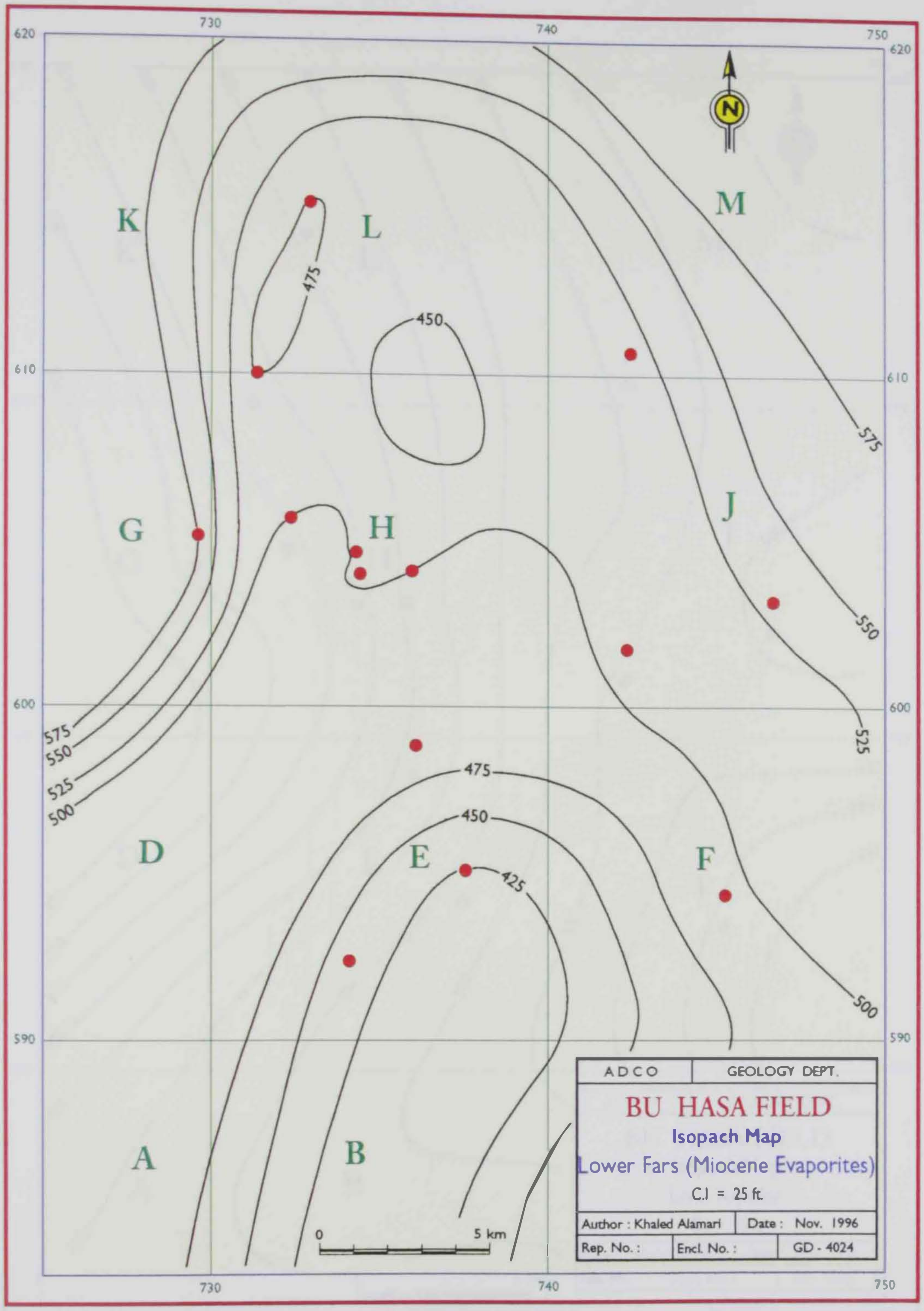

Figure 23. Isopach map of the Lower Fars Formation (Miocene Evaporites) at the Bu Hasa area. Contour interval = 25 ft.

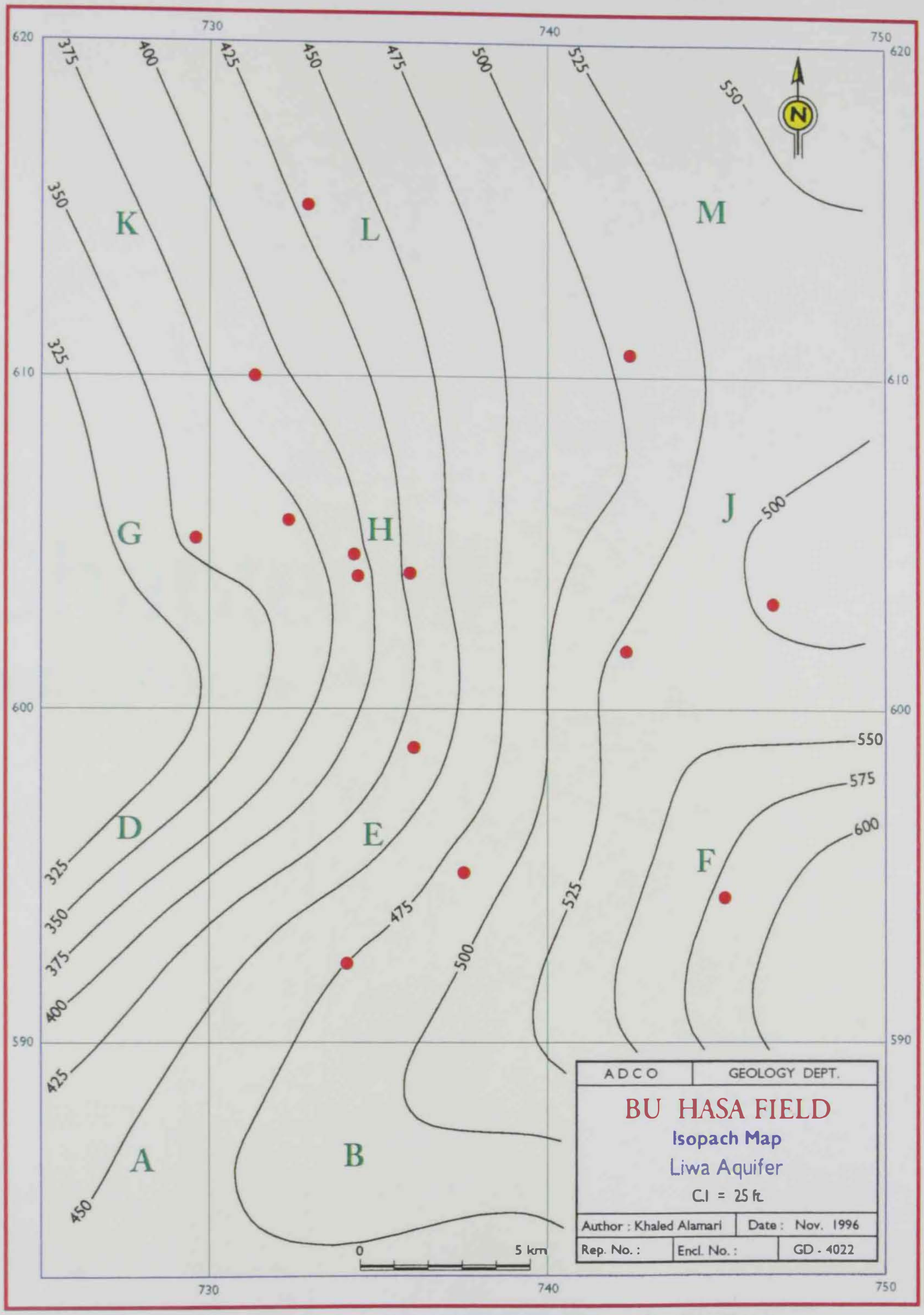

Figure 24. Isopach map of the Liwa aquifer at the Bu Hasa area.
Contour interval = 25 ft.

Chapter III

Hydrogeology

CHAPTER III

HYDROGEOLOGY

3.1 Climatic Conditions

Climatological data for the period 1979-1992 show that the mean annual temperature in the Bu Hasa field is 28°C (Ministry of Agriculture and Fisheries, 1993). Rainfall records show that the Bu Hasa area receives most of the annual rainfall, 0.60 in (15 mm) during February. Trace amounts are recorded in December and March (Ministry of Communications, 1996); no rainfall data were recorded in January. The total mean annual rainfall at the Bu Hasa Meteorological station for the period 1979-1992 is 0.62 in (15.7 mm). At Asab meteorological station (100 Km to the South-East), the average annual rainfall for a 20-year period (1965-1985), is 1.6 in (40 mm), and the potential evapotranspiration varies between 27.3 in (690 mm) during November-March and 102.7 in (2,600 mm) during April-October.

3.2 Aquifers

The water-bearing units (aquifers) within the study area can be classified into (Figure 2):

a. Brine-Produing aquifers include the Simsima, UER and Dammam aquifers. Water produced from these aquifers is injected into oil reservoirs to maintain pressure. The hydraulic properties of these aquifers are summarized in Table 1.

b. Waste-water disposal aquifer is represented by the Miocene clastic sediments. In these sediments, water used for oil-wash are disposed after treatment.

c. Domestic water-supply aquifer is the Quaternary Liwa aquifer in the Bu Hasa area. Water from this aquifer are produced for domestic uses and oil washing.

The lithology, salinity and thickness of the most important aquifers and confining units in the Bu Hasa area are discussed in the following subsection and summarized in Table 2.

Table 1. Hydraulic properties of the Dammam, UER and Simsima aquifers in the Bu Hasa oil field (modified after Hassan and Al Aidarous, 1985).

Aquifer	Porosity (%)	Intrinsic Permeability (k)		Transmissivity (T) (ft^3/day)	Storage Coefficient (S_c)
		Darcy	cm/sec		
Simsima	06-35	0.0001-0.4	8.5×10^{-8} - 3.4×10^{-4}	15-220	4.0×10^{-4}
UER	15-25	0.01-0.05	8.5×10^{-6} - 4.3×10^{-6}	40-150	9.0×10^{-4}
Dammam	22-25	0.02-0.04	1.7×10^{-5} - 3.4×10^{-5}	30-60	6.8×10^{-4}

Table 2. The main hydrogeologic units and groundwater use in the Bu Hasa oil field (NDC-USGS, 1996).

Hydrogeologic unit	Thickness (m)	Nature	Lithology	Salinity (mg/L)	Importance and use
Liwa aquifer	135	aquifer	eolian sand	3,000	Domestic supply, wash water and fire fighting
Lower Fars confining unit	160	confining unit	evaporites/ clastics	5,000	Prevents vertical flow
Miocene Clastics aquifer	100	aquifer	sand	100,000	Receives injected brines
Dammam aquifer	265	aquifer	limestone	70,000	Source of water for injection into reservoirs
Rus confining unit	215	confining unit	anhydrite/ limestone	unknown	none
UER aquifer	415	aquifer	limestone	160,000	Source of water for injection into reservoirs
Simsima aquifer	270	aquifer	limestone	230,000	Source of water for injection into reservoirs

3.2.1 Brine-Producing Aquifers

The hydraulic properties and the relationship between the Quaternary Liwa aquifer and the Miocene clastic aquifer are the main focus of this chapter. However, because saline waters are produced from the Dammam, UER and Simsima aquifers for injection into petroleum reservoirs, the following is a brief discussion on each of these aquifers (Table 3 and Figure 25):

3.2.1.1 Simsima Aquifer

The carbonate sequence of the Simsima aquifer has been subdivided into three units; the lower unit is composed of chalky, shaly packstones and wackestones, the middle unit is made up of dolomitic and chalky packstones and wackestones and the upper part is characterized by a rather dense, clean limestone. The Simsima aquifer reaches its maximum thickness, 1200 ft (366 m), at the center of the Falaha syncline, from which the thickness decreases towards the north, west and southwest. The aquifer's hydraulic properties are given in Table 1.

Table 3. Volumes of water produced from various aquifers, injected into the petroleum reservoirs and diverted to unlined pits in the desert during the period 1970-1996.

Year	Water produced from the Simsima, Dammam and UER and aquifers (10^6 barrels)	Water injected into oil reservoirs (10^6 barrels)	Water diverted into unlined pits in the desert (10^6 barrels)
1970	003.1	003.1	000.0
1971	026.3	026.3	000.0
1972	192.2	192.2	000.0
1973	268.3	268.3	000.0
1974	273.8	273.8	000.0
1975	227.8	227.8	000.0
1976	210.7	210.7	000.0
1977	265.7	260.6	005.1
1978	217.3	214.5	002.8
1979	215.9	215.2	000.7
1980	167.9	166.6	001.3
1981	156.1	156.1	000.0
1982	135.8	135.4	000.4
1983	085.8	075.6	010.3
1984	104.1	085.1	019.0
1985	099.5	092.6	006.9
1986	086.3	071.8	014.5
1987	220.8	184.6	036.2
1988	238.5	201.4	037.1
1989	223.0	193.7	029.2
1990	239.3	220.3	019.0
1991	274.2	261.8	012.4
1992	303.3	300.1	003.2
1993	313.0	309.7	003.3
1994	314.0	311.7	002.2
1995	308.8	307.2	001.6
1996	319.0	318.5	000.6
Total	**5,490**	**5,285**	**0206**

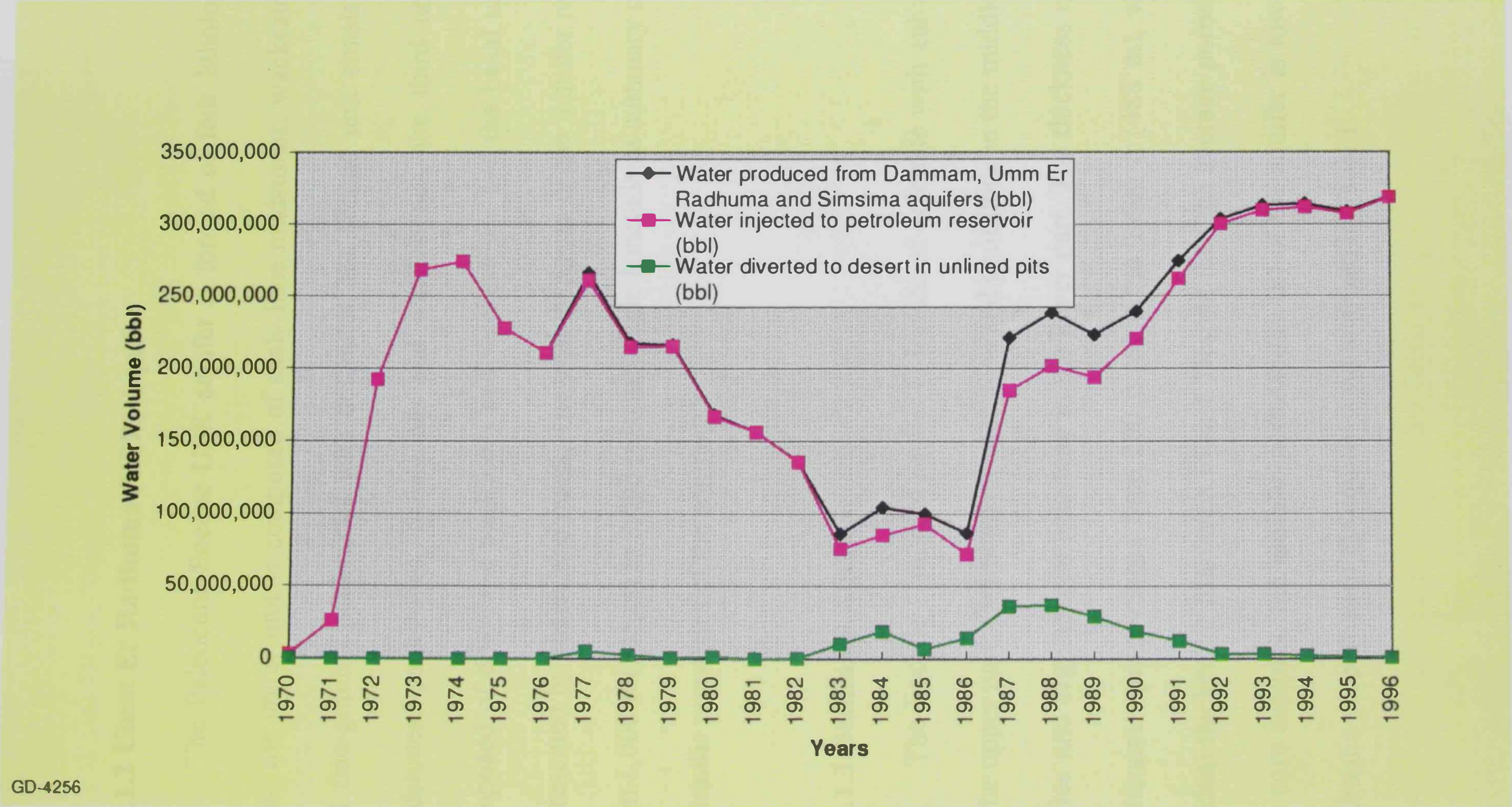

Figure 25. Chart showing the annual summary of water volumes produced from various aquifers, injected into the petroleum reservoirs and diverted to the desert in unlined pits (bbl)

3.2.1.2 Umm Er Radhuma (UER) Aquifer

The Paleocene-Eocene UER aquifer is formed of four lithological units; the upper unit is composed of shaly lime mudstones, wackestones, and fine-grained packstones with dolomites, the second unit consists of mudstones, packstones, grainstones and wackestones, the third unit is composed of dolomitic mudstones and wackestones and the basal unit is represented by shales and marls. The total thickness of the aquifer ranges from 1,000 ft (305 m) to 2,000 (610 m). Table 1 includes a summary of the hydraulic properties of the aquifer.

3.2.1.3 Dammam Aquifer

The Eocene Dammam aquifer is formed of dolomite with anhydrite in the upper part, foraminiferal packstone and grainstone in the middle and shales and argillaceous limestone in the lower part. The thickness of the Dammam aquifer ranges from 200 ft (61 m) to 1,600 ft (488 m), with a gradual thickening from west to east. Despite the high average porosity of the core samples, the intrinsic permeability (k) of the aquifer is low. The hydraulic properties of the aquifer is summarized in Table 1.

3.2.2 Waste-Water Disposal Aquifer

The Miocene clastic aquifer in the study area is used for disposal of oil-wash water. The aquifer is also utilized as the receiving zone for injection of waste brines from petroleum production. The aquifer attains an average thickness of about 328 ft (100 m). The water in this aquifer is brine, containing two to three times the TDS concentration of sea water. During the 1964-1994 period, 23 million barrels of treated waste water were injected into the Miocene clastic aquifer in the Bu Hasa field, whereas 204 million barrels were diverted to unlined pits in the desert.

3.2.3 Domestic Water-Supply Aquifer

The Quaternary Liwa aquifer contains water that is slightly (500-3,000 mg/l TDS) to moderately (3,000-10,000 mg/l TDS) saline, with an average TDS concentration of about 3,000 mg/l. Because it has the lowest salinity in the study area, water of the Quaternary aquifer is used for oil-camp domestic supply, irrigation, fire fighting and as dilution water to reduce the salinity of petroleum “wash water”. The aquifer is shallow, unconfined and composed predominantly of eolian sand. Consequently, there is a high potential for aquifer contamination by waste water moving downward from unlined pits in the desert or upward from the Miocene aquifer through the Fars Formation.

3.2.3.1 Depth to Groundwater

Figure 26 is based on field measurements of depth to water in the domestic wells and shallow rig wells during April 1996. It shows that the depth to the groundwater in the Quaternary Liwa aquifer within the Bu Hasa field ranges from 80 ft (24 m) in the northwest and southeast to 170 ft (52 m) in northeast and southwest. Together with the ground elevations, this map was used for construction of a general hydraulic head map for the Liwa aquifer in the Bu Hasa field in April 1996.

3.2.3.2 Saturated Thickness

The saturated thickness contour map of the Quaternary Liwa aquifer in the Bu Hasa area during April 1996 was constructed by subtraction of the field-measured depth-to-water from the base of the aquifer at each sampling point (Figure 27). The direction of groundwater flow, contamination of shallow groundwater and direction of contaminant movement suggest the re-location of the domestic water-supply field from its present position in the central part to the southeastern corner of the study area. The proposed new position has the following advantages:

a. The aquifer's saturated thickness is about 100 m compared with 25 to 45 m thickness in its present position.

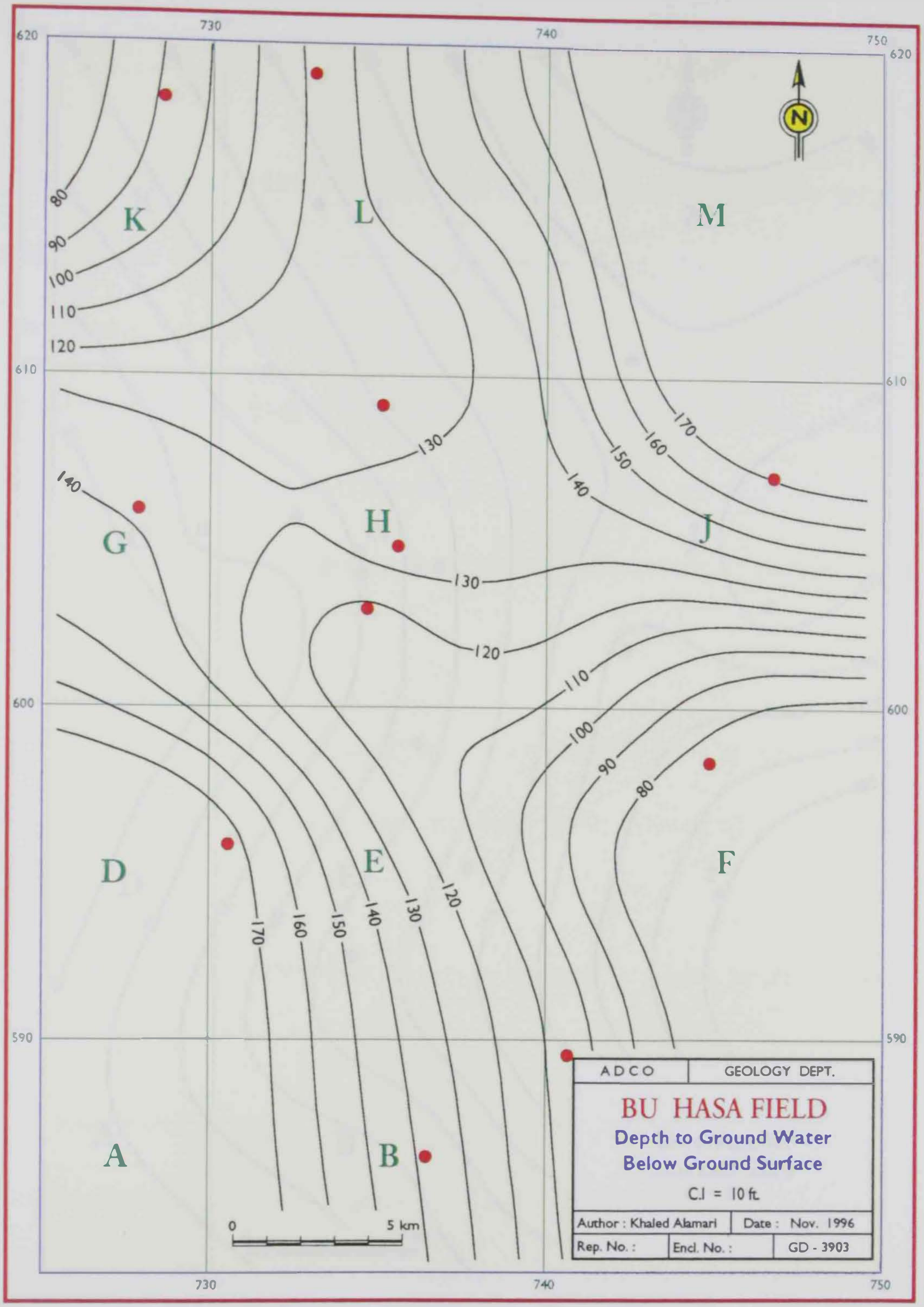

Figure 26. Depth to ground water contour map, in feet below the ground surface, in the Bu Hasa area, based on field measured data in April 1996.

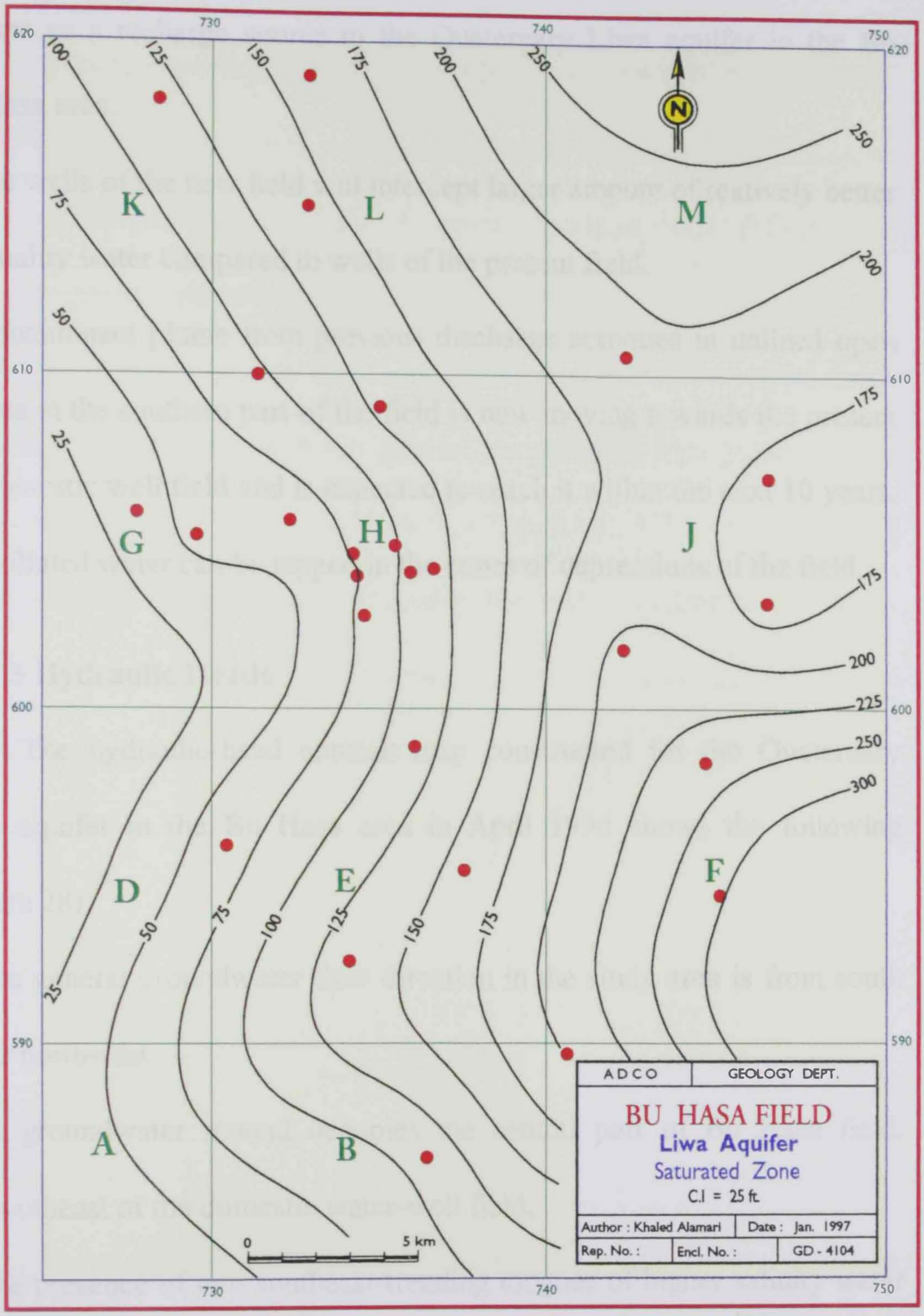

Figure 27. Saturated thickness contour map of the Quaternary Liwa aquifer, in feet, in the Bu Hasa area in April 1996.

b. The new site is relatively closer to the Liwa fresh-water mound which acts as a recharge source to the Quaternary Liwa aquifer in the Bu Hasa area.

c. The wells of the new field will intercept larger amount of reatively better quality water compared to wells of the present field.

d. Contaminant plume from previous discharge activities in unlined open pits in the southern part of the field is now moving towards the present domestic well field and is expected to reach it within the next 10 years. Polluted water can be tapped in the cones of depressions of the field.

3.2.3.3 Hydraulic Heads

The hydraulic-head contour map constructed for the Quaternary Liwa aquifer in the Bu Hasa area in April 1996 shows the following (Figure 28):

a. The general groundwater flow direction in the study area is from south to northwest.

b. A groundwater mound occupies the central part of Bu Hasa field, southeast of the domestic water-well field.

c. The presence of two southeast-trending tongues of higher salinity water (poor quality water) in the northwestern part of the study area reflects the effect of groundwater pumping from the Liwa aquifer in the area occupied by the domestic water-well field.

d. The hydraulic gradient is highly variable in the field ranging from 0.01 in the southwest to 0.001 in the southeast and northwest. In addition to the effect of pumping, the hydraulic gradient also reflects the heterogeoeous mature of the aquifer.

Figure 28 also indicates that the general groundwater flow from south to northwest agrees with the general groundwater flow pattern in the sandstone aquifer system in U. A. E. (Rizk et. al., 1996). However, the presence of a groundwater mound in the central part of the Bu Hasa field represents a local feature which is possibly related to the infiltration of waste water disposed off in open, unlined pits in this area.

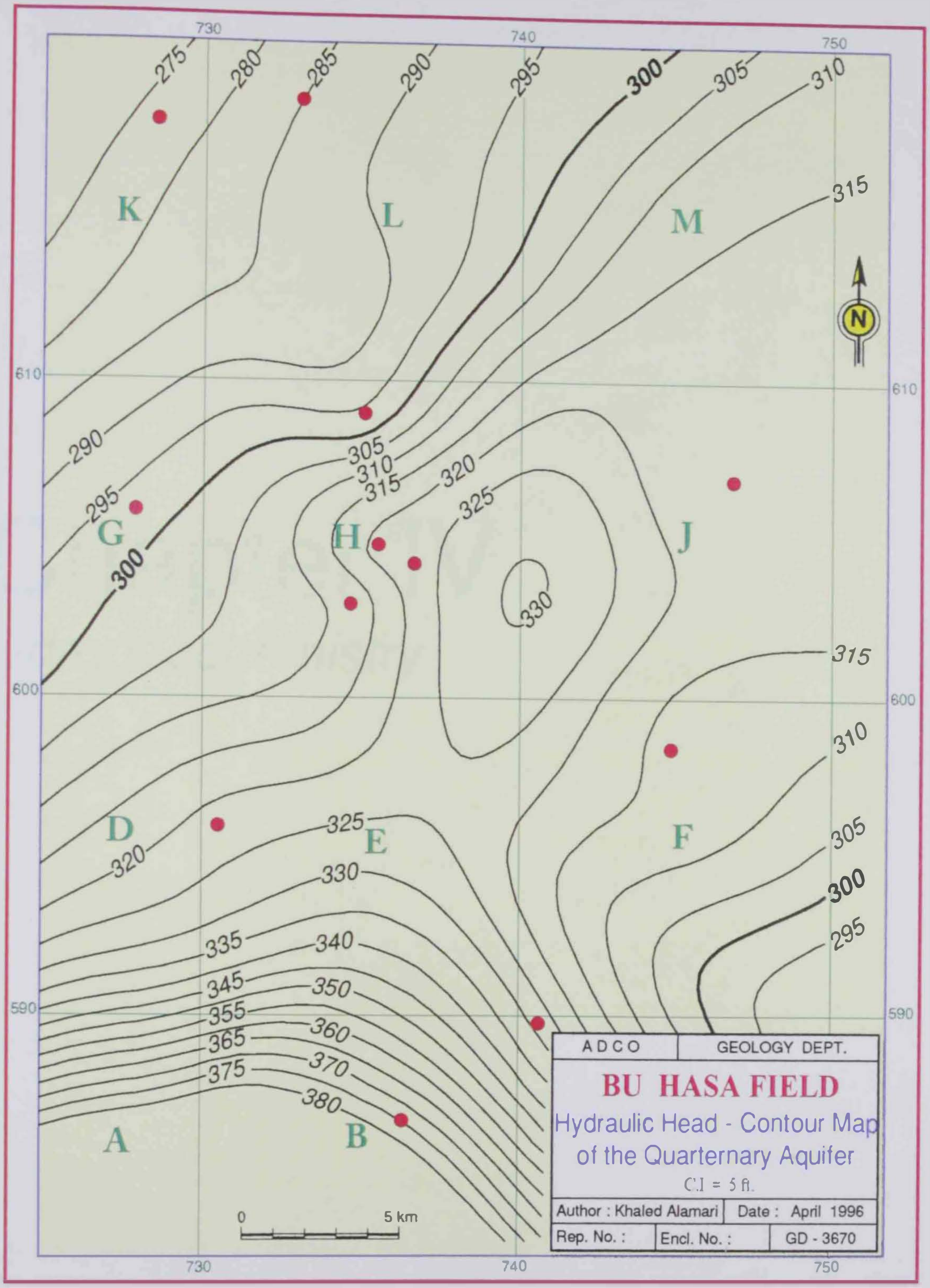

Figure 28. Hydraulic head contour map of the Quaternary Liwa aquifer, in feet above sea level, in the Bu Hasa area, based on field-measurements in April 1996.

Chapter IV

Hydrogeochemistry

CHAPTER IV

HYDROGEOCHEMISTRY

The objectives of this chapter are to study the hydrochemical characteristics of groundwater in the Quaternary Liwa aquifer at the Bu Hasa field, investigate the effect of geological and hydrogeological conditions on water chemistry and determine the possibility of groundwater contamination in the Quaternary Liwa aquifer as a result of disposal of oil-field water in the Miocene clastic aquifer.

In April 1996, 32 groundwater samples were collected from domestic water wells (Figure 29) and shallow ones close to selected water-supply wells and two waste-water disposal wells. The collected samples cover the central area of the field and its perimeter. Collected samples were directly analyzed in the Food Control Laboratory, Abu Dhabi, for major, minor and trace constituents. In September 1996, 17 samples were collected, mainly from the domestic water wells, and analyzed for some major and trace constituents in the Desert and Marine Environment Research Center, U. A. E. University. Figure 30 shows the location of the collected water samples and Table 4 shows a description of water sampling.

Figure 29. Water sampling and measurement of temperature, pH and electrical conductivity in a domestic water well of the Bu Hasa Field in April 1996.

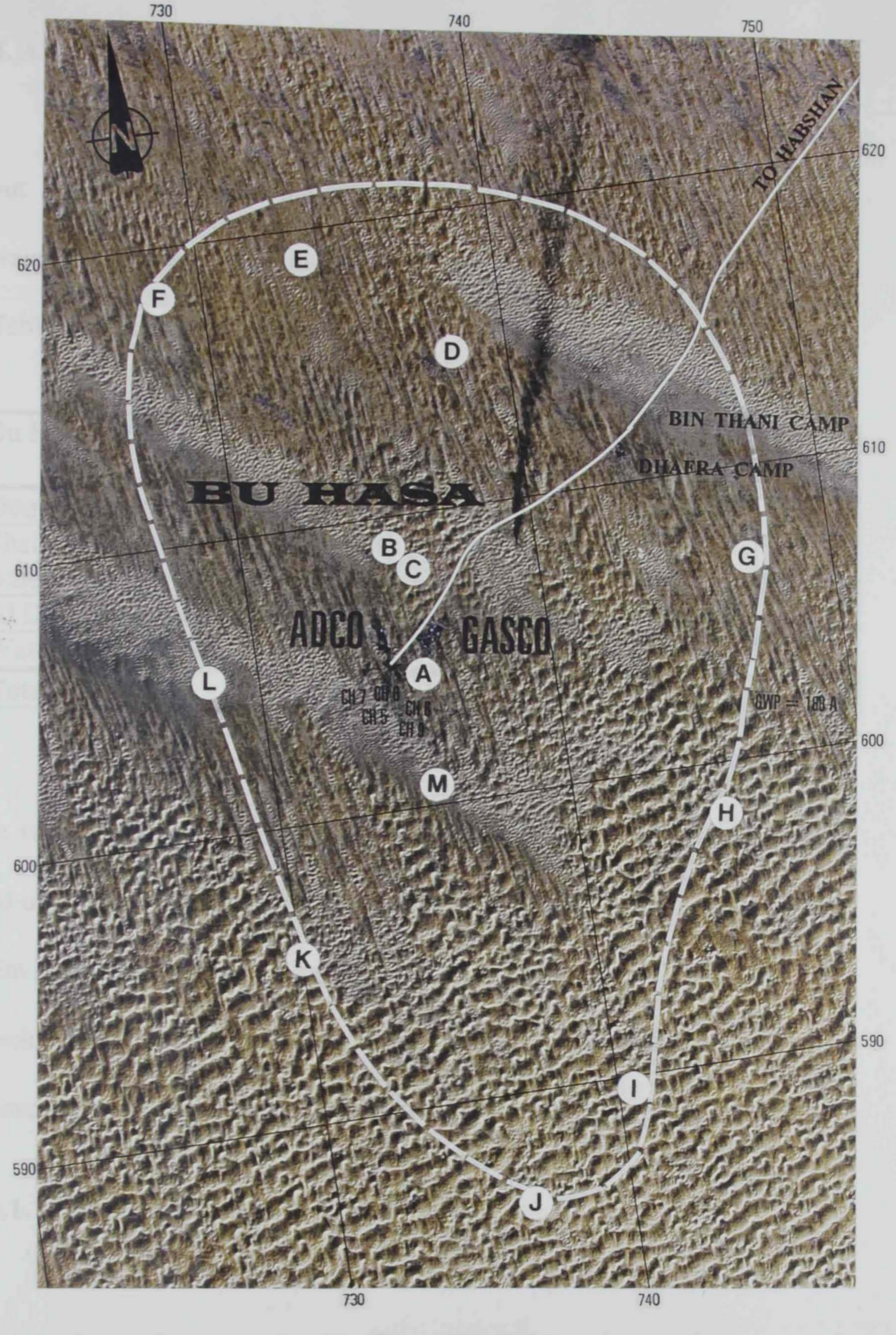

Figure 30. Landsat image of the Bu Hasa Field. Location of wells that have chemical analysis listed in this study.

4. Analytical Techniques

The measurements of the critical physical parameters were carried out in the field, while the complete chemical analysis of the collected water samples was performed in the laboratories.

Table 4. Location, season and number of samples collected from the Bu Hasa oil field for the present study.

Bu Hasa Field	Number of groundwater samples		
	April 1996	September 1996	Total
Domestic water well	17	13	27
Shallow water wells close to water-supply or injection wells	12	1	14
Al Dhafra and Bin Thani camps	2	2	4
Water injector plant	1	1	2
Total	**32**	**17**	**49**

The complete chemical analysis of the water samples was conducted in two laboratories, namely; the Food and Environment Control Center, Abu Dhabi Municipality, Abu Dhabi, and the Desert and Marine Environment Research Center, U. A. E. University, Al Ain. Different techniques have been employed for analysis. The following is a brief description of each of the analytical methods used in the present work:

4.1.1 Inductively Coupled Plasma

A Perkin-Elmer Plasma-400 Emission Spectrometer was used for the analysis of some major (Ca, Mg, Na and K) and several trace metals (Fe, Mn, Li, Sr, Ba, B, Cr, Zn, Ni, Pb, Cu, Co, Cd, As and Se).

The Inductively Coupled Plasma (ICP) is an optically thin emission source formed by coupling radiofrequency power into a stream of argon gas. The argon is constrained into three concentric streams in a plasma torch fabricated from fused silica. A toroidal shaped plasma is formed, and the sample is injected through the central tunnel, heated to a high temperature (~8000 K) and thereby atomized to a large extent. Emission from the excited atoms and ions is observed at a height of 10 to 20 mm above the load coil by a conventional spectrometer system.

4.1.2 Ion Chromatography

Ion chromatography, model Dionex-2020i, was used for the analysis of the anions: Cl^-, F^-, NO_3^-, SO_4^{2-} and HCO_3^-. The Dionex-2020i ion chromotograph is a dual-channel, high-performance chromatographic system featuring two precision Analytical Pumps, a dual-channel, and two conductivity detectors. The components are housed in three sturdy, corrosion-resistant enclosures. The operating conditions were 10 to 40 °C temperature range and 1900 psi (129 atm) maximum pressure.

4.1.3 Solid-Phase Extraction

Solid-Phase Extraction (SPE) for isolation of organic contaminants was performed by a capillary column according to the following steps:

1. Preparation of an extraction tube of superclean ENVI-C18, 6 ml, 0.5g packing (SUPELCO).
2. Conditioning of tube of 2x 6 ml n. hexane; diethyl ether (1:Iv/v); 6 ml methanol and 6 ml deionized water.
3. Sample Addition of 300 ml of water, about 10 ml/ minute. 6 ml of deionized water.
4. Drying for about 15 minutes with nitrogen.
5. Elution of organics: 2 x 1 ml n. hexane: diethyl ether (1:1 v/v)

4.1.4 Gas Chromatography-Mass Spectrometry

This technique was also used for identification of organic pollutants present in water samples collected from the Quaternary aquifers and the water injection plant in the Bu Hasa area. The gas chromatography (GC) and mass spectrometry (MS) parameters include the following:

a. GC parameters

Oven: 60 (3 minutes) to 280 C° at 10 C° min, hold 20 minutes

Column: SPB-5, 30 m X 0.25 mm id X 0.25 mm film, SUPELCO.

Linear velocity: 35 cm/sec (Helium, 60°C)

Split ratio: 15:1

b. MS parameters

Solvent delay: 2.5 minutes

Mass range: 30-450 amu (full scan)

Scan time: 0.80 (seconds)

Inter-Scan delay: 0.20 (seconds.)

Ionization mode: EI+

4.1.5 Atomic Absorption Spectrophotometry

This technique was used for the analysis of some major ions (Ca, Mg, Na and K) and several trace metals (Fe, Li, Sr, Ba, B, Cr, Zn, Ni, Pb, Cu, Co, Cd, Mn, As and Se). For determination of total metals in water, the water sample is acidified with nitric acid (8 ml/l) and boiled for 4-5 minutes and then filtered, if necessary. Simultaneously a blank, in duplicate with deionized water having the same amount of nitric acid run in identical conditions. This blank, to some extent, takes care of the errors due to reagents and/or environment. The contamination of iron, chromium, copper, nickel and zinc from different equipment of the laboratory is very common. The sample is then a spirated to double beam Atomic Absorption Spectrometer (GBC-906) equipped with autosampler and background corrector directly.

4.2 Field-measured Parameters

The pH, temperature (°C) and Electrical Conductivity (EC), in microsiemens per centimeter (μS/cm), were measured for samples collected in April 1996, using a portable pH meter, model HI-8314. The electrical conductivity was measured by a Myron-L EC-meter with the following specifications:

Range	0 to 5,000 (μS)
Accuracy	± 2% of full scale
Repeatability	± 1%
Temperature Compensation	0.00 to 49 °C

Because their values change with time, the temperature (°C), hydrogen-ion concentration (pH) and Electrical Conductivity (μS/cm) of collected water samples were directly measured in the field. The following is a brief discussion on each of these parameters:

4.2.1 Water Temperature

Groundwater temperature (°C) was only measured for domestic water wells in the central part of the Bu Hasa field. Measured temperatures varied between 30.4 °C in Wells No. CH-3 and CH-6 and 35.0 °C in Well No. WW-2. The average groundwater temperature in 17 domestic wells in the Bu Hasa field was 34.8 °C.

4.2.2 Electrical Conductivity

The Electrical Conductance (EC) of water samples collected from the domestic water wells of the Bu Hasa field in April 1996 ranged from 2,700 μS/cm (WW-22) to 8,500 in Well No. CH-6, with an average of 4588 μS/cm.

4.2.3 Hydrogen-Ion Concentration

The pH value of water is a function of its hydrogen-ion concentration and affects, to a great extent, its suitability for different uses. The water pH is controlled by the amount of dissolved carbon dioxide (CO_2), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) (Domenico and Schwartz, 1990). The pH values of water samples collected from the domestic wells ranged from 6.9 in Well No. WW-17 to 7.8 in Well No. CH-6.

4.3 Chemical Parameters

Chemical analyses of water samples collected from the Bu Hasa area in September 1996 are given in Appendix I. The following discussion will include the salinity, major cations, major anions, minor constituents and water type.

4.3.1 Total Dissolved Solids

The total dissolved solids in a water sample includes all solid materials in solution whether ionized or not. It does not include suspended sediments, colloids or dissolved gases. The TDS content in groundwater is an indication of its salinity. A simple classification of groundwater salinity depending on the total concentration of dissolved constituents, as proposed by Todd (1980), is given in Table 5.

Table 5. Classification of groundwater according to its TDS content in mg/l (Todd, 1980).

Water type	Total Dissolved Solids (mg/l)
Fresh water	0 - 1,000
Brackish water	1,000 - 10,000
Saline water	10,000 - 100,000
Brine	> 100,000

Based on the data obtained from the literature, iso-salinity contour maps (Figures 31, 32, 33 and 34) were constructed for the Quaternary Liwa aquifer in the Bu Hasa area for the years 1964, 1973, 1976 and 1985. All maps show a gradual increase in groundwater salinity from southeast towards northwest, in the direction of groundwater flow.

A steady increase in groundwater salinity around the camp area is clearly indicated in the salinity profiles (Figure 35). Between 1964 and 1985, the groundwater salinity increased in the camp area from 3,500 mg/l to 5,500 mg/l.

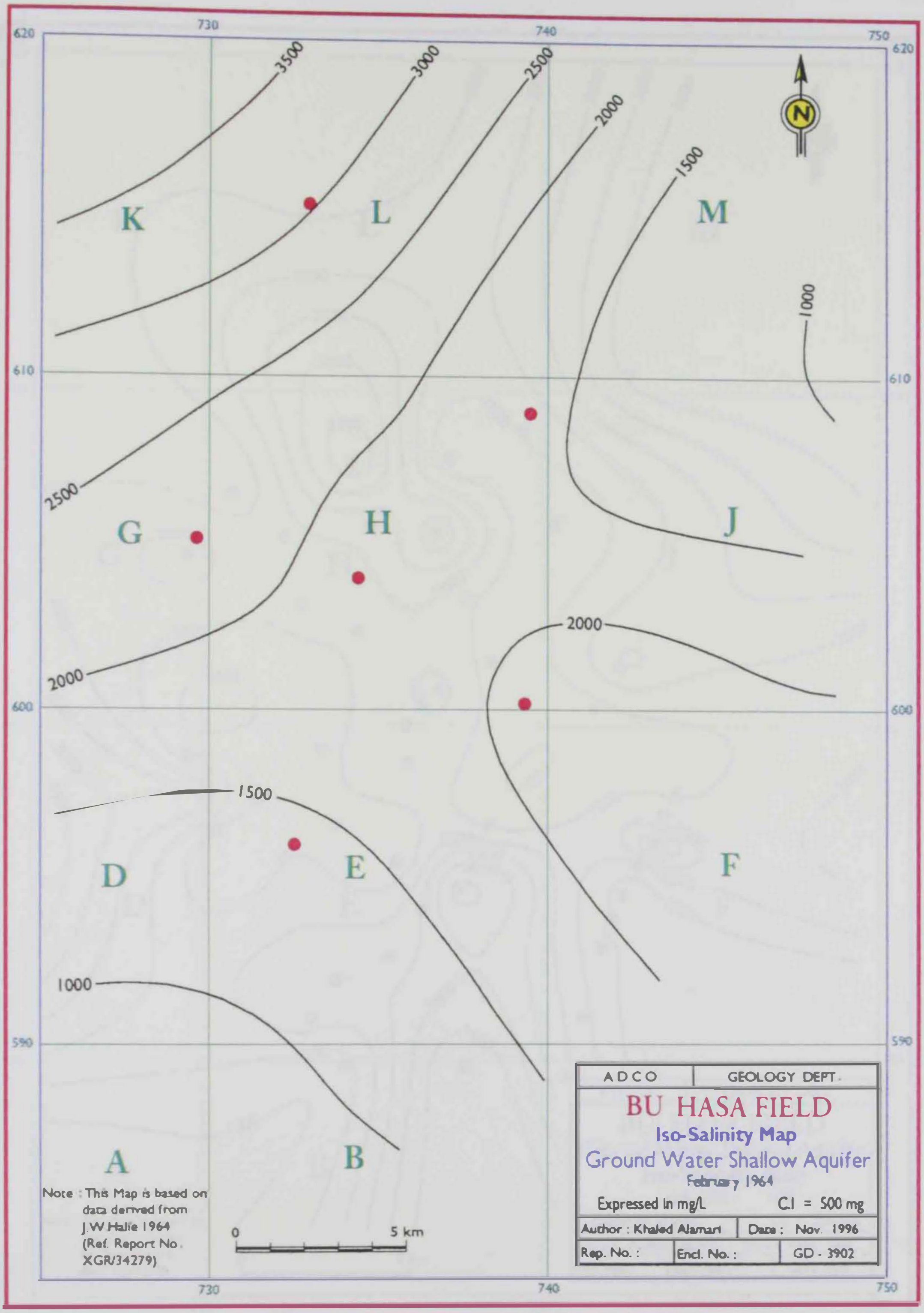

Figure 31. Iso-salinity contour map, in mg/l, of shallow groundwater in the Quaternary Liwa aquifer at the Bu Hasa area in April 1964.

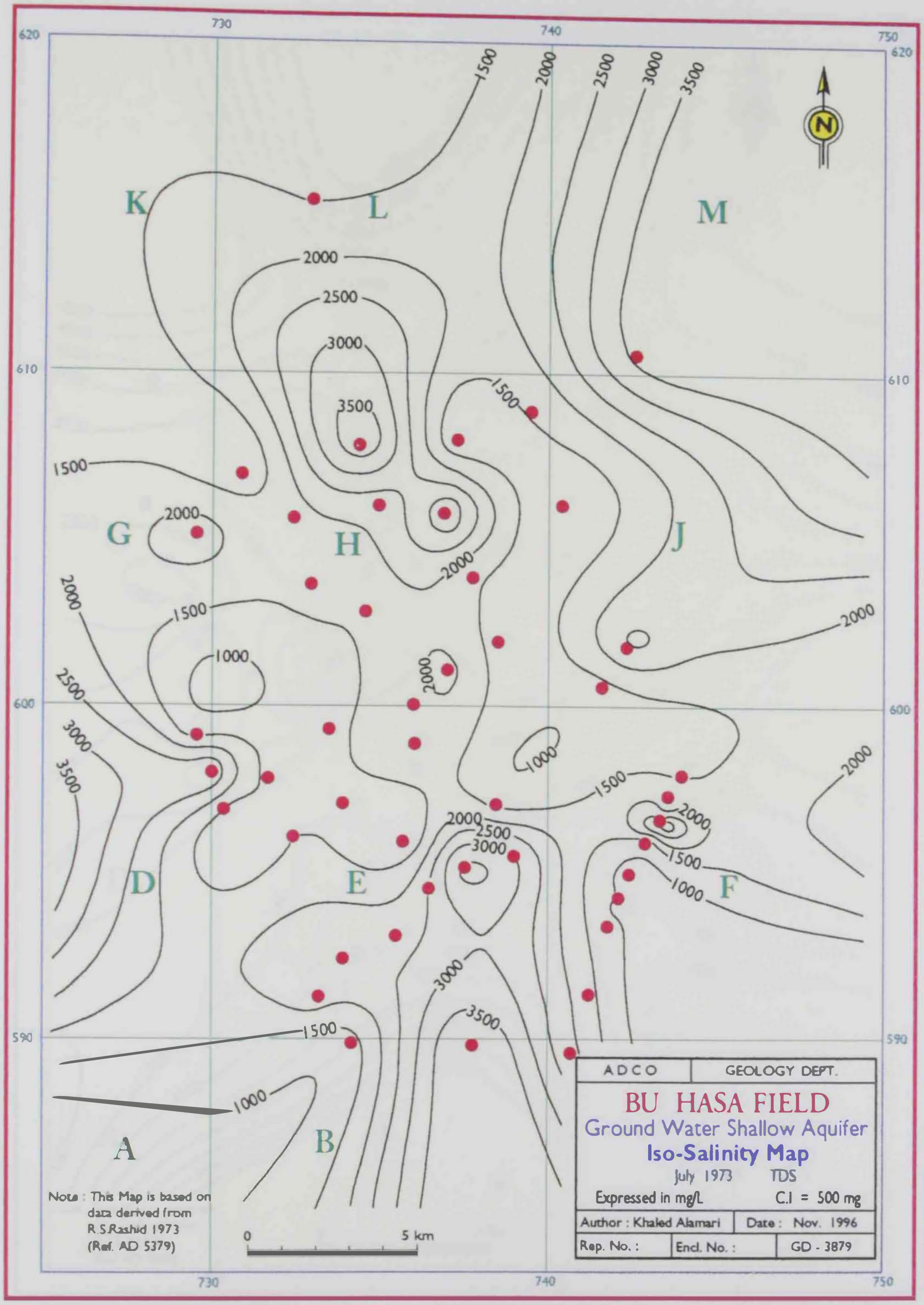

Figure 32. Iso-salinity contour map, in mg/l, of shallow groundwater in the Quaternary Liwa aquifer at the Bu Hasa area in July 1973.

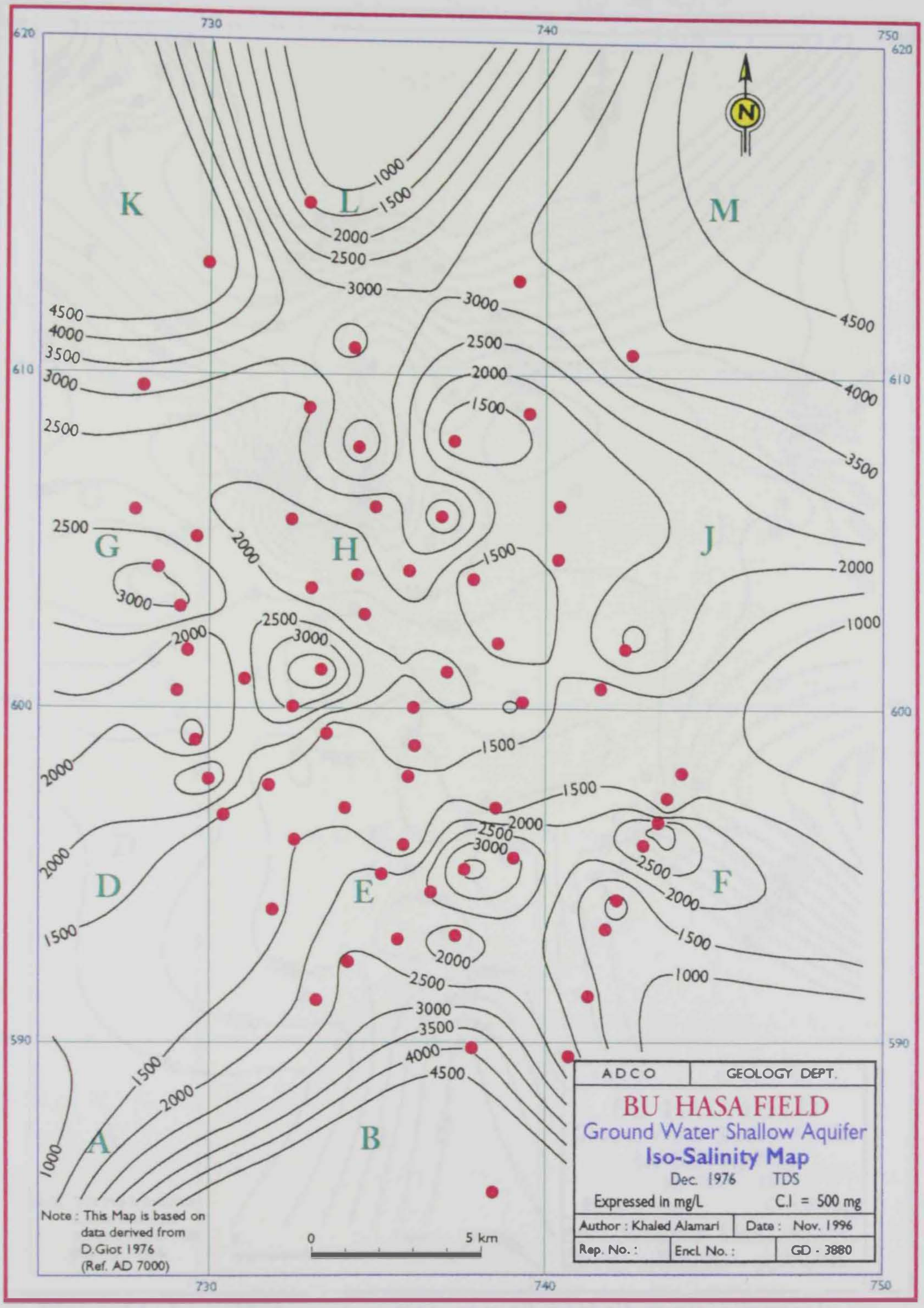

Figure 33. Iso-salinity contour map, in mg/l, of shallow groundwater in the Quaternary Liwa aquifer at the Bu Hasa area in December 1976.

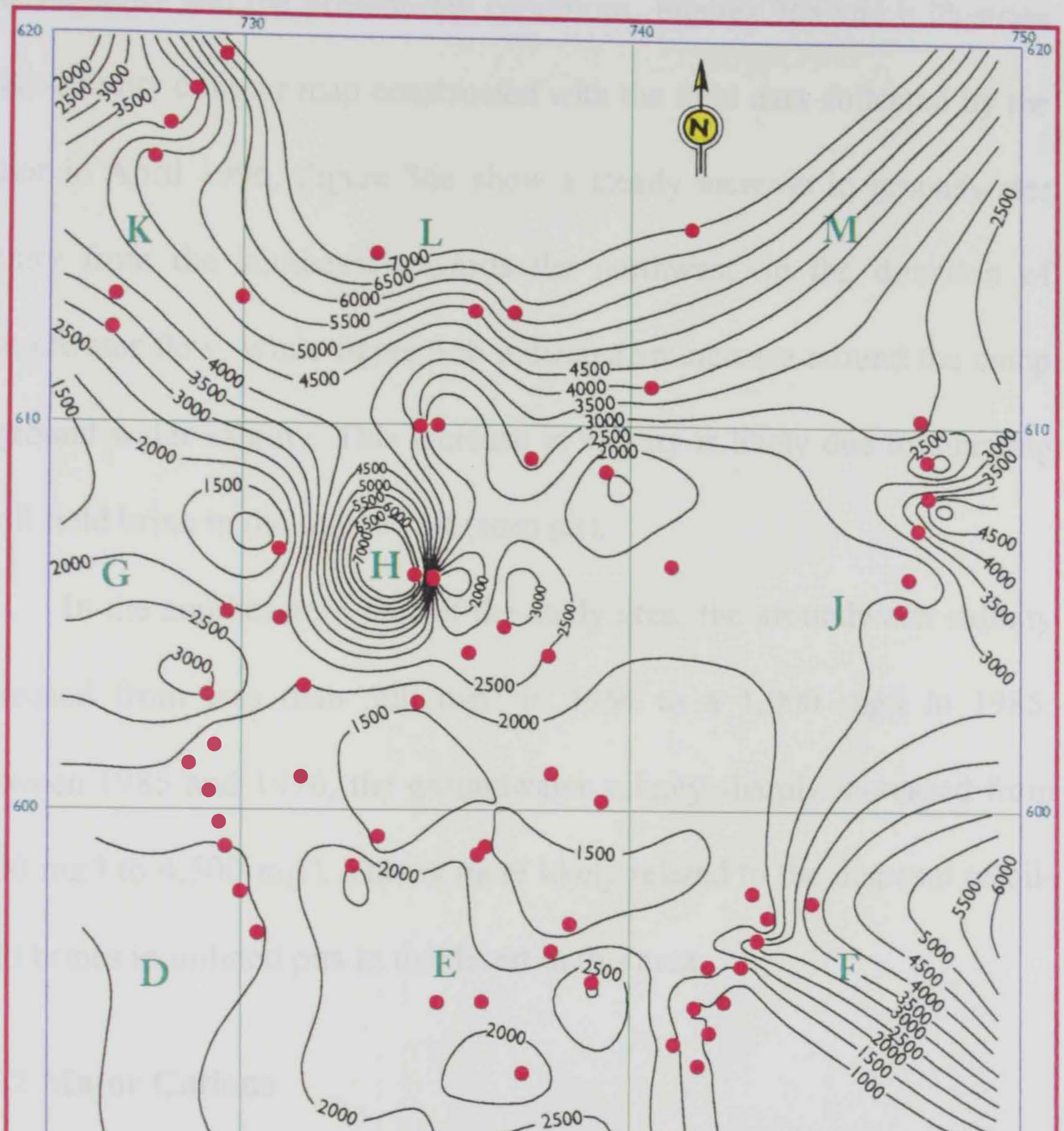

Figure 34. Iso-salinity contour map, in mg/l, of shallow groundwater in the Quaternary Liwa aquifer at the Bu Hasa area in July 1985.

Figure 35 is to compare the evolution of groundwater salinity obtained from literature and the present-day conditions, Figures 36a and b illustrate an iso-salinity contour map constructed with the field data collected by the author in April 1996. Figure 36a show a steady increase in groundwater salinity from the southeast towards the northwest, in the direction of groundwater flow, while figure 36b indicates an increase around the camp in ground water salinity. This increase in salinity is likely due to dumping of oil field brine in the unlined pit (seep pit).

In the southeastern part of the study area, the groundwater salinity increased from less than 500 mg/l in 1964 to a 1,000 mg/l in 1985. Between 1985 and 1996, the groundwater salinity sharply increased from 1000 mg/l to 4,500 mg/l. This is more likely related to the disposal of oil-field brines in unlined pits in the desert in this area.

4.3.2 Major Cations

The sequence of cation dominance in groundwater of the Quaternary Liwa aquifer in the Bu Hasa area has the order: $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+}$. Based on chemical analysis of water samples collected in April 1996 the following is a brief discussion on each cation (Table 6):

The primary source of most sodium ions (Na^{+}) in natural water is the release of soluble products during the weathering of sodium-bearing

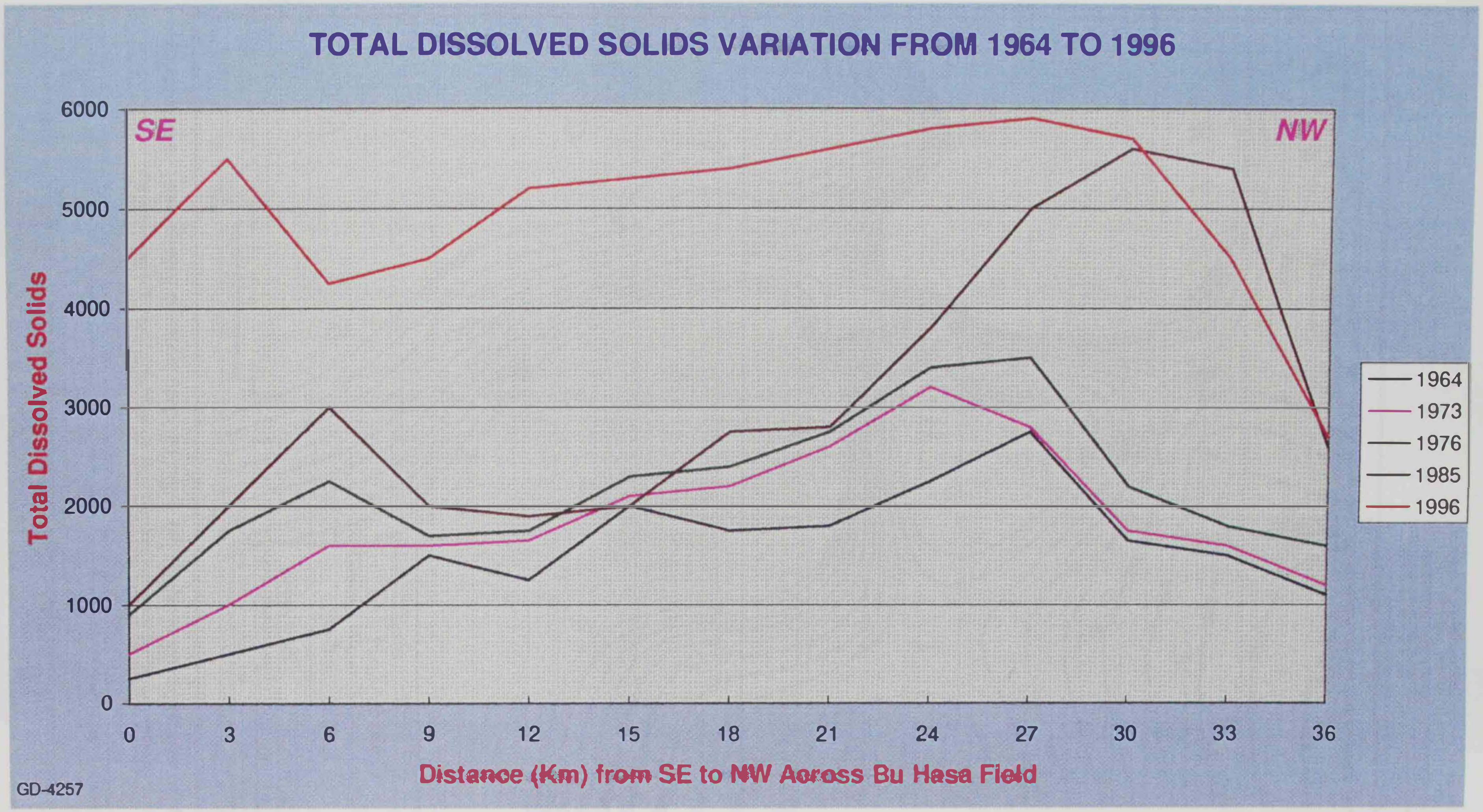

Figure 35. Iso-salinity profile in southeast-northwest direction across the Bu Hasa field showing the evolution of ground water salinity between 1964 1996

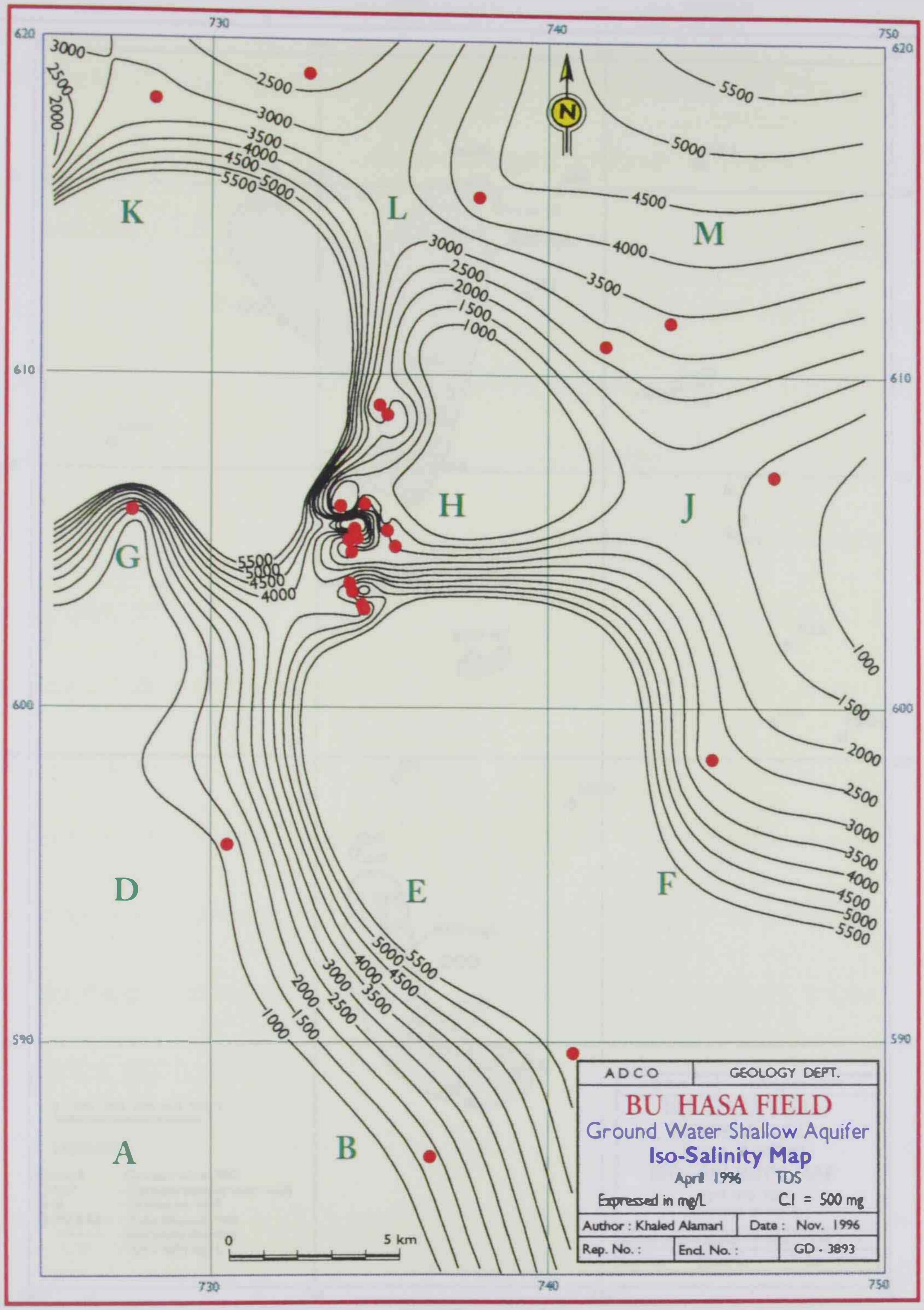

Figure 36a. Iso-salinity contour map, in mg/l, of shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

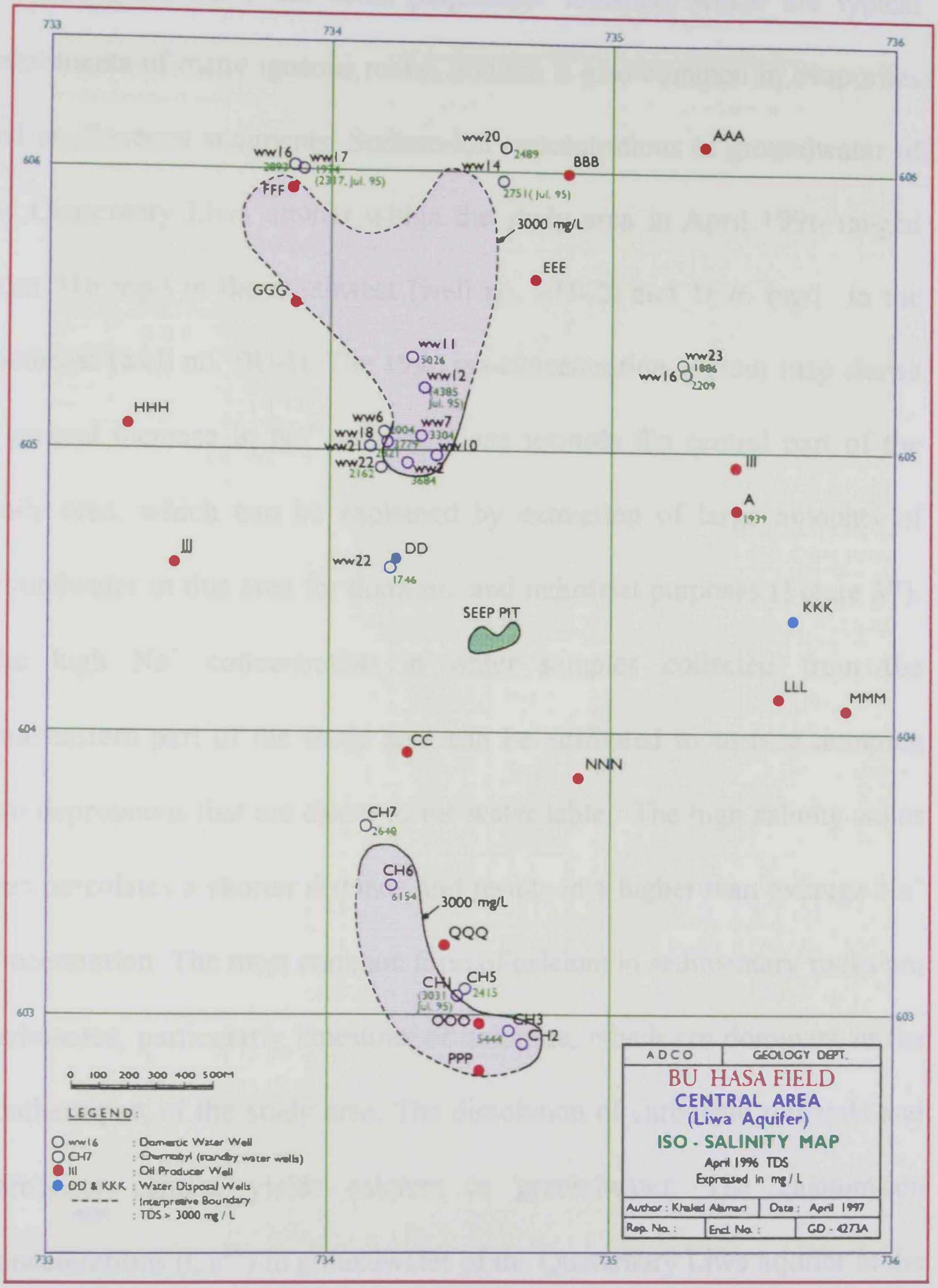

Figure 36b. Close-up map of central Bu Hasa area indicating an increase in ground water salinity.

minerals, particularly the sodic plagioclase feldspars which are typical constituents of many igneous rocks. Sodium is also common in evaporites and argillaceous sediments. Sodium-ion concentrations in groundwater of the Quaternary Liwa aquifer within the study area in April 1996 ranged from 316 mg/l in the southwest (well no. BU-K) and 1696 mg/l in the southeast (well no. BU-I). The 1996 iso-concentration contour map shows a general increase in Na$^+$ concentrations towards the central part of the study area, which can be explained by extraction of large amounts of groundwater in this area for domestic and industrial purposes (Figure 37). The high Na$^+$ concentration in water samples collected from the southeastern part of the study area can be attributed to surface dumping into depressions that are closer to the water table. The high salinity water then percolates a shorter distance and results in a higher than average Na$^+$ concentration. The most common form of calcium in sedimentary rocks are carbonates, particularly limestone or dolomite, which are dominant in the southern part of the study area. The dissolution of carbonate minerals and carbonate cement yields calcium to groundwater. The calcium-ion concentrations (Ca^{2+}) in groundwater of the Quaternary Liwa aquifer in the study area in April 1996 ranged from 4 mg/l in the extreme southern tip of

Table 6. Major inorganic chemical constituents in groundwater samples collected from the Quaternary Liwa aquifer in Bu Hasa Oil Field during April 1996.

Well No.	Cal.TDS	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	SO_4^{-}	Cl^{-}
WW2	3,684	140.46	64.94	988.29	45.04	11.95	148.25	634.70	1638.60
WW7	3.304	73.44	54.15	921.70	37.64	38.24	243.04	435.60	1485.50
WW19	2,162	74.96	26.63	603.45	20.13	7.17	132.46	393.66	889.26
WW21	2.821	86.83	37.28	805.76	25.91	5.98	106.94	586.62	1148.40
WW6	2,004	70.98	31.10	535.81	22.56	14.34	178.63	320.12	816.78
WW18	3,779	159.29	66.92	988.61	41.75	11.95	120.30	725.56	1646.30
WW11	5,026	241.61	95.78	1112.77	49.20	8.37	91.14	899.80	2505.60
WW17	1,974	58.68	25.24	450.32	16.66	7.17	106.94	387.83	903.18
WW16	2,893	116.74	47.14	637.66	24.97	7.17	104.51	549.27	1387.35
WW20	2,489	90.41	40.18	540.75	21.08	9.56	142.18	468.42	1157.55
WW15	2,209	63.25	29.63	492.32	15.01	7.17	114.23	424.40	1046.00
WW23	1,886	49.28	19.98	440.18	15.91	13.15	126.38	336.86	868.02
WW22	1,746	42.97	16.36	478.59	12.32	7.17	109.37	395.33	669.78
CH7	2,640	73.79	29.13	654.12	20.28	9.56	104.51	519.46	1212.90
CH6	6,154	247.89	102.39	1206.47	49.75	5.98	88.71	1521.10	2908.80
CH5	2,415	66.50	26.99	491.67	14.51	5.98	109.37	545.70	1139.30
CH3	5,444	189.72	76.78	852.87	34.63	3.59	83.85	1489.80	2690.40
A	1,939	11.03	6.64	508.33	8.44	2.39	76.56	268.08	1053.66
B	1,857	5.46	2.49	590.76	10.32	14.34	164.05	7.01	1058.40
C	2,692	79.10	32.85	703.49	21.11	13.15	120.30	494.16	1213.80
D	4,258	136.58	59.55	960.03	35.25	7.17	100.86	941.40	1997.40
E	2,319	6.48	0.15	663.22	9.73	5.98	83.85	29.74	1516.20
F	3,029	214.37	60.33	594.20	44.73	N.D.	N.D.	575.88	1530.70
Al Dhafra	2,769	113.85	47.29	646.63	33.64	8.37	97.21	553.22	1250.40
Bin Thani	3,399	128.95	48.16	766.96	34.21	9.56	100.86	646.47	1644.60
G	1,348	9.56	1.98	342.67	8.53	3.59	81.42	134.08	762.30
H	2,829	0.94	0.11	801.50	9.60	41.83	313.52	156.80	1501.30
I	5,829	111.66	62.76	1696.29	50.44	8.37	82.63	17.97	3796.80
J	1,771	4.19	4.84	440.51	7.94	14.34	157.98	102.58	1035.30
K	1,210	4.69	1.93	316.72	6.70	8.37	117.87	56.68	694.44
L	1,806	20.90	9.83	535.59	14.96	10.76	31.59	7.54	1167.30
Waste Water	78,541	4628.8	413.55	8671.13	744.27	N.D.	132.46	625.90	63303.0

N.D : not detected

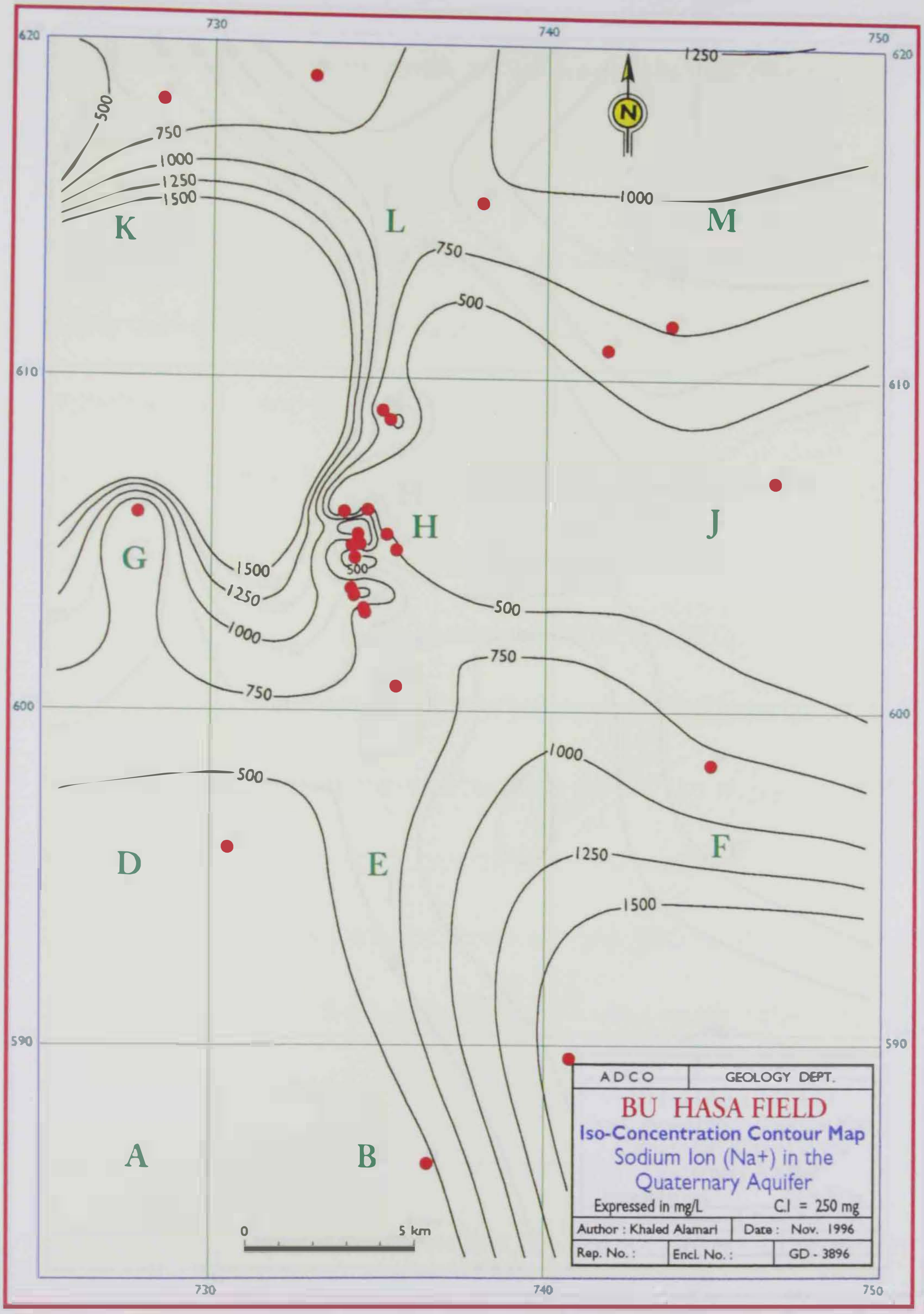

Figure 37. Iso-concentration contour map, in mg/l, of the sodium ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

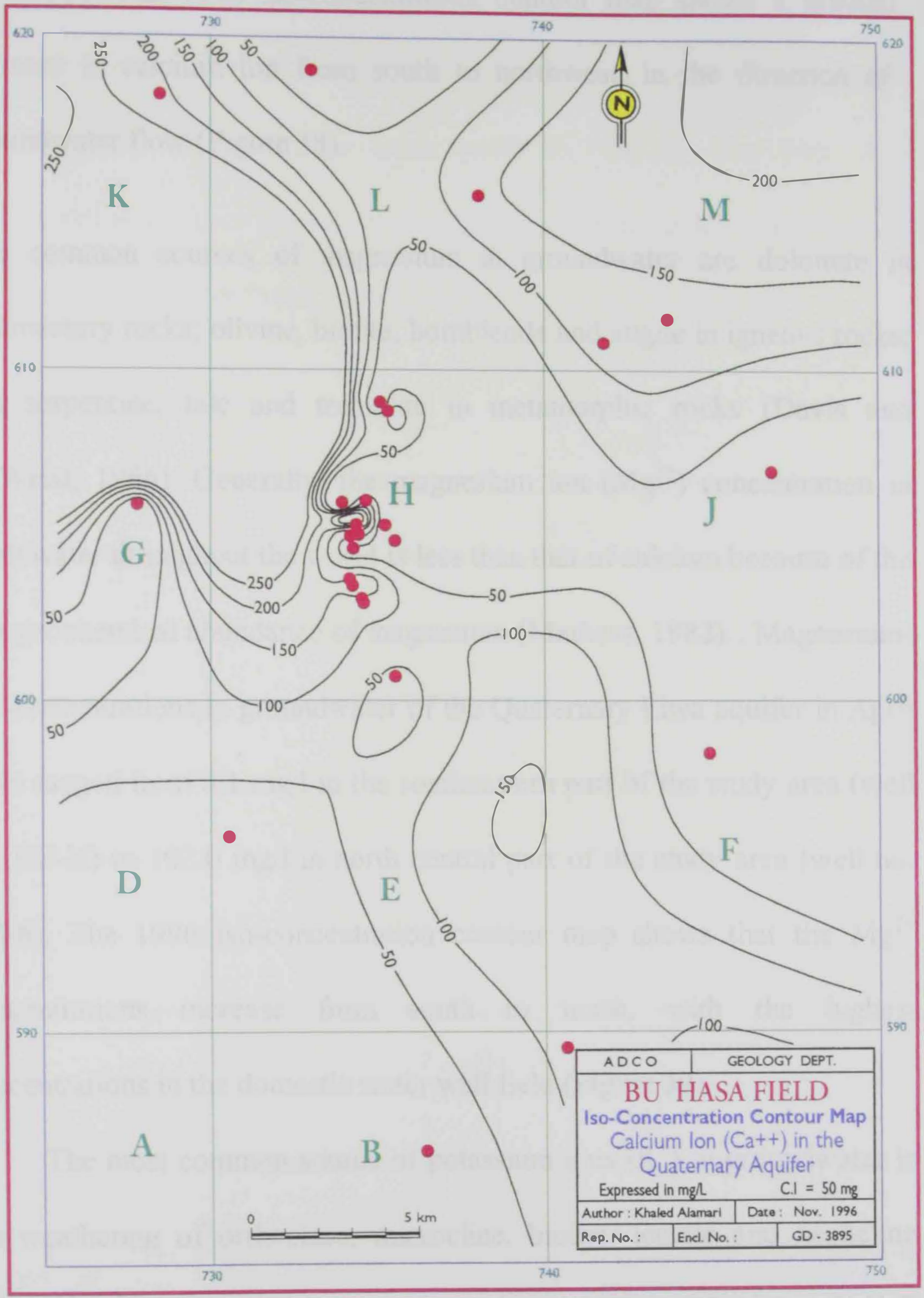

Figure 38. Iso-concentration contour map, in mg/l, of the calcium ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

the field (well no. BU-J) to 248 mg/l in the central part of the area (well no. CH-6). The 1996 iso-concentration contour map shows a gradual increase in calcium ion from south to northwest, in the direction of groundwater flow (Figure 38).

The common sources of magnesium in groundwater are dolomite in sedimentary rocks; olivine, biotite, hornblende and augite in igneous rocks; and serpentine, talc and tremolite in metamorphic rocks (Davis and DeWeist, 1966). Generally, the magnesium ion (Mg^{2+}) concentration in fresh water throughout the world is less than that of calcium because of the low geochemical abundance of magnesium (Mathess, 1982). Magnesium-ion concentrations in groundwater of the Quaternary Liwa aquifer in April 1996 ranged from 0.1 mg/l in the southeastern part of the study area (well no. BU-H) to 102.0 mg/l in north central part of the study area (well no. CH-6). The 1996 iso-concentration contour map shows that the Mg^{2+} concentrations increase from south to north, with the highest concentrations in the domestic water well field (Figure 39).

The most common source of potassium ions (K^+) in groundwater is the weathering of orthoclase, microcline, biotite, leucite and nepheline minerals. Water percolating through evaporite deposits may contain high concentrations of potassium ion (Hem, 1985). Potassium concentration is commonly less than one-tenth the concentration of sodium in natural water because potassium is rarely taken into solution. Potassium-ion (K^+) concentration in groundwater of the Quaternary Liwa aquifer within the study area in April 1996 ranged from 7 mg/l in the southwest (well no. BU-K) to 50 mg/l in the north (well no. CH-6). The 1996 iso-concentration contour map shows a steady increase in K^+ concentration from southwest to southeast, northeast and northwest (Figure 40).

4.3.3 Major Anions

The sequence of anion dominance in groundwater of the Quaternary aquifer in the study area has the order: $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$. Based on chemical analysis of water samples collected in April 1996, the following is a brief discussion on each anion:

Chloride (Cl^-) is the most widely distributed ion in natural water. Dissolution of certain evaporites commonly provide high concentrations of Cl^- in groundwater (El-Shami, 1982). However, most Cl^- in groundwater comes from three principal sources: ancient sea water entrapped in sediments, dissolution of halite and related minerals in evaporite deposits, and the solution of dry fallout from the atmosphere, particularly in arid regions (Davis and DeWeist, 1966). Chloride ion concentrations in groundwater of the Quaternary Liwa aquifer in the study area in April 1996 ranged from 694 mg/l in the southwest (well no. BU-K) to 2,909 mg/l in north central part of the study (well no. CH-6). The April 1996 iso-

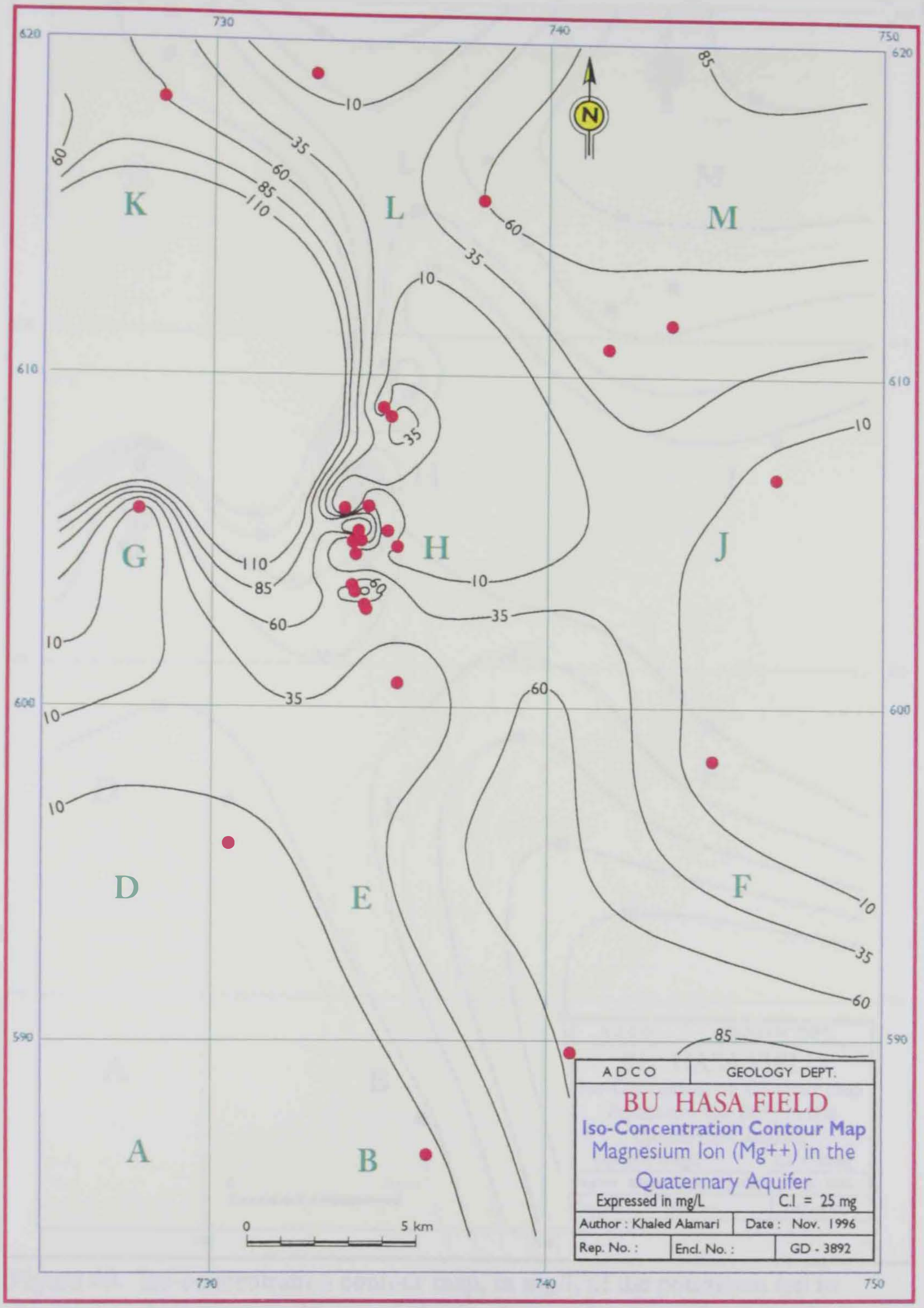

Figure 39. Iso-concentration contour map, in mg/l, of the magnesium ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996

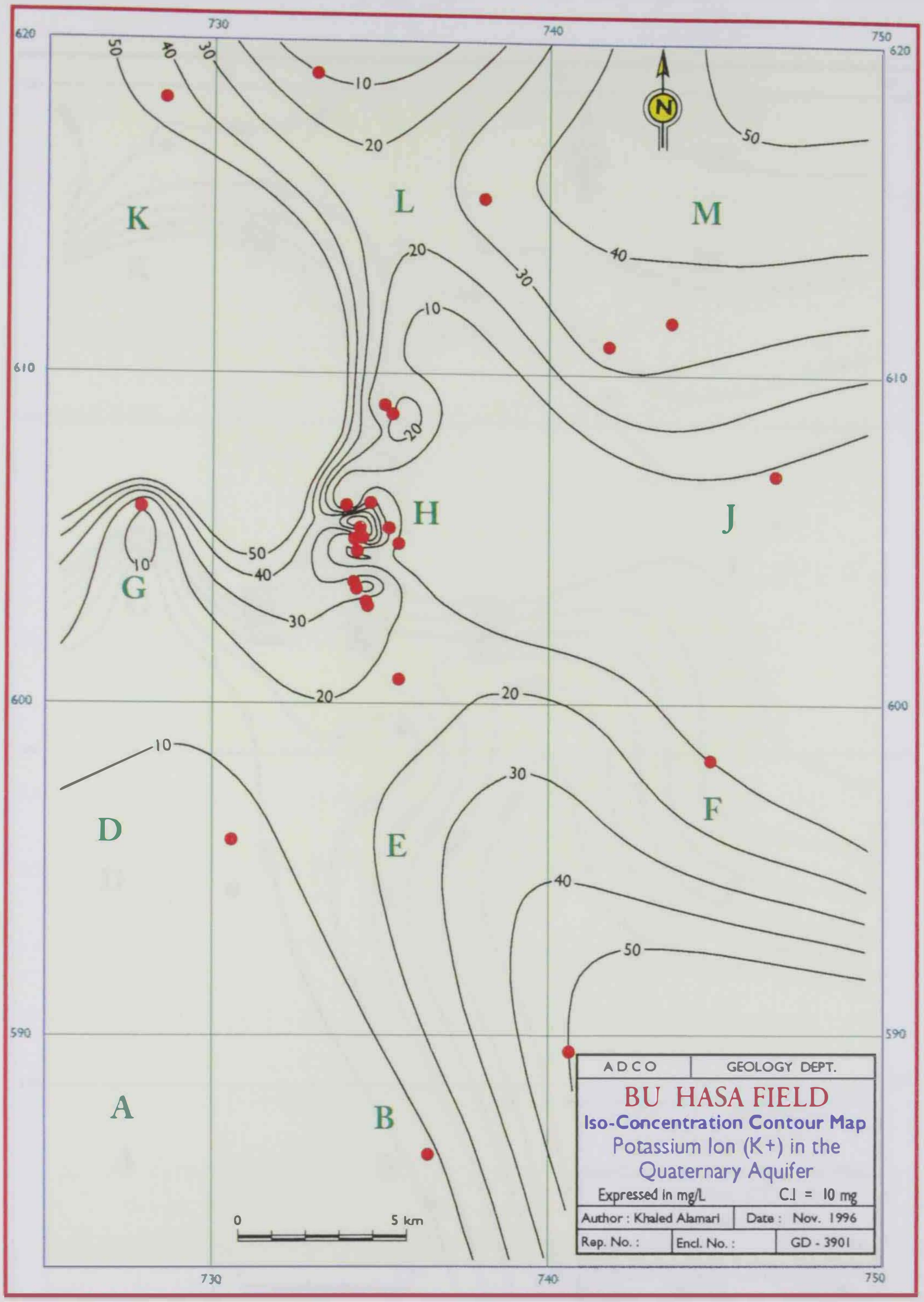

Figure 40. Iso-concentration contour map, in mg/l, of the potassium ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

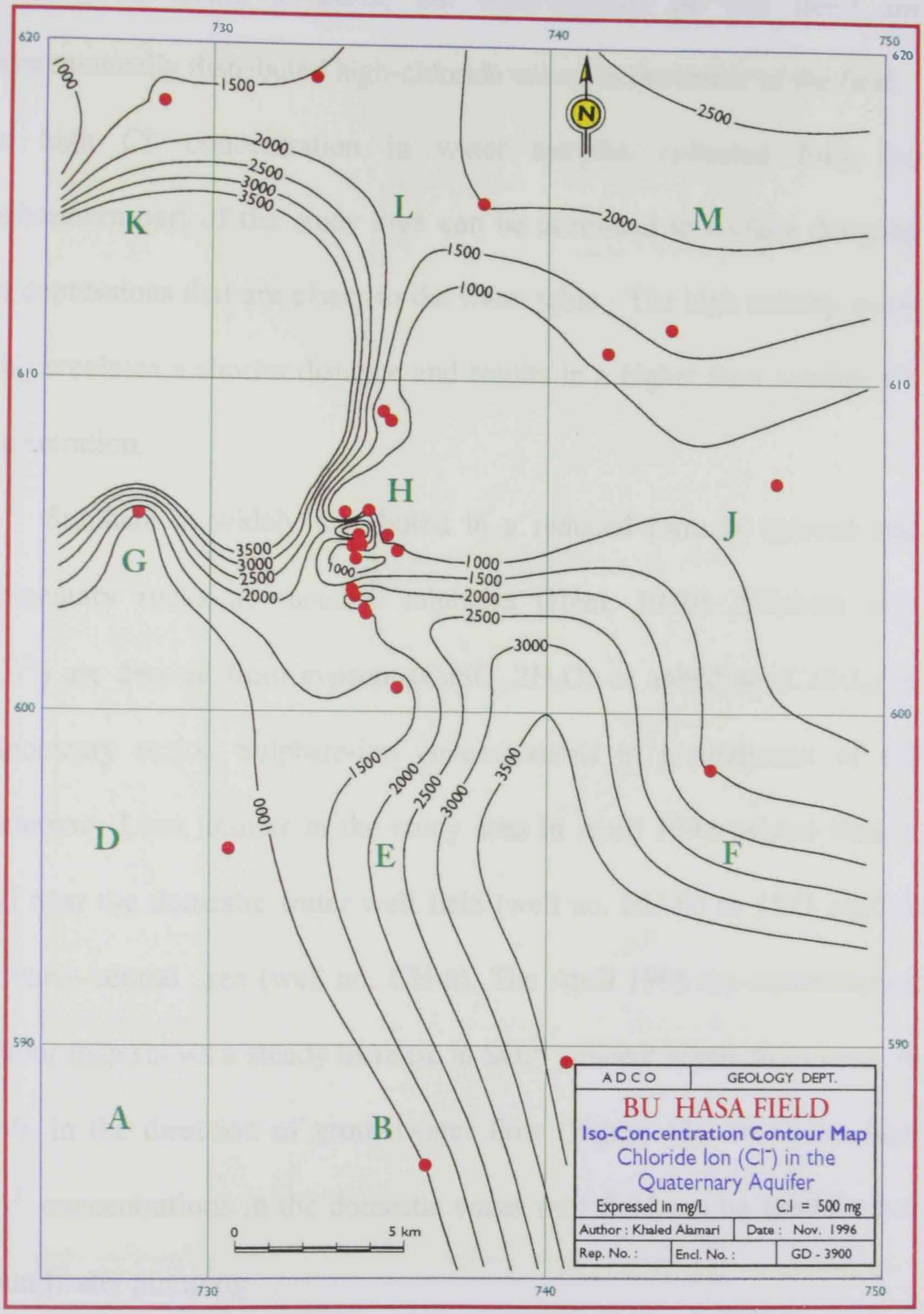

Figure 41. Iso-concentration contour map, in mg/l, of the chloride ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

concentration contour map (Figure 41) shows the regional increase in chloride from south to north, but superimposed on this trend are unsystematically distributed high-chloride values in the center of the field. The high Cl^- concentration in water samples collected from the southeastern part of the study area can be attributed to surface dumping into depressions that are closer to the water table. The high salinity water then percolates a shorter distance and results in a higher than average Cl^- concentration.

Sulphate is widely distributed in a reduced form in igneous and sedimentary rocks as metallic sulphides (Hem, 1970). Sulphate ions (SO_4^{2-}) are derived from gypsum ($CaSO_4.2H_2O$) or anhydrite ($CaSO_4$) in sedimentary rocks. Sulphate-ion concentrations in groundwater of the Quaternary Liwa aquifer in the study area in April 1996 ranged from 7 mg/l near the domestic water well field (well no. BU-B) to 1521 mg/l in the north central area (well no. CH-6). The April 1996 iso-concentration contour map shows a steady increase in SO_4^{2-} concentrations from south to north, in the direction of groundwater flow (Figure 42). However, high SO_4^{2-} concentrations in the domestic water well field can be attributed to groundwater pumping.

Most bicarbonate ions (HCO_3^-) in groundwater are derived from carbon dioxide in the atmosphere, carbon dioxide in soils and by

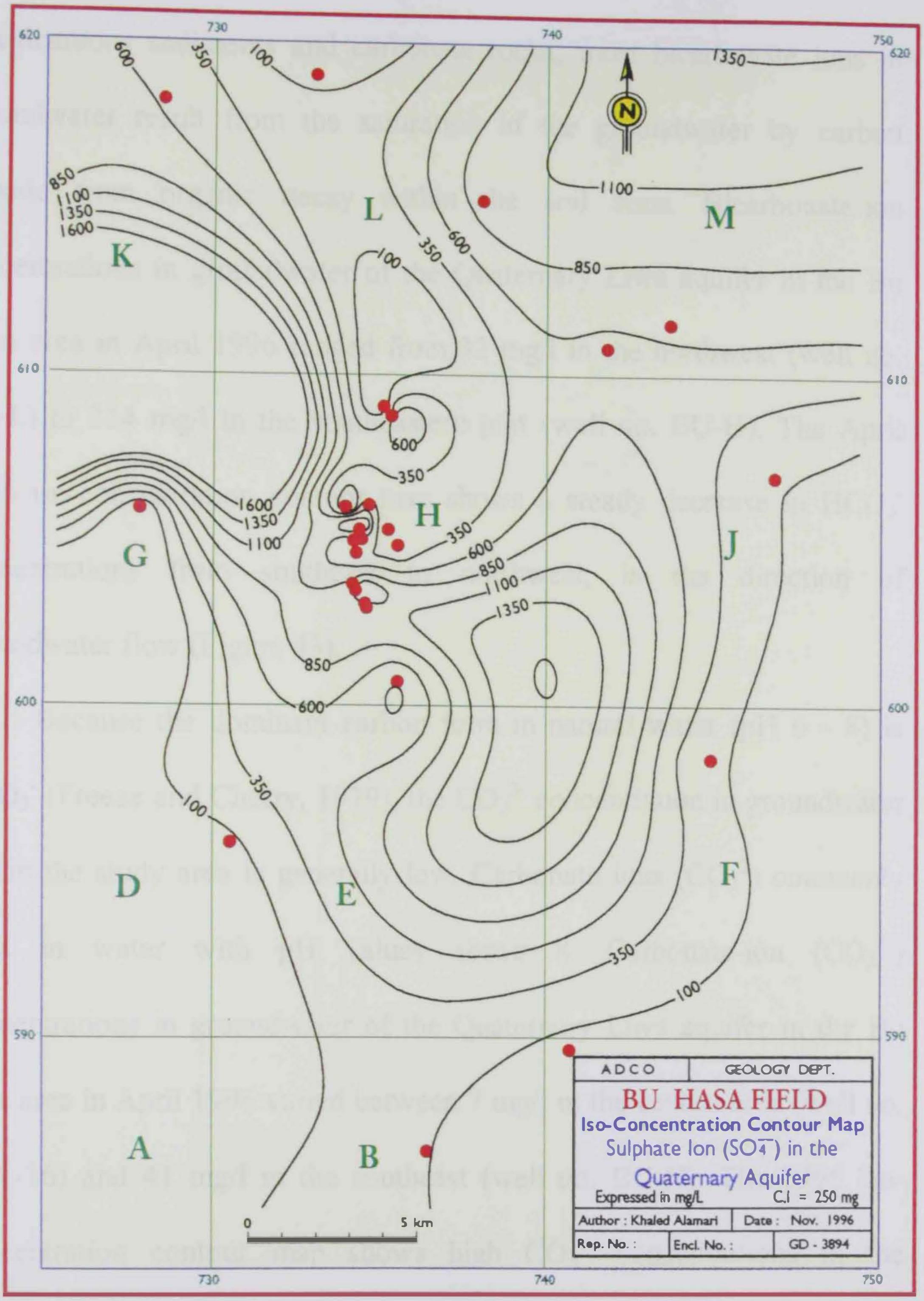

Figure 42. Iso-concentration contour map, in mg/l, of the sulfate ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

dissolution of carbonate rocks (Davis and DeWeist, 1966). In the absence of calcareous sediments and carbonate rocks, most bicarbonate ions in groundwater result from the saturation of the groundwater by carbon dioxide from organic decay within the soil zone. Bicarbonate-ion concentrations in groundwater of the Quaternary Liwa aquifer in the Bu Hasa area in April 1996 ranged from 32 mg/l in the northwest (well no. BU-L) to 314 mg/l in the southeastern part (well no. BU-H). The April 1996 iso-concentration contour map shows a steady decrease in HCO_3^- concentrations from southeast to northwest, in the direction of groundwater flow (Figure 43).

Because the dominant carbon form in natural water (pH 6 - 8) is HCO_3^- (Freeze and Cherry, 1979), the CO_3^{2-} concentration in groundwater within the study area is generally low. Carbonate ions (CO_3^{2}) commonly exist in water with pH values above 8. Carbonate-ion (CO_3^{2-}) concentrations in groundwater of the Quaternary Liwa aquifer in the Bu hasa area in April 1996 varied between 7 mg/l in the central area (well no. WW-16) and 41 mg/l in the southeast (well no. BU-H). The 1996 iso-concentration contour map shows high CO_3^{2-} concentrations in the southeastern part of the study area, decreasing towards the west, northwest and northeast (Figure 44).

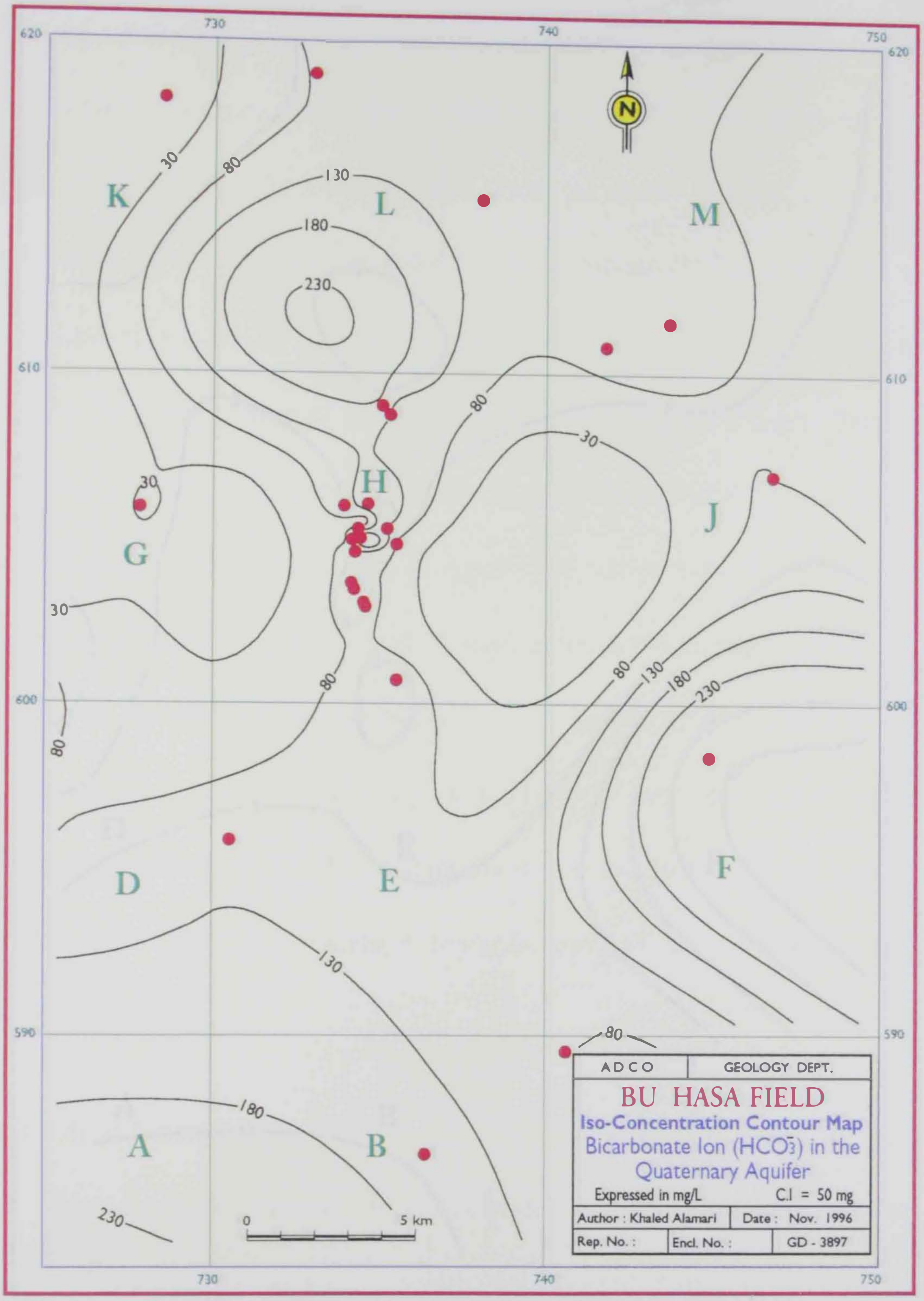

Figure 43. Iso-concentration contour map, in mg/l, of the bicarbonate ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

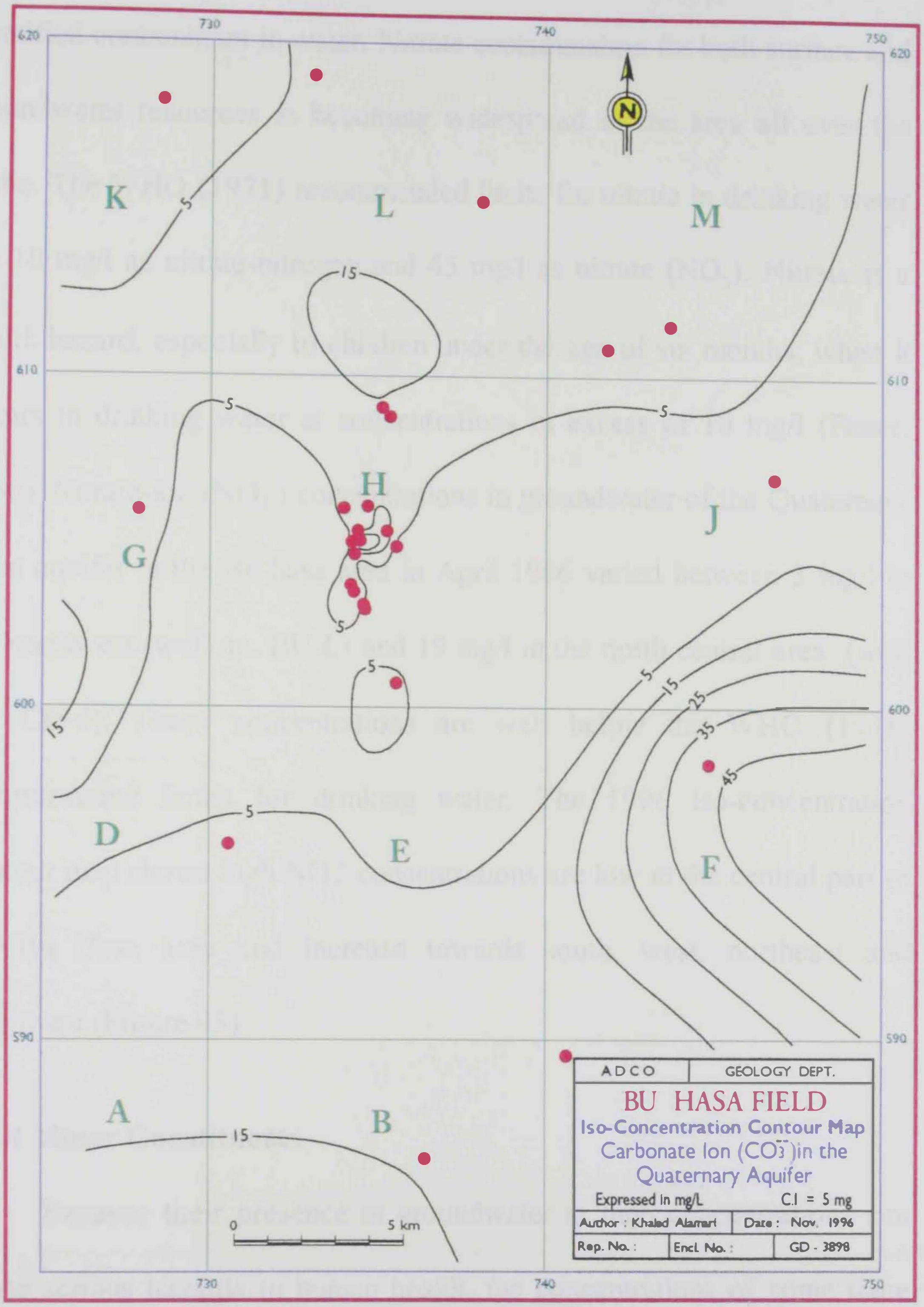

Figure 44. Iso-concentration contour map, in mg/l, of the carbonate ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

According to Freeze and Cherry (1979), nitrate (NO_3^-) is the most common identified contaminant in water. Nitrate contamination for both surface and groundwater resources is becoming widespread in the area all over the globe. The WHO (1971) recommended limits for nitrate in drinking water are 10 mg/l as nitrate-nitrogen and 45 mg/l as nitrate (NO_3). Nitrate is a health hazard, especially to children under the age of six months, when it occurs in drinking water at concentrations in excess of 10 mg/l (Fetter, 1980). Nitrate-ion (NO_3^-) concentrations in groundwater of the Quaternary Liwa aquifer in the Bu hasa area in April 1996 varied between 3 mg/l in the northwest (well no. BU-L) and 19 mg/l in the north central area (well no. CH-6). These concentrations are well below the WHO (1971) recommended limits for drinking water. The 1996 iso-concentration contour map shows high NO_3^- concentrations are low in the central part of the Bu Hasa area and increase towards south, west, northeast and northwest (Figure 45).

4.3.4 Minor Constituents

Because their presence in groundwater at high concentrations can cause serious hazards to human health, the concentrations of some trace metals were measured in groundwater samples collected from the

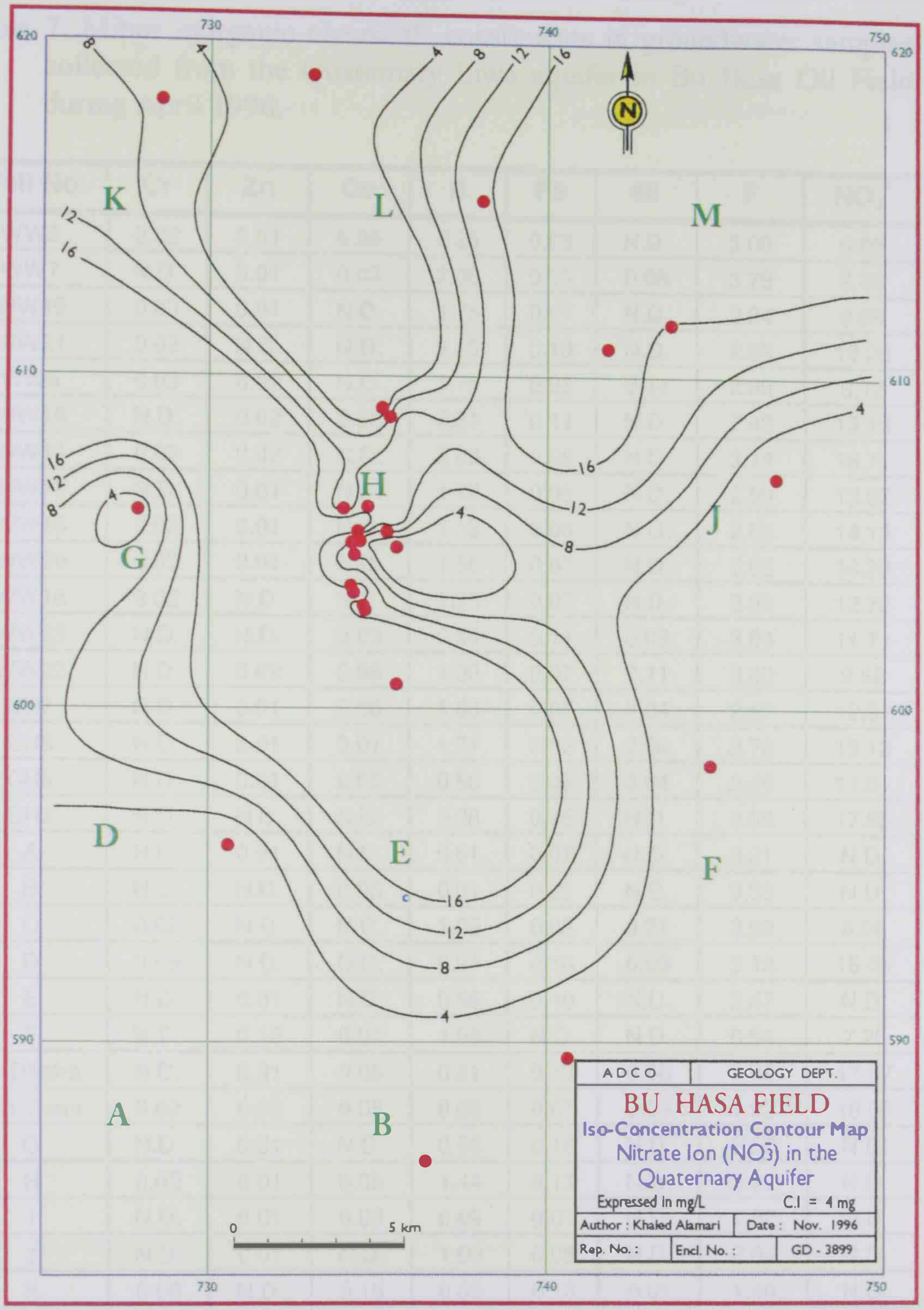

Figure 45. Iso-concentration contour map, in mg/l, of the nitrate ion in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

Table 7. Minor inorganic chemical constituents in groundwater samples collected from the Quaternary Liwa aquifer in Bu Hasa Oil Field during April 1996.

Well No.	Cr	Zn	Cu	B	Fe	Ni	F	NO_3^-
WW2	0.02	0.01	0.05	2.25	0.03	N.D.	3.00	6.69
WW7	N.D.	0.01	0.03	2.06	0.13	0.08	3.79	8.46
WW19	0.03	0.01	N.D.	1.75	0.07	N.D.	2.94	9.88
WW21	0.02	N.D.	N.D.	2.13	0.10	N.D.	2.98	12.28
WW6	0.03	0.02	N.D.	1.75	0.03	0.14	2.69	8.72
WW18	N.D.	0.02	0.02	2.31	0.11	N.D.	2.43	13.19
WW11	0.02	0.02	N.D.	2.00	0.08	N.D.	3.14	16.71
WW17	N.D.	0.01	N.D.	1.50	0.03	N.D.	2.99	13.02
WW16	0.02	0.01	N.D.	1.13	0.08	N.D.	2.89	14.13
WW20	0.02	0.01	N.D.	1.56	0.07	N.D.	2.52	14.73
WW15	0.02	N.D.	N.D.	1.25	0.07	N.D.	2.99	12.73
WW23	N.D.	N.D.	0.03	0.94	0.11	0.08	3.04	11.71
WW22	N.D.	0.02	0.05	1.00	0.07	0.11	3.00	9.62
CH7	N.D.	0.01	0.06	1.00	0.07	0.04	2.57	12.91
CH6	N.D.	0.01	0.01	1.31	0.02	0.06	2.72	19.13
CH5	N.D.	0.01	0.05	0.56	0.05	0.04	2.46	11.81
CH3	N.D.	N.D.	N.D.	0.88	0.15	N.D.	3.35	17.55
A	N.D.	0.01	N.D.	0.81	0.07	N.D.	3.21	N.D.
B	N.D.	N.D.	0.05	0.81	0.23	N.D.	3.33	N.D.
C	0.02	N.D.	N.D.	1.06	0.03	0.21	3.59	8.99
D	0.05	N.D.	N.D.	0.94	0.18	0.09	3.12	15.09
E	N.D.	0.01	N.D.	0.56	0.10	N.D.	3.47	N.D.
F	N.D.	0.16	0.04	1.06	N.D.	N.D.	0.54	7.20
Al Dhafra	N.D.	0.01	0.06	0.81	0.13	0.06	0.38	17.07
Bin Thani	0.02	0.02	0.05	0.63	0.07	0.06	1.92	16.09
G	N.D.	0.01	N.D.	0.63	0.18	N.D.	2.57	N.D.
H	0.02	0.01	0.05	1.44	0.13	N.D.	2.17	N.D.
I	N.D.	0.01	0.03	0.69	0.07	N.D.	1.32	N.D.
J	N.D.	0.01	N.D.	1.00	0.05	N.D.	2.64	N.D.
K	0.06	N.D.	0.15	0.69	0.13	0.01	1.40	N.D.
L	0.01	0.01	0.09	0.69	3.07	0.07	0.73	2.73
Waste water	0.01	0.11	0.15	17.62	4.20	0.12	N.D.	N.D.

N.D : not detected

Quaternary Liwa aquifer in the Bu Hasa area in April and September 1996 (Table 7). The following is a brief discussion on each of these elements:

Copper is a common metal which occurs in nature as native metal and various copper minerals and salts. Copper is an essential trace element for the growth of plants and animals. In excessive amounts, however, copper can be toxic and its toxicity depends on water hardness, alkalinity (Fetter, 1988). The World Health Organization (WHO) (1971) standard for maximum copper concentration in drinking water is 1.0 mg/l.

Copper (Cu) concentrations in groundwater samples collected from the Quaternary Liwa aquifer in the study area in April and September 1996 are generally less than the WHO recommended limit for drinking water. The highest concentrations of copper in groundwater samples occurred in the southwestern part of the study area. Low Cu concentrations were encountered in the eastern, central, northeastern and northwestern parts (Figure 46).

Iron is toxic to some aquatic species at concentrations of 0.32 to 1.00 mg/l. A water quality criterion for iron of 0.3 mg/l has been suggested for domestic use. For aquatic life, maximum iron content of 1.0 mg/l is the maximum limit (Fetter, 1988). Iron concentrations in groundwater samples

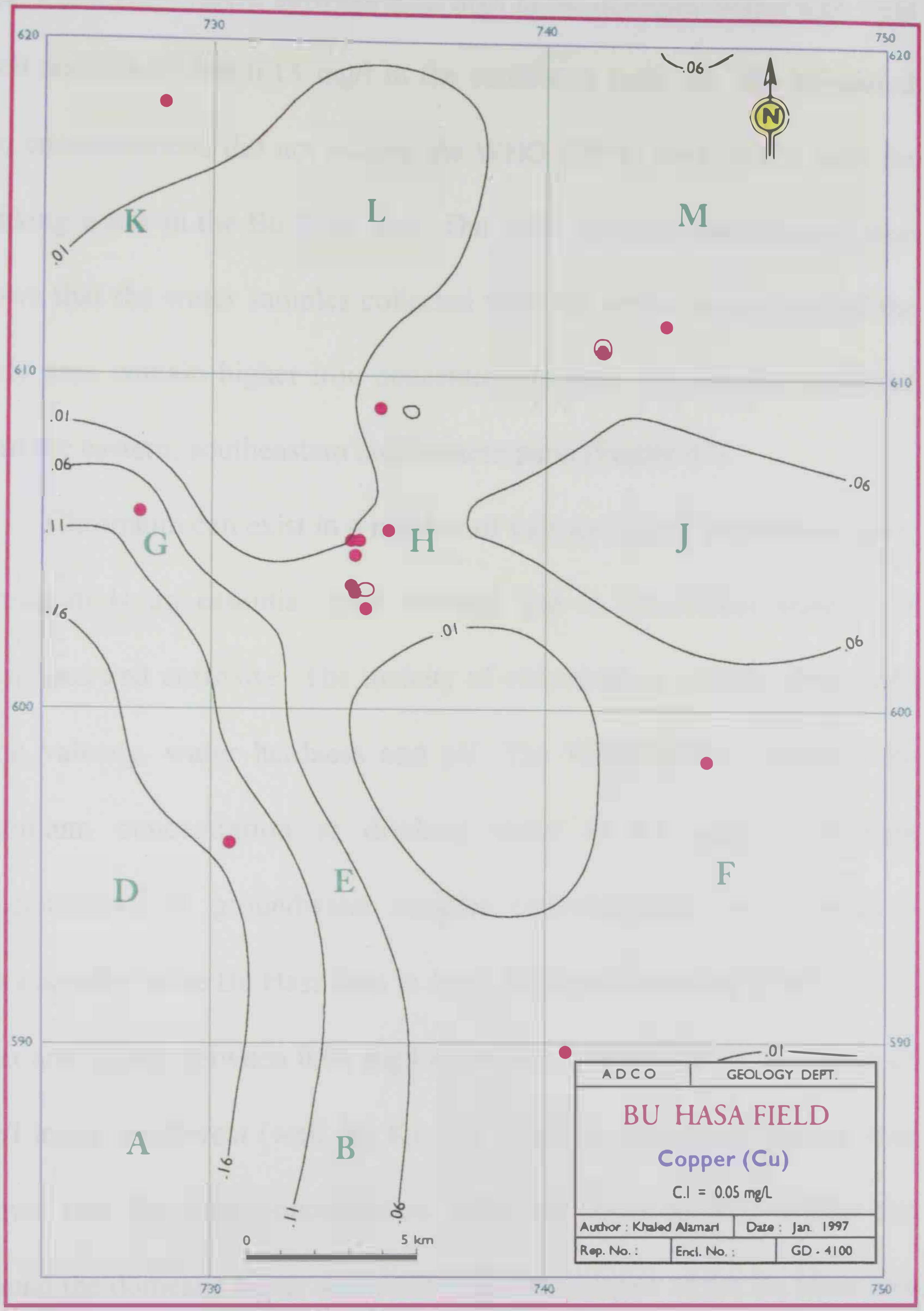

Figure 46. Iso-concentration contour map, in mg/l, of the copper in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

collected from the Quaternary Liwa aquifer in the study area in April and September 1996 varied between 0.02 mg/l in the domestic water well field (well no. CH-6) and 0.13 mg/l in the southwest (well no. K). Measured iron concentrations did not exceed the WHO (1971) limit of 0.3 mg/l for drinking water in the Bu Hasa area. The 1996 iso-iron concentration map shows that the water samples collected from the northwestern part of the study area contain higher iron concentrations than the samples collected from the eastern, southeastern and western parts (Figure 47).

Chromium can exist in a number of valence states. In trivalent state, chromium is an essential trace nutrient and in hexavalent state, it is poisonous and corrosive. The toxicity of chromium is variable depending upon valency, water hardness and pH. The WHO (1971) standard for chromium concentration in drinking water is 0.1 mg/l. Chromium concentrations in groundwater samples collected from the Quaternary Liwa aquifer in the Bu Hasa area in April 1996 are below the WHO (1971) limit and varied between 0.01 mg/l in the northwest (well no. L) and 0.06 mg/l in the southwest (well no. K). The 1996 iso-chromium contour map shows that the high concentration wells are those located within and around the domestic water well field in the central part of the Bu Hasa area (Figure 48).

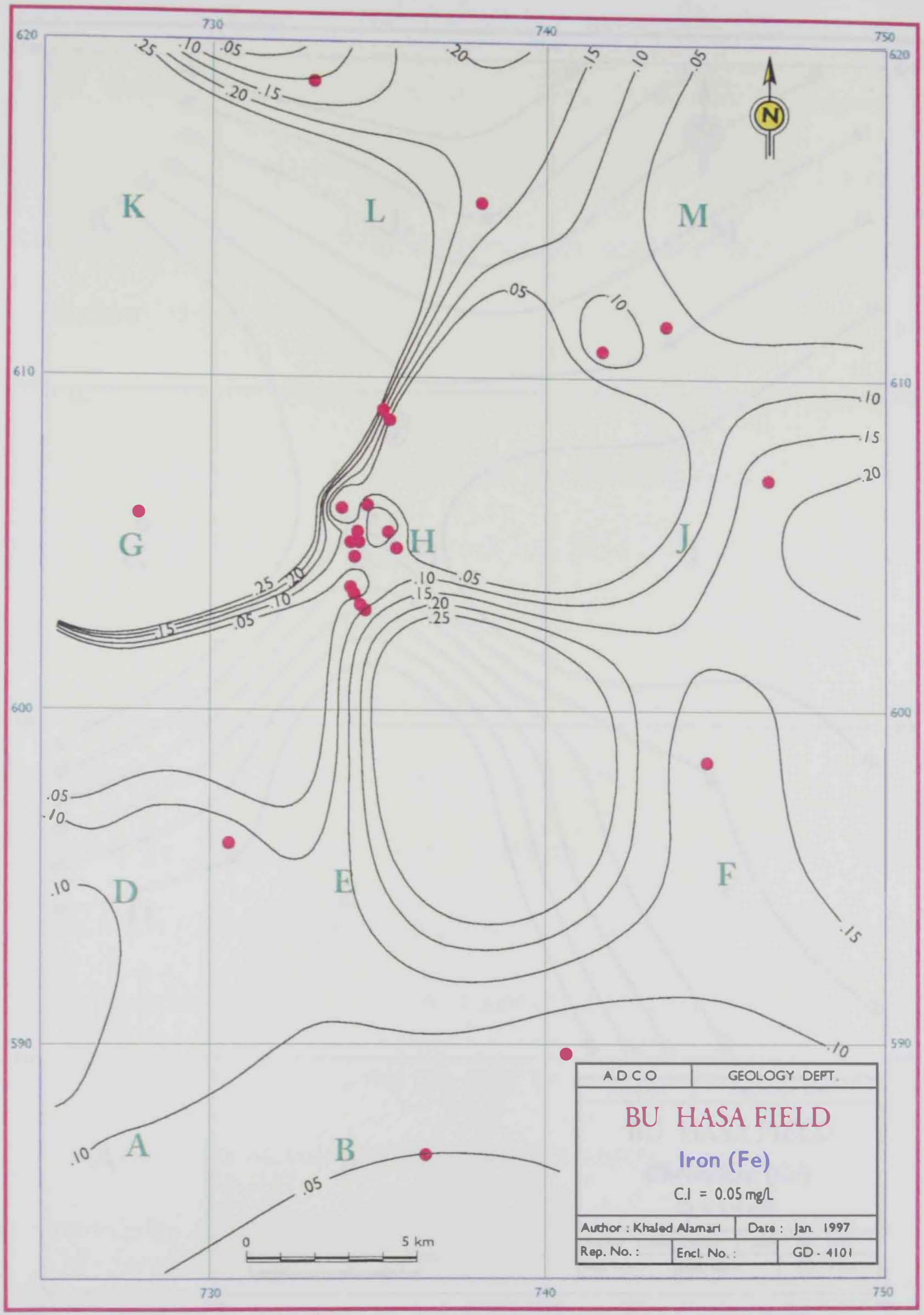

Figure 47. Iso-concentration contour map, in mg/l, of the iron in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.
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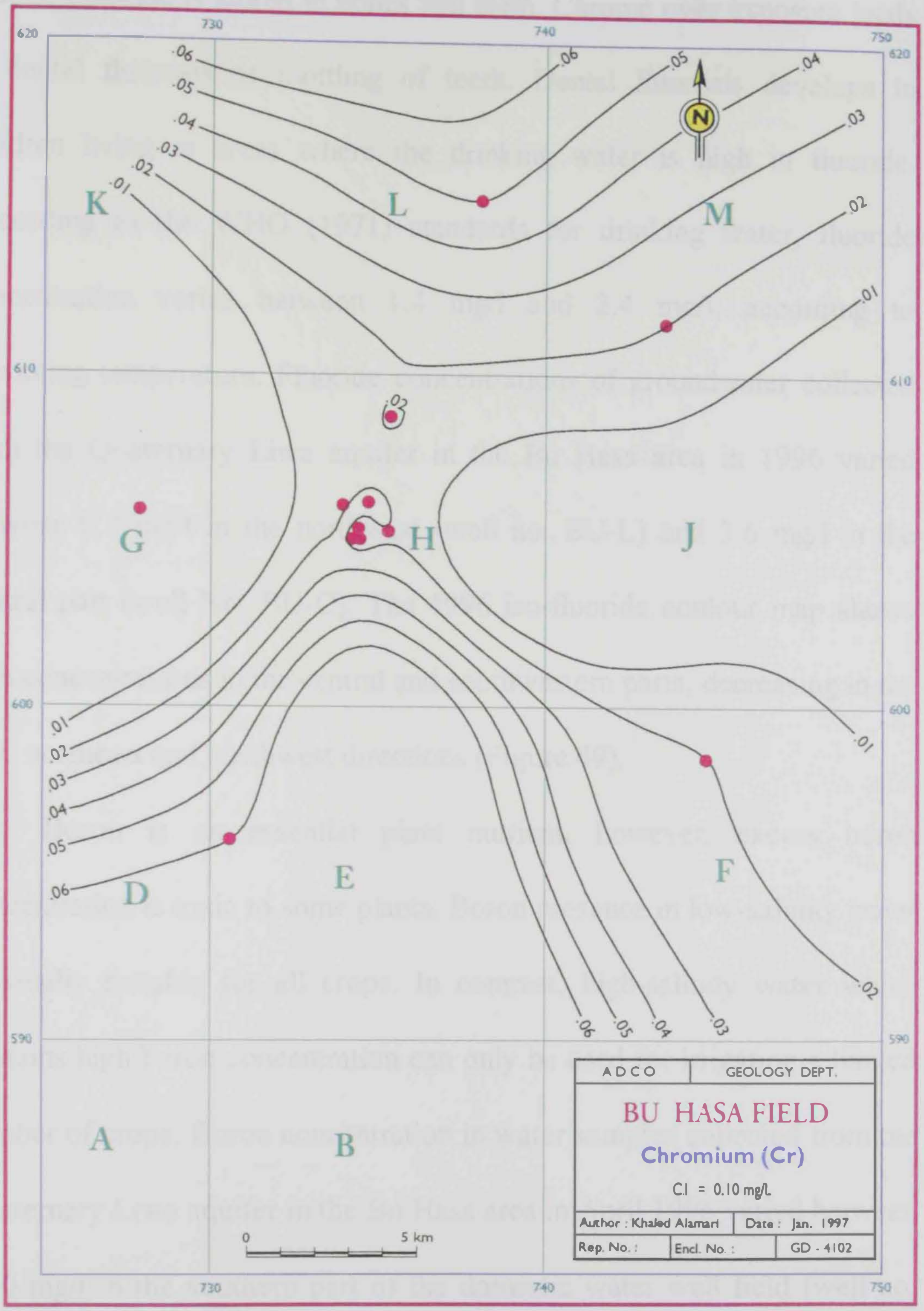

Figure 48. Iso-concentration contour map, in mg/l, of the chromium in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

Fluoride is naturally present in minerals as fluorite, cryolite and apatite. Fluoride is stored in bones and teeth. Chronic over exposure leads to dental fluorosis or mottling of teeth. Dental fluorosis develops in children living in areas where the drinking water is high in fluoride. According to the WHO (1971) standards for drinking water, fluoride concentration varies between 1.4 mg/l and 2.4 mg/l, according to prevailing temperature. Fluoride concentrations of groundwater collected from the Quaternary Liwa aquifer in the Bu Hasa area in 1996 varied between 0.7 mg/l in the northwest (well no. BU-L) and 3.6 mg/l in the central part (well No. BU-C). The 1996 iso-fluoride contour map shows high concentrations in the central and southwestern parts, decreasing in the east, northeast and northwest directions (Figure 49).

Boron is an essential plant nutrient, however, excess boron concentration is toxic to some plants. Boron presence in low-salinity water is usually suitable for all crops. In contrast, high-salinity water which contains high boron concentration can only be used for irrigating a limited number of crops. Boron concentration in water samples collected from the Quaternary Liwa aquifer in the Bu Hasa area in April 1996 varied between 0.60 mg/l in the southern part of the domestic water well field (well no. CH-6) and 2.25 mg/l in the central part of the field (well no. WW-2).

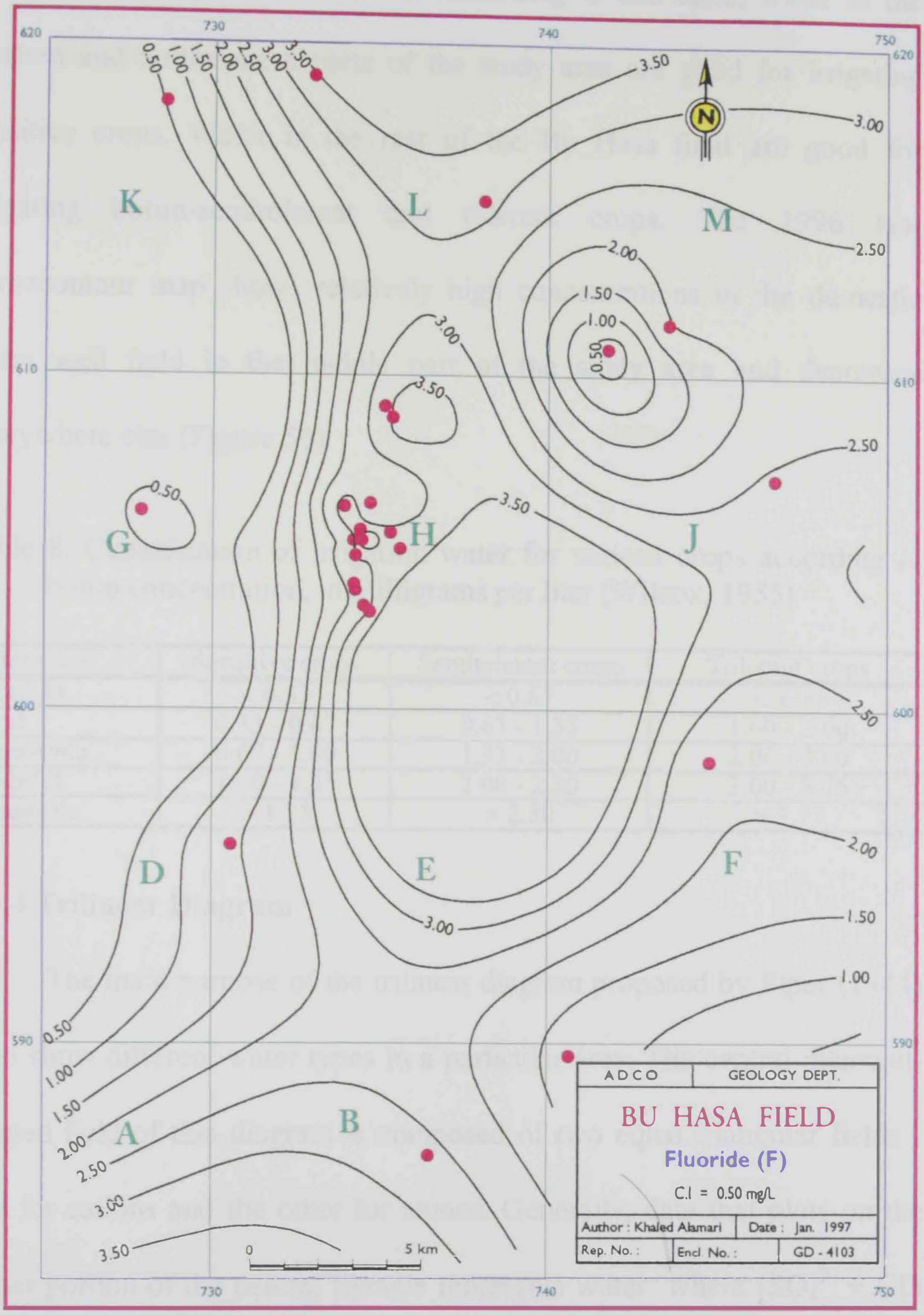

Figure 49. Iso-concentration contour map, in mg/l, of the fiuoride in shallow groundwater in the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

Classification of irrigation water for various crops on the basis of boron concentration is given in Table 8. According to this table, water in the western and northeastern parts of the study area are good for irrigating sensitive crops. Water in the rest of the Bu Hasa field are good for irrigating boron-semitolerant and tolerant crops. The 1996 iso-boroncontour map shows relatively high concentrations in the domestic water well field in the middle part of the study area and decreases everywhere else (Figure 50).

Table 8. Classification of irrigation water for various crops according to boron concentration, in milligrams per liter (Wilcox, 1955)

Water class	Sensitive crops	Semitolerant crops	Tolerant crops
Excellent	< 0.33	< 0.67	< 1.00
Good	0.33 - 0.67	0.67 - 1.33	1.00 - 2.00
Permissible	0.67 - 1.00	1.33 - 2.00	2.00 - 3.00
Doubtful	1.00 - 1.25	2.00 - 2.50	3.00 - 3.75
Unsuitable	> 1.25	> 2.50	> 3.75

4.3.4 Trilinear Diagram

The main purpose of the trilinear diagram proposed by Piper (1944) is to show different water types in a particular area. The central diamond-shaped field of this diagram is composed of two equal triangular fields - one for cations and the other for anions. Generally, data that plots on the upper portion of the central triangle represents water where (SO_4^{2-} + Cl^-) exceeds (Na^+ and K^+) and the characteristic water types are Ca and Mg

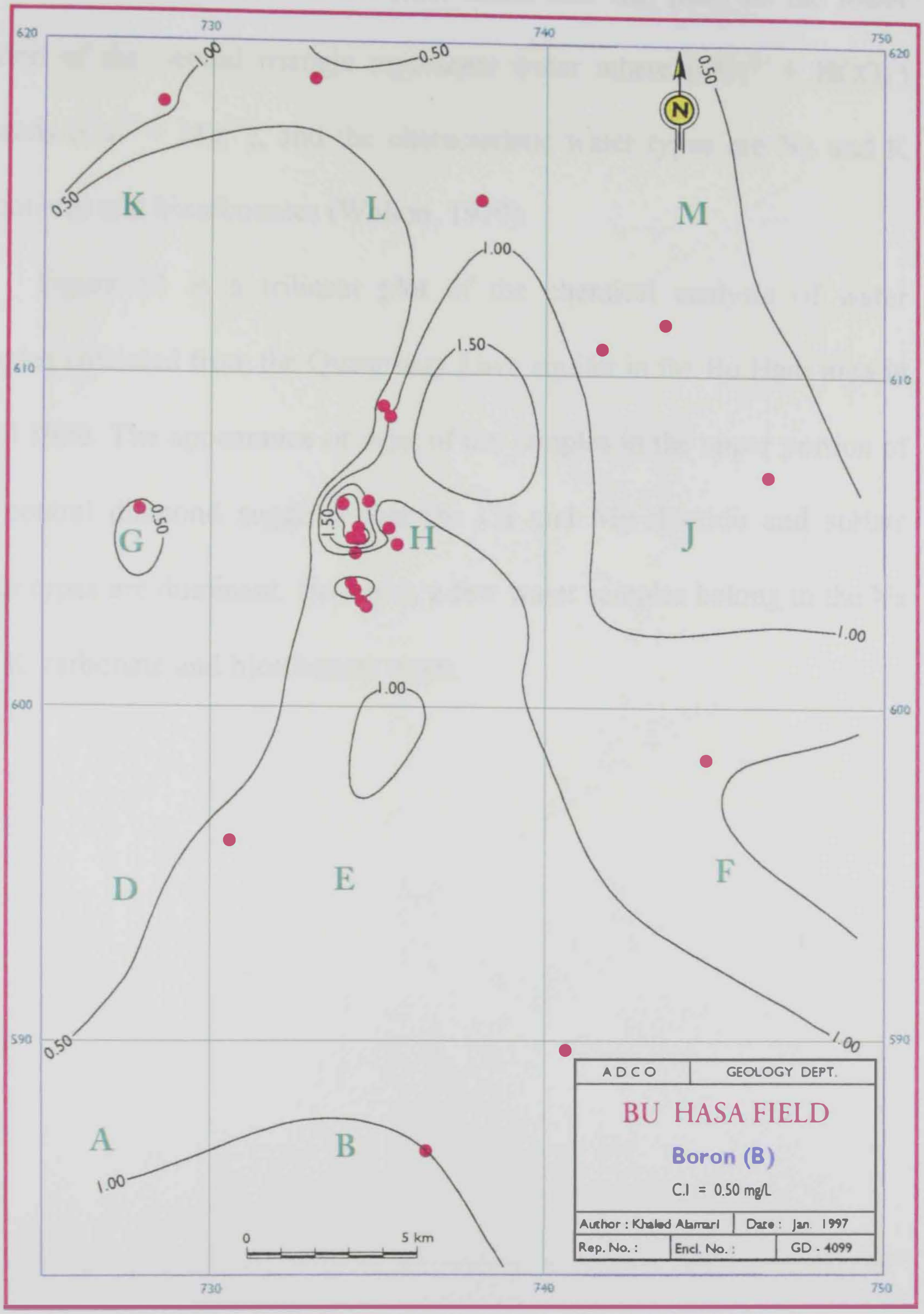

Figure 50. Iso-concentration contour map, in mg/l, of the boron in shallow groundwater of the Quaternary Liwa aquifer at the Bu Hasa area in April 1996.

chlorides and sulphates. On the other hand, data that plots on the lower portion of the central triangle represents water where (CO_3^{2-} + HCO_3^-) exceeds (Ca^{2+} + Mg^{2+}), and the characteristic water types are Na and K carbonates and bicarbonates (Walton, 1970).

Figure 51 is a trilinear plot of the chemical analysis of water samples collected from the Quaternary Liwa aquifer in the Bu Hasa area in April 1996. The appearance of most of the samples in the upper portion of the central diamond suggests that the Ca and Mg-chloride and sulfate water types are dominant. However, a few water samples belong to the Na and K-carbonate and bicarbonate types.

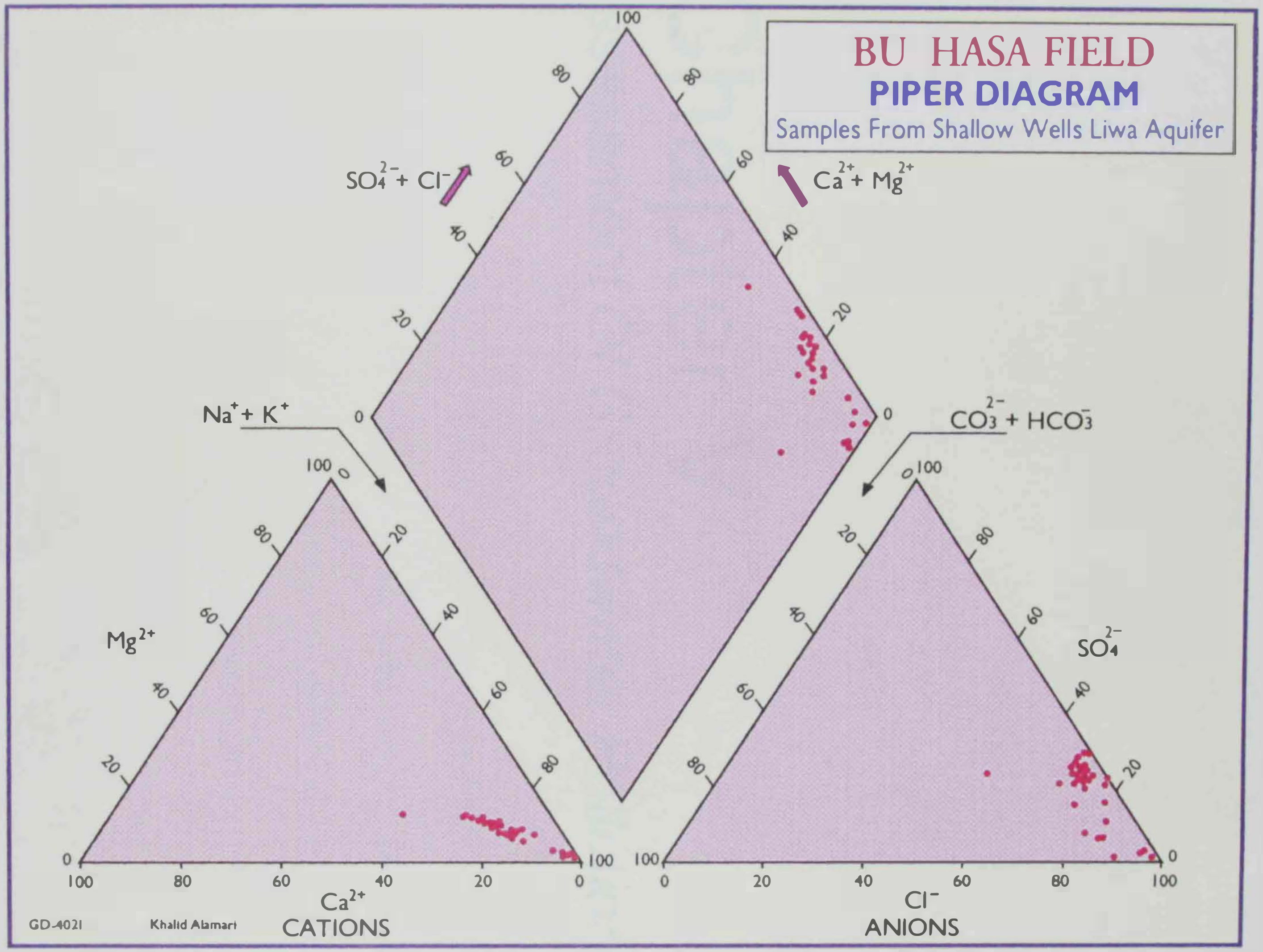

Figure 51. A trilinear diagram of the chemical analysis of water samples collected from the Quaternary Liwa aquifer in the Bu Hasa area, April 1996.

Chapter V

Assessment Of Groundwater Pollution

CHAPTER V

ASSESSMENT OF GROUNDWATER POLLUTION

The Quaternary Liwa aquifer in the Bu Hasa area represents the main source of good-quality water in western Abu Dhabi Emirate. Possible contamination caused by oil-related activities can represent a serious hazard to this important resource. Because large amounts of waste water were disposed in the Miocene clastic aquifer since early 1970's, upward movement of this brine is possible.

The main objective of this chapter is to assess the groundwater pollution of the Quaternary Liwa aquifer as a result of re-injection of oil-field water in the Miocene clastic aquifer in the Bu Hasa area.

To achieve this objective, the results of chemical analysis of water samples were presented and interpreted. Two water samples from the Liwa aquifer and the injector plant were analyzed for hydrocarbon content. Samples from re-injected water and the Liwa aquifer were analyzed for stable isotopes (^{2}H and ^{18}O) in August 1996.

5.1 Identification of Organic Pollutants

The organic pollutants were isolated and identified in two water samples from the Bu Hasa oil field. These samples represent the disposed and the fresh-aquifer waters. The isolation of the organic pollutants was done by the solid-phase extraction (SPE) and gas chromatography-mass spectrometry (GC-MS) described in section 4.1.

The identification of the organic pollutants was conducted by (GC/MS-MD-800 Fission) technique. The identification was done at a temperature range between 60°C and 280°C at a rate of 10°C/min. Sample was kept to rest for 20 min. at 280°C. The chromatographic bands obtained are given in Figures 52 and 53.

The analysis of the fresh-aquifer water sample indicates that it is almost free of pollution by organic components. The disposal water, however, is seriously polluted by various aliphatic and aromatic organic compounds. The aliphatic compounds identified include different derivatives of decane, such as tridecane, tetradecane, pentadecane, hexadecane, heptadecane, octadecane, nonadecane, undecane and 6-ethyl-2-methyl decane, besides eicosane and heneicosane. The aromatic compounds identified include various derivatives of phenol and benzeamine. The following phenols are identified; 2-methyl-phenol, 3-methyl-phenol, 4-methyl-phenol, 3,5-dimethyl-phenol, 3,4-dimethyl-phenol, and 2,5-dimethyl-phenol. Other aromatic derivatives such as tricarbonyl benzeamine have also been identified.

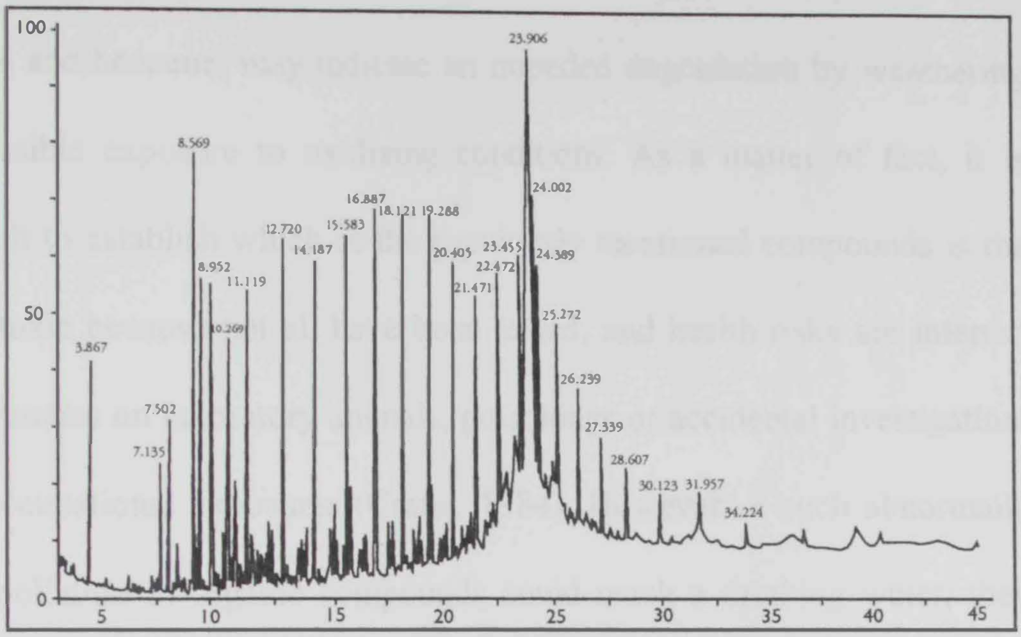

Figure 52. Chromatographic identification of organic pollutants in oil-field water injected in the Miocene Clastic Aquifer, Bu Hasa Field, April 1996

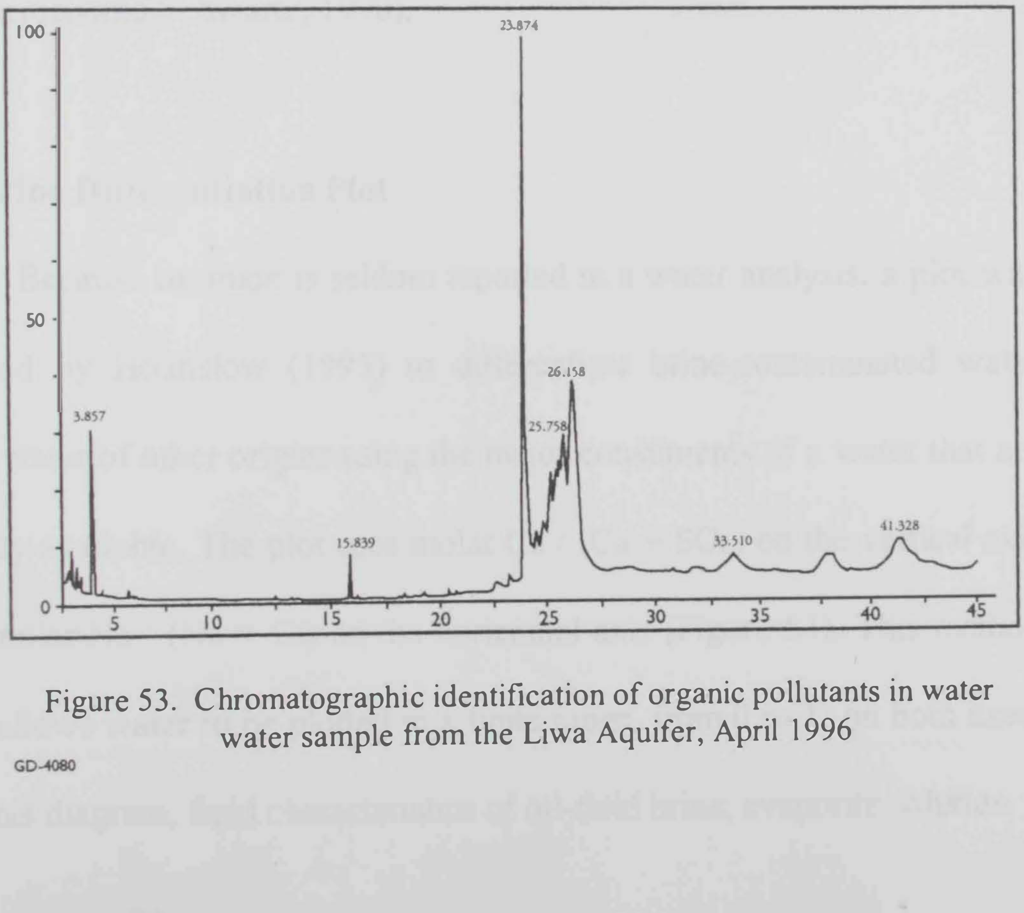

Figure 53. Chromatographic identification of organic pollutants in water water sample from the Liwa Aquifer, April 1996

GD-4080

The presence of aliphatic and aromatic compounds such as decane, phenol and benzene, may indicate an impeded degradation by weathering or possible exposure to oxidizing conditions. As a matter of fact, it is difficult to establish which of the previously mentioned compounds is the most toxic because not all have been tested, and health risks are inferred from studies on laboratory animals, poisonings or accidental investigation, and occupational exposures (Craun, 1984). However, if such abnormally high pollution of organic compounds could reach a drinking water, they can cause cancer and other problems, including liver damage, impairment of cardiovascular function brain disorders and various kinds of lesions (Domenico and Schwartz, 1990).

5.2 Brine Differentiation Plot

Because bromide is seldom reported in a water analysis, a plot was devised by Hounslow (1995) to differentiate brine-contaminated water from water of other origins using the major constituents of a water that are usually available. The plot uses molar Ca / (Ca + SO_4) on the vertical axis and molar Na / (Na + Cl) on the horizontal axis (Figure 54). This method also allows water to be plotted in a finite range, from 0 to 1, on both axes. On this diagram, field characteristics of oil-field brine, evaporite solution

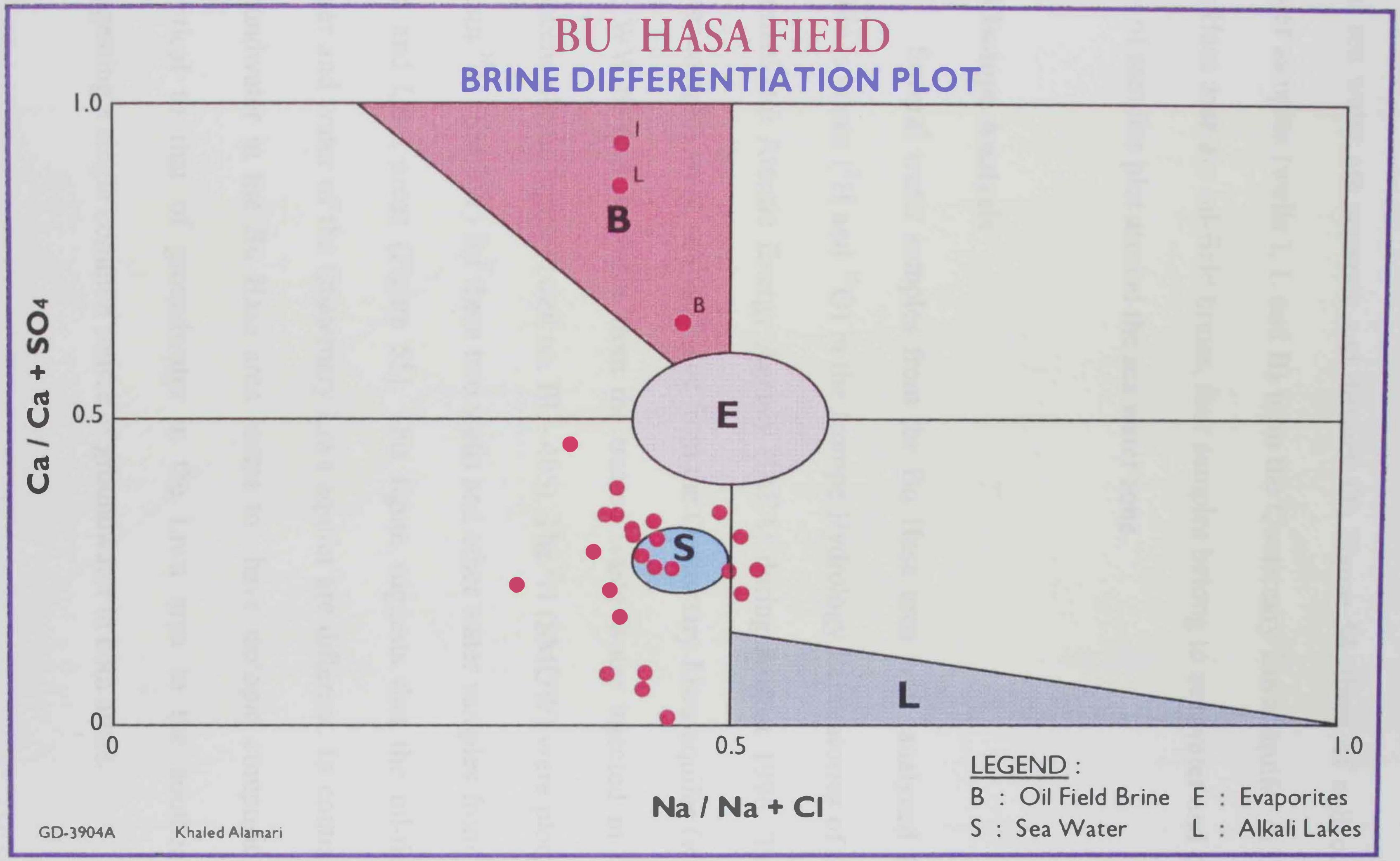

Figure 54. Brine differentiation plot of water samples collected from the Quaternary Liwa aquifer in the Bu Hasa area, April 1996.

and sea water are separate and distinct. On Figure 54, three of collected water samples (wells I, L and B) from the Quaternary Liwa aquifer in the Bu Hasa area are oil-field brines, four samples belong to sea water and the rest of samples plot around the sea water zone.

5.3 Isotope Analysis

Several water samples from the Bu Hasa area were analyzed for stable isotopes (^{2}H and ^{18}O) in the Isotope Hydrology Laboratories of the International Atomic Energy Agency (IAEA) during August 1996. Two water samples were analysed, one from the Quaternary Liwa aquifer (well no. WW-6) and the other from the treated waste water injected in the Miocene clastic aquifer (well no. BU- 405). The ^{2}H (SMOW) were plotted versus ^{18}O (SMOW) for these two wells and other water samples from Al Ain and Liwa areas (Figure 55). This figure suggests that the oil-field water and water of the Quaternary Liwa aquifer are different. In contrast, groundwater in the Bu Hasa area seems to have isotopic composition identical to that of groundwater in the Liwa area in the southeast, suggesting a single common source of groundwater in both areas.

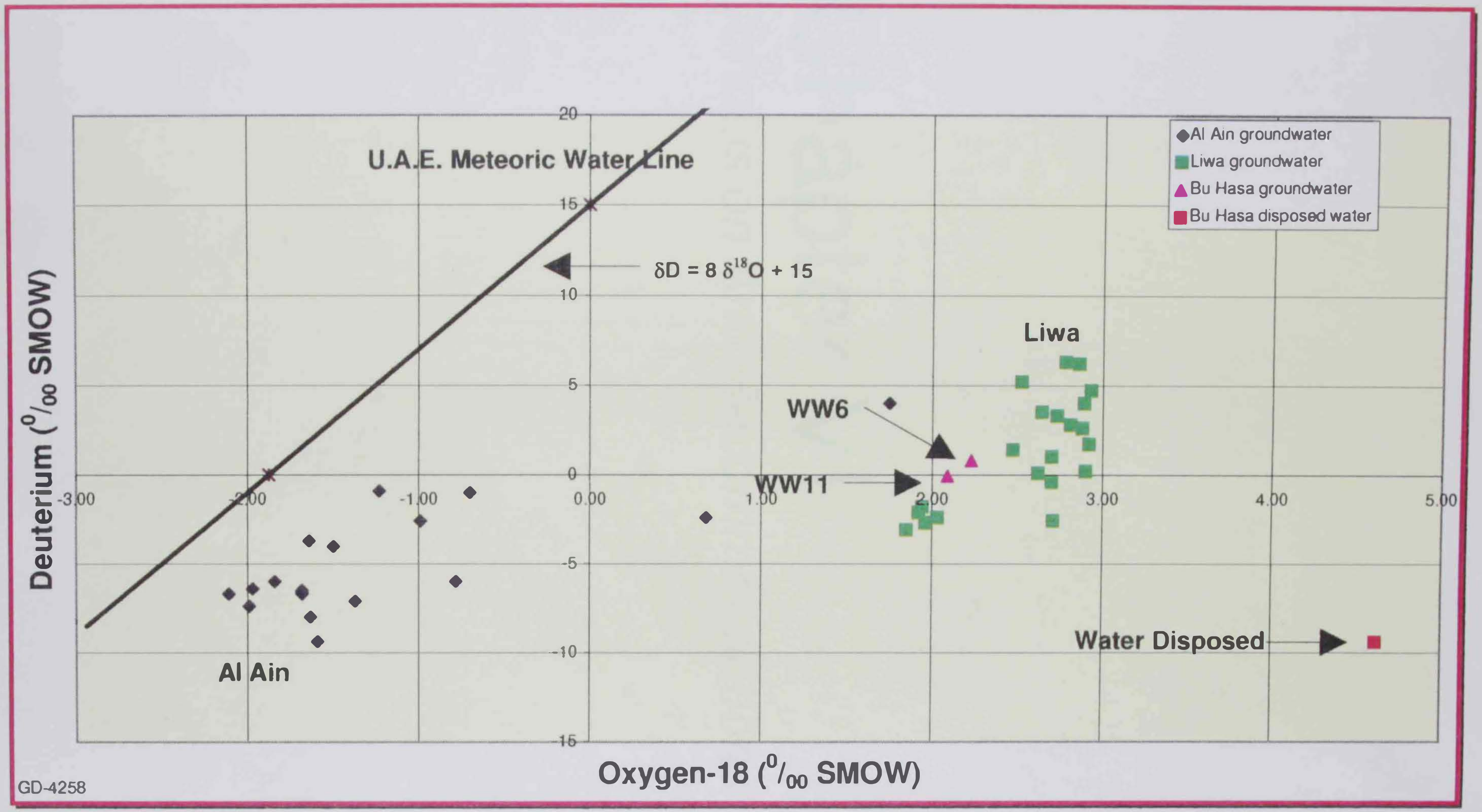

Figure 55. Stable isotopes (^{2} H and ^{18} O) in groundwater of the Quaternary Liwa aquifers and water disposed in the Miocene aquifer at the Bu Hasa Field, April 1996.

Chapter VI

Conclusion And Recommendations

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

a. Core samples recovered from the Lower Fars Formation in the Bu Hasa area include gypsum, anhydrite, siltstone-claystone, claystone-limestone and wackestone-packstone. This lithology is believed to represent a good sealing interval against vertical communication between the Miocene clastic aquifer and the Quaternary Liwa aquifer. Therefore, it is unlikely that oil water disposed off into the Miocene clastic aquifer would move upward to contaminate the shallow aquifers.

b. The hydraulic-head map constructed for the Quaternary Liwa aquifer in the Bu Hasa field in April 1996 shows that: (i) the general groundwater flow direction is from south to northwest, whereas the presence of a groundwater mound east of the domestic water-well field has created local flow systems from the center to all directions, (ii) the presence of two southeast trending tongues of relatively poor-quality water in the northwestern part of the study area reflects the effect of heavy groundwater pumping from the Liwa aquifer in an area occupied by the domestic water-well field and (iii) the hydraulic gradient is highly variable in the field ranging from 0.01 in the southwest to 0.001 in the southeast and northwest. In addition to the effect of pumping, the hydraulic gradient also reflects the heterogeneous nature of the aquifer.

c. Between 1964 and 1985, the groundwater salinity increased in the camp area from 3,500 mg/l to 5,500 mg/l. The iso-salinity contour map constructed with the field data collected by the author in April 1996 indicates that the salinity of groundwater in the southeastern part of the Bu Hasa area has tripled during the period 1985-1996, mainly because of the disposal of oil-field brines in unlined pits in this area, heavy pumping, and absence of recharge.

d. The sequence of cation dominance in groundwater of the Quaternary Liwa aquifer in the Bu Hasa area has the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, and the sequence of anion dominance has the order: $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$. This indicates that the ground-water in the study area is dominated by Na^+ and Cl^- ions, suggesting its old age and that aquifer does not receive present-day recharge. This was collaborated by the trilinear plot of the chemical analysis of water samples which suggests that the sodium-chloride water type is dominant.

e. Concentration of the trace metals such as copper, iron and chromium are below the WHO limits for drinking water. This means that desalination of this water and its use for domestic purposes is safe. Nitrate-ion (NO_3^-) concentrations in groundwater of the Quaternary Liwa aquifer in the Bu Hasa area in April 1996 were also below the WHO (1983) standard for drinking water (45 mg/l).

f. Examined groundwater from the Quaternary Liwa aquifer is free of hydrocarbon pollution with the exception of three samples that show indications of oil field brine. In contrast, the water disposed in the Miocene clastic aquifer is loaded with high concentrations of aliphatic and aromatic compounds. If this water could reach the Quaternary aquifer, it can cause a serious contamination problem, especially for the domestic water-well field.

g. The plot of ^2H (SMOW) versus ^{18}O (SMOW) for water samples from the Liwa and Bu Hasa areas suggests that the oil-field water and water of the Quaternary Liwa aquifer are different, indicating the effective sealing of the Miocene evaporites in the Bu Hasa area. This seal prevents upward movement of waste water from the Miocene clastic sediments into the Quaternary Liwa aquifer. In contrast, groundwater in the Bu Hasa area seems to have stable isotopic composition identical to that of groundwater in the Liwa area, indicating a common source.

h. Based on the geologic, hydrogeologic, hydrochemical and stable isotope analyses, there is no reason to believe that the disposal of waste water in the Miocene clastic aquifer in the Bu Hasa area can lead to the upward movement of this water contaminating the shallow Quaternary aquifer. In contrast, the disposal of brines in unlined pits is the practice that has a definite adverse effect on the Quaternary Liwa aquifer in the Bu Hasa area.

6.2 Recommendations

a. A monitoring water well should be drilled in central part of Bu Hasa field to promptly detect any accidental leaks and observe the migration of contaminated groundwater.

b. A two-dimensional groundwater flow model has to be constructed for the Quaternary and Miocene aquifers in the Bu Hasa area to examine the impact of brine injection in the Miocene aquifer on water movement between both aquifers.

c. Disposal of oil-field brines in unlined pits in the desert should be stopped, because the Quaternary Liwa aquifer in the study area is an unconfined and very vulnerable to reception of surface contaminants related to oil industry.

d. The direction of groundwater flow, contamination of shallow groundwater and direction of contaminant movement suggest that the domestic water-supply field should be re-located from its present position in the central part to the far southeastern corner of the study area. The proposed new position has the following advantages: (i) the aquifer's saturated thickness is about 100 m compared with 25 to 45 m thickness in its present position, (ii) the new site is relatively closer to the Liwa fresh water mound which acts as the re-charge area to the Liwa aquifer in the Bu Hasa field, (iii) the wells of the new field will intercept a larger amount of relatively better-quality water compared to wells of the present field and (iv) contaminant plumes from previous discharge activities in unlined open pits are now moving towards the present well field and are expected to reach it within the next 10 years. Polluted water will flow toward the cone-of-depression created by the domestic well field and ultimately will be produced through these wells if they are kept in the same location.

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Appendices

APPENDIX I RESULTS OF CHEMICAL ANALYSIS OF WATER SAMPLES COLLECTED FROM BU HASA FIELD, SEPT. 1996,(mg / L)

Ser. No.	Well No.	EC (uS)	pH	TDS	Units	Ca++	Mg++	Na+	K+	T. Cat.	CO3--	HCO3-	SO4--	Cl-	T. Ani.
1	WW-02	6740.0	7.3	4212	ppm	116.0	57.3	1023.0	48.0		10.8	188.4	691.8	2371.0	
					epm	5.8	4.7	44.5	1.2	**56.2**	0.4	3.1	14.4	66.9	**84.7**
					e%	10.3	8.4	79.1	2.2		0.4	3.6	17.0	78.9	
2	WW-06	5020.0	7.4	3137	ppm	65.0	31.3	788.0	26.0		7.2	111.8	593.2	1826.1	
					epm	3.2	2.6	34.3	0.7	**40.8**	0.2	1.8	12.4	51.5	**65.9**
					e%	8.0	6.3	84.1	1.6		0.4	2.8	18.7	78.1	
3	WW-11	8570.0	7.6	5356	ppm	191.0	81.4	1192.0	65.1		8.4	75.3	458.6	1896.8	
					epm	9.5	6.7	51.9	1.7	**69.7**	0.3	1.2	9.5	53.5	**64.6**
					e%	13.7	9.6	74.3	2.4		0.4	1.9	14.8	82.9	
4	WW-15	4440.0	7.1	2775	ppm	57.0	25.5	667.0	23.7		9.6	110.6	454.1	1438.1	
					epm	2.8	2.1	29.0	0.6	**34.6**	0.3	1.8	9.5	40.6	**52.2**
					e%	8.2	6.1	83.9	1.8		0.6	3.5	18.1	77.8	
5	WW-17	3480.0	6.9	2175	ppm	53.0	22.3	593.0	16.7		8.4	977.2	400.8	1207.0	
					epm	2.6	1.8	25.8	0.4	**30.7**	0.3	16.0	8.3	34.0	**58.7**
					e%	8.6	6.0	84.0	1.4		0.5	27.3	14.2	58.0	
6	WW-18	6690.0	7.6	4181	ppm	125.0	57.8	975.0	45.5		9.6	114.2	801.1	2761.0	
					epm	6.2	4.8	42.4	1.2	**54.6**	0.3	1.9	16.7	77.9	**96.8**
					e%	11.4	8.7	77.7	2.1		0.3	1.9	17.2	80.5	
7	WW-19	3700.0	7.4	2312	ppm	47.0	19.3	591.0	18.9		6.0	111.8	429.5	1208.5	
					epm	2.3	1.6	25.7	0.5	**30.1**	0.2	1.8	8.9	34.1	**45.1**
					e%	7.8	5.3	85.3	1.6		0.4	4.1	19.8	75.6	
8	WW-20	4760.0	7.5	2975	ppm	80.0	37.4	709.0	31.9		9.6	142.2	476.8	1587.0	
					epm	4.0	3.1	30.8	0.8	**38.7**	0.3	2.3	9.9	44.8	**57.3**
					e%	10.3	7.9	79.6	2.1		0.6	4.1	17.3	78.1	
9	WW-21	4930.0	7.7	2768	ppm	64.0	28.0	687.0	29.0		4.8	89.9	584.9	1429.0	
					epm	3.2	2.3	29.9	0.7	**36.1**	0.2	1.5	12.2	40.3	**54.1**
					e%	8.8	6.4	82.7	2.1		0.3	2.7	22.5	74.5	
10	WW-23	4080.0	7.2	2550	ppm	51.0	24.3	658.0	23.1		7.2	109.4	423.6	1330.0	
					epm	2.5	2.0	28.6	0.6	**33.8**	0.2	1.8	8.8	37.5	**48.4**
					e%	7.5	5.9	84.8	1.8		0.5	3.7	18.2	77.6	
11	CH-03	9460.0	7.6	5912	ppm	156.0	58.3	1545.0	49.8		12.0	46.2	1281.3	3663.8	
					epm	7.8	4.8	67.2	1.3	**81.1**	0.4	0.8	26.7	103.4	**131.2**

APPENDIX I RESULTS OF CHEMICAL ANALYSIS OF WATER SAMPLES COLLECTED FROM BU HASA FIELD, SEPT. 1996,(mg / L)

					e%	9.6	5.9	82.9	1.6		0.3	0.6	20.3	78.8	
12	CH-05	4010.0	7.6	2506	ppm	43.0	18.3	682.0	17.2		0.0	62.0	414.7	1418.0	
					epm	2.1	1.5	29.7	0.4	**33.8**	0.0	1.0	8.6	40.0	**49.7**
					e%	6.4	4.5	87.9	1.3		0.0	2.0	17.4	80.6	
13	CH-07	3410.0	7.5	2131	ppm	36.0	16.0	592.0	16.3		3.6	91.1	416.8	1020.7	
					epm	1.8	1.3	25.8	0.4	**29.3**	0.1	1.5	8.7	28.8	**39.1**
					e%	6.1	4.5	87.9	1.4		0.3	3.8	22.2	73.7	
14	BU-M	0.00	0.0	2437	ppm	42.0	18.8	699.0	17.2		6.0	97.2	391.0	1333.0	
					epm	2.1	1.5	30.4	0.4	**34.5**	0.2	1.6	8.1	37.6	**47.5**
					e%	6.1	4.5	88.2	1.3		0.4	3.4	17.1	79.1	
15	AL DHAFRA	4840.00	0.0	3025	ppm	93.0	41.3	796.0	36.4		4.8	88.9	626.4	1645.5	
					epm	4.6	3.4	34.6	0.9	**43.6**	0.2	1.5	13.0	46.4	**61.1**
					e%	10.6	7.8	79.4	2.1		0.3	2.4	21.4	76.0	
16	BIN THANI	9020.00	0.0	5637	ppm	229.0	100.0	1363.0	87.5		8.4	155.5	956.9	3386.2	
					epm	11.4	8.2	59.3	2.2	**81.2**	0.3	2.5	19.9	95.5	**118.3**
					e%	14.1	10.1	73.0	2.8		0.2	2.2	16.8	80.8	

Arabic Summary

٨. بناء على نتائج الدراسات الجيولوجية والهيدروجيولوجية والهيدروكيميائية ودراسات النظائر فان لا يوجد سبب للاعتقاد أن المياه العادمة التى يتم حقنها فى رواسب عصر الايوسين الفتاتية فى منطقة أبو حصا قد أدت الى تلوث المياه الجوفية فى الخزان المائى للعصر الرباعى. ولكن على النقيض فان التخلص من المياه المصاحبة للبترول أحيانا فى حفر غير مبطنة فى المنطقة قد أدى الى تلوث خطير لمياه ذلك الخزان المائى الهام.

ثانيا : التوصيات

١. يجب حفر بئر مراقبة فى المنطقة المركزية من حقل بترول أبو حصا للتعرف المباشر على نتائج تسرب المياه العادمة من أبار الحقن فى الخزانات البترولية أو فى رواسب الايوسين الفتاتية. كما يمكن استخدام هذا البئر أيضا فى دراسة حركة الملوثات فى الخزان المائى للعصر الرباعى.

٢. انشاء نموذج رياضى ثلاثى الأبعاد من طبقتين لدراسة تأثير حقن المياه العادمة فى الخزان المائى لعصر الايوسين على المياه الجوفية فى الخزان المائى للعصر الرباعى وحساب الضغوط الهيدروليكية فى كلا الخزانين لمعرفة اتجاه حركة المياه بينهما.

٣. التوقف الفورى عن التخلص من المياه المصاحبة للبترول فى حفر غير مبطنة فى المنطقة حيث أن ذلك يمثل المصدر الرئيسى لتلوث المياه الجوفية بالمنطقة والذى تم رصده بالفعل من خلال تلك الدراسة بالاضافة الى دراسات أخرى سابقة.

٤. بناء على نتائج دراسة حركة المياه الجوفية بالمنطقة واتجاه حركة الملوثات يوصى بالتفكير فى نقل موقع حقل آبار المياه فى منطقة الدراسة من موقعه الحالى الى أقصى الركن الجنوبى الشرقى الموقع الذى يتميز بما يلى:

ا. السمك المشبع للخزان المائى بتلك المنطقة يبلغ ١٠٠ متر مقارنة ٣٥ متر متوسط سمك الخزان المائى فى موقع الحقل الحالى.

ب. الموقع الجديد أكثر قربا من سنام منطقة ليوا العذب الذى يمثل مصدر تغذية رئيسى للمياه الجوفية فى منطقى الدراسة.

ج. سوف يمكن لآبار الحقل الجديد اختراق سمك أكبر للخزان المائى والذى يتميز بنوعية أكثر جودة من المياه فى موقعه الحالى.

د. المياه الملوثة التى دخلت الخزان المائى للعصر الرباعى نتيجة التخلص منها فى حفر غير مبطنة تتحرك نحو موقع حقل الآبار الحالى ويتوقع أن تصله خلال العشر سنوات القادمة.

أ. الاتجاه العام لحركة المياه الجوفية فى الخزان تتم من الجنوب نحو الشمال الغربى. كما يؤدى وجود سنام مائى محلى الى الشرق من حقل مياه الآبار فى أبو حصا الى حركة المياه من مركزه الى جميع الاتجاهات.

ب. يوضح وجود لسانين من المياه الأقل جودة واللذان يمتدان من الشمال الغربى نحو الجنوب الشرقى فى الركن الشمالى الغربى لمنطقة الدراسة تأثير الضخ الشديد للمياه الجوفية فى المنطقة على زيادة ملوحة المياه الجوفية فى الخزان.

ج. يتميز التدرج الهيدروليكى فى منطقة الدراسة بالتغير الشديد حيث يتراوح بين ٠،٠٠١ فى الجنوب الغربى و ٠،٠٠٠١ فى الجنوب الشرقى. ولذا فبالاضافة الى تأثير الضخ ، فان التدرج الهيدروليكى يعكس عدم تجانس الخزان المائى.

٣. بين عامى ١٩٦٤ و ١٩٨٥ ازدادت ملوحة المياه الجوفية فى منطقة معسكر حقل بترول بوحصا من ٢٠٠٠ ملليجرام فى اللتر الى ٥٥٠٠ ملليجرام فى اللتر. كما توضح الخرائط الكنتورية لتساوى ملوحة الخزان المائى لعصر الرباعى فى ابريل ١٩٩٦ أن ملوحة المياه الجوفية فى المنطقة الجنوبية الشرقية من الحقل قد زادت ثلاثة أضعاف خلال الفترة من ١٩٨٥ و ١٩٩٦. ويعزى ذلك بصفة رئيسية الى تأثير التخلص - أحيانا - من مياه النفط العادمة عن طريق صرفها فى حفر غير مبطنة فى تلك المنطقة. ونظرا لأن الخزان المائى فى منطقة الدراسة هو خزان حر ، فان تلك المياه تجد طريقها نحوه ملوثة مياهه.

٤. يوضح ترتيب تركيز الأيونات الموجبة فى الخزان المائى للعصر الرباعى فى منطقة الدراسة أنها تأخذ الشكل التالى: الصوديوم يلية الكالسيوم ثم الماغنيسيوم فالبوتاسيوم ، أما تتابع الأيونات السالبة فانه: الكلورايد يلية الكبريتات ثم البيكربونات فالكربونات. وهذا يوضح أن المياه الجوفية فى منطقة الدراسة يسودها أيونى الكلور والصوديوم مما يرجح قدم عمرها. هذا الرأى يعضده أيضا توقيع نتائج التحليل الكيميائى لمياه المنطقة على شكل بيبر الذى يوضح أن المياه تنتمى الى نوع كلوريد الصوديوم.

٥. يدل تركيز العناصر النادرة مثل النحاس والحديد والكروميوم وكذلك أيون النترات أنها أقل من الحدود المسموح بها من قبل منظمة الصحة العالمية لمياه الشرب.

٦. أوضح تحليل بعض عينات مياه الخزان المائى للعصر الرباعى فى منطقة الدراسة أنها خالية من التلوث بواسطة الهيدروكربونات وان كان هذا لايعنى أن كل مياه الخزان المائى غير ملوثة. أما مياه النفط العادمة التى يتم حقنها فى رواسب عصر الايوسين الفتائية فانها بالطبع مثقلة بالعديد من المركبات الهيدروكربونية التى يمثل وصولها الى الخزان المائى للعصر الرباعى خطورة كبيرة.

٧. يستدل من توقيع نظائر الديوتيريوم والأكسجين ١٨ فى بعض عينات مياه أبو حصا والتى جمعت من الخزان المائى للعصر الرباعى والمياه العادمة التى يتم التخلص منها فى رواسب الايوسين الفتائية ، انهما متباينتين مما يوضح التأثير الفعال لرواسب المتبخرات التى تنتمى لعصر الميوسين فى منع مياه الخزانين من الاختلاط.

باضافة الى مشاركته الكاملة فى اجراء التحاليل الكيميائية لعينات المياه الجوفية التى جمعت خلال ابريل وسبتمبر ١٩٩٦، فى مركز الرقابة على الأغذية والبيئة ومركز بحوث الصحراء والبيئة البحرية بجامعة الامارات العربية المتحدة. قام الباحث أيضا بتحليل عينات مياه جوفية من الخزان المائى للعصر الرباعى والخزان المائى لعصر الايوسين بالنسبة لمحتواها من الهيدروكاربونات.

٣. الأنشطة المكتبية

قام المؤلف ببحث مكتبى حول موضوع الأطروحة فى مكتبة شركات أدكو وأدنوك وفى مكتبات الجامعة مركزا على عمليات اعادة الحقن ومواصفاتها ومخاطرها بالاضافة الى البحث عن دراسات حالات خاصة. وخلال تلك المرحلة تم جمع المعلومات الجيولوجية والهيدروجيولوجية والهيدروكيميائية والجيوفيزيائية السابقة حول منطقة الدراسة والتى استخدمت فى مناقشة نتائج الدراسة الحالية.

استخدم الباحث المعلومات الجيولوجية والهيدروجيولوجية فى اعداد خرائط كنتورية للتراكيب الجيولوجية وسماكات الوحدات الصخرية المختلفة. كما أعد قطاعات هيدروجيولوجية طولية وعرضية لمنطقة الدراسة.

مثل الباحث نتائج التحاليل الكيميائية التى حصل عليها على خرائط كنتورية وقطاعات توضح الملوحة فى الخزان المائى للعصر الرباعى وتطورها مع مرور الوقت وخرائط عديدة أخرى توضح توزيع الأيونات الرئيسية والثانوية والشحيحة وذلك بغرض قرأتها وتفسيرها.

بالاضافة الى نتائج التحاليل الكيميائية ، استفاد الباحث أيضا من نتائج تحاليل النظائر لبعض العينات التى جمعت من منطقة الدراسة وتم تحليلها خلال أغسطس ١٩٩٦ فى معامل الوكالة الدولية للطاقة الذرية بفيينا. هذا وقد خلص الباحث من دراسته الحالية الى النتائج والتوصيات التالية.

أولا: النتائج

١. أوضحت الدراسة الوصفية والبتروجرافية لعينات القطاع الصخرى لمتكون الفارس الذى ينتمى الى عصر الميوسين السفلى أنه يتكون من الجبس والأنهيدريت والحجر الطينى والحجر الرملى. تلك المكونات يعتقد أنها تمثل حاجز جيد يفصل بين رواسب الأيوسين الفتاتية أسفلها والخزان المائى للعصر الرباعى أعلاها ، مما لا يساعد على انتقال مياه النفط العادمة شديدة الملوحة والتى يتم التخلص منها فى رواسب الايوسين الى أعلى نحو الخزان المائى للعصر الرباعى والذى يمثل أهم موارد المياه فى المنطقة.

٢. توضح الخريطة الكنتورية لتوزيع الجهد الهيدروليكى فى الخزان المائى للعصر الرباعى فى منطقة بوحصا الحقائق التالية:

ملخص

تمثل صناعة النفط عصب الاقتصاد فى دولة الامارات العربية المتحدة ولذا توليها الدولة أهمية خاصة. ونظرا لأن تلك الصناعة تمر بالعديد من المراحل التى تشتمل على الاستكشاف والضخ والمعالجة والتصنيع والتصدير فان تأثير المواد والأنشطة البترولية على البيئة يخضع لمراقبة دقيقة أيضا.

ونظرا لأن الاهتمام الشديد بالبيئة هو أحد مقومات النهضة الحديثة بدولة الامارات العربية المتحدة ، فان الهدف الأساسى من اعداد هذه الأطروحة هو "تقييم التأثير البيئى لحقن المياه المصاحبة للنفط فى رواسب عصر الميوسين الفتاتية على الخزان المائى الضحل للعصر الرباعى فى حقل بترول أبو حصا" وذلك لأن هذا الخزان يحتوى على مياه ذات نوعية جيدة تستخدم فى غسيل أملاح البترول والرى ومكافحة الحرائق علاوة على الاستخدامات المنزلية المختلفة.

يقع حقل بترول أبو حصا – منطقة الدراسة – على بعد ٢٠٠ كيلومتر جنوب غرب مدينة أبوظبى و ٦٠ كيلومتر جنوب ساحل الخليج العربى و ٦٥ كيلومتر شمال شرق منطقة ليوا. ويبلغ طول الحقل ٣٥ كيلومتر فى اتجاه شمال-جنوب وأقصى عرض له ٣٠ كيلومتر فى اتجاه شرق-غرب. كما تبلغ مساحته ٦٣٩ كيلومتر مربع.

وقد استغرق اعداد هذه الأطروحة عامين تمت خلالها أنشطة حقلية ومعملية ومكتبية يمكن تلخيصها فى النقاط التالية:

١. الدراسات الحقلية

قام الباحث بزيارتين الى منطقة الدراسة فى ابريل وسبتمبر عام ١٩٩٦ جمع خلالهما ٤٧ عينة مياه جوفية ، ٣٢ عينة خلال ابريل جمعت من الآبار التى تستخدم للأغراض المنزلية وتستمد مياهها من الخزان المائى للعصر الرباعى ومن بعض آبار المياه الضحلة بجوار أبار الحقن ومن معسكرات الظفرة وبن ثانى لخدمات حقول النفط ومن وحدة حقن المياه فى خزان عصر الميوسين.

تم قياس درجة حرارة عينات المياه المجمعة وتوصيلها الكهربى وتركيز أيون الهيدروجين والأكسجين الذائب مباشرة فى الحقل وأرسلت المياه فى اليوم التالى الى معمل الرقابة على الأغذية والبيئة ببلدية أبوظبى حيث تم تحليلها تحليلا كيميائيا كاملا من حيث الأيونات الرئيسية والمكونات الثانوية والشحيحة. أما فى سبتمبر ، فبالاضافة الى تحليلات مركز الرقابة على الأغذية والبيئة بأبوظبى تم تحليل العناصر النادرة بجهاز الامتصاص الذرى بمركز الصحراء والبيئة البحرية بجامعة الامارات العربية المتحدة بالعين.

٢. التحاليل المعملية

قام الباحث بدراسة تفصيلية وصفية وبتروجرافية لقطاع صخرى يبلغ طوله ٣٢ متر تم الحصول عليه من متكون طبقة الفارس السفلى الذى ينتمى الى عصر الميوسين السفلى.