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INVESTIGATION OF THE REGIONAL BASALT AQUIFER SYSTEM IN JORDAN AND THE SYRIAN ARAB REPUBLIC

96-0386

NOTE

FOREWORD

The ESCWA region possesses major shared surface and groundwater basins, and there is an urgent need to promote cooperation between neighbouring countries with a view to unifying their efforts and resources to carry out the investigations necessary for the efficient utilization and effective management of their water resources. If such investigations rely solely on unilateral efforts at the national level, their results often lack preciseness. Therefore, an integrated approach to the management of shared water resources is required for the benefit of neighbouring countries.

A sound quantitative and qualitative knowledge of the potential of the available water resources is a prerequisite for planning, development, utilization and efficient allocation of water resources. Therefore, initiation of action plans for collection, processing and dissemination of hydrological and hydrogeological data should receive high priority at the national level, as should the formulation of long-term monitoring programmes to achieve realistic assessments of the available water resources.

Within the framework of the ESCWA mandate to promote regional and subregional cooperation, an investigation study on the subregional basalt aquifer system shared by the Hashemite Kingdom of Jordan and the Syrian Arab Republic has been conducted. The present technical publication on the study is the outcome of close scientific cooperation between experts from the ESCWA Energy, Natural Resources and Environment Division, and the competent authorities in both countries, namely the Jordanian Ministry of Water and Irrigation and the Syrian Ministry of Irrigation, as well as the provision of advisory services from the Federal Institute for Geosciences and Natural Resources (BGR) of Germany. As a result of the dedicated efforts of these experts, it is now possible to publish this document containing a comprehensive investigation of the prevailing geologic, hydrologic, hydrogeologic and water quality conditions within the basalt aquifer system shared by Jordan and the Syrian Arab Republic.

In this respect, it must be stressed that the present technical publication could not have been possible without the high level of subregional cooperation witnessed during the investigation. It is hoped that the competent authorities in the two countries will take into consideration the recommendations highlighted in this document, and ESCWA will be ready to provide any guidance or advisory services deemed necessary to implement these recommendations.

Hazem El-Beblawi
Executive Secretary of ESCWA

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Dr. Samir Hijazin Eng. Mohammad Al-Moumani	Eng. Aziz Ghadban Dr. Hisham Abu Ayyash Geologist Adnan Al-Beini Geologist Yehia Nofel
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Jordan	**Syria**

The valuable participation of the above-mentioned government-designated experts through: the provision of data and information, field investigations, their deliberation in the expert group meetings held during the course of implementing the study and their views on the final draft document, were so substantive that made the issuance of this technical publication possible.

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ABBREVIATIONS AND GLOSSARY

a.s.l	Above sea level
EC	Electric conductivity, reported in μS (microsiemens/cm) or mS (millisiemens/cm)
K	Hydraulic conductivity or permeability
km^2	Square kilometer
km^3	Cubic kilometer
l/s	Liters per second
l/s.m	Liters per second per meter
m	Meters
m/d	Meters per day
m^3/d	Cubic meters per day
mg/l	Milligrams per liter
mm	Millimeters
mm/a	Millimeters per annum
MCM	Million Cubic Meters
MCM/a	Million Cubic Meters per annum
Q	Rate of discharge
ppm	Parts per million
swl	Static water level
S	Storage coefficient
T	Transmissivity
TDS	Total dissolved solids in mg/l or g/l

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^{14}C	Radiocarbon
pmc	Percent modern carbon, unit for specific ^{14}C activity
^{3}H	Tritium
TU	Tritium unit, 1 TU = 1 tritium atom per 10^{18} hydrogen atoms
$\delta^{18}O$	Value calculated from the oxygen isotope ratio $^{18}O/^{16}O$, referred to a standard substance
$\delta^{2}H$	Value calculated from the oxygen isotope ratio $^{2}H/^{1}H$, referred to a standard substance
d	Deuterium excess, calculated as $d = \delta^{2}H - 8*\delta^{18}O$
$\delta^{13}C$	δ value calculated from the atomic ratio of carbon isotopes ($^{13}C/^{12}C$)
pMC	Percent modern carbon. Unit for the specific ^{14}C activity and referred to that of the NBS oxalic acid standard

TDIC	Total dissolved inorganic carbon compounds in groundwater
PDB	Pee Dee Belemnite limestone; isotope standard for the determination of $\delta^{13}C$ values from carbonates

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AWSA	Amman Water Supply and Sewerage Authority
BGR	Federal Institute for Geosciences and Natural Resources, Hannover, Germany
FAO	Food and Agriculture Organization
IAEA	International Atomic Energy Agency
NLfB	Niedersächsisches Landesamt für Bodenforschung (State Geological Survey of Lower Saxony), Hannover, Germany
WAJ	Water Authority of Jordan
WHO	World Health Organization
WMO	World Meteorological Organization

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Term	**Definition**
Aquiclude, Aquitard	A geologic formation which contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring
Aquifer	A geologic formation which contains water and transmits it from one point to another in quantities sufficient to permit economic development
Drawdown	Change in surface elevation of the groundwater resulting from withdrawal of water from a well
Equipotential line	A contour line which represents or traces the equal head in the aquifer
Fossil or Connate Water	The groundwater which occurs in the rock at its formation and frequently highly saline
Permeability	The capacity of a porous medium (aquifer) for transmitting water

Piezometric level	The elevation to which the water level rises in a well that taps an artesian (confined) aquifer
Safe yield	The rate at which water can be withdrawn for human supply without depleting the source to such an extent that withdrawal at this rate is no longer economically feasible
Specific capacity	The yield per unit of drawdown in a pumping well
Storage coefficient	The volume of water released from storage, or taken into storage, per unit of surface area of the aquifer per unit change in head
Transmissivity	The rate at which water will flow through a vertical strip of the aquifer with unit length wide and extending through the full saturated thickness, under a hydraulic gradient of 1.00
Baseflow	Part of the flow which enters a stream channel from groundwater
Isohyetal Map	The map which defines or describes rainfall distribution and behaviour in a given period. Isohyets: lines of equal rainfall amount
Runoff coefficient	The ratio of surface runoff volume to total volume of storm rainfall over an area and depends on the characteristics of the drainage basin
Surface runoff	That part of storm precipitation which flows over the land surface before it reaches definite channel or stream
Water age	Conventional ^{14}C age from the TDIC of groundwater minus reservoir correction
Conventional age	Based on the radioactive decay of radiocarbon in any carbon-containing material, e.g. TDIC in groundwater which is formed by both biogenic carbon dioxide in the topsoil and soil lime during the process of groundwater recharge
Delta value (δ)	$[(R_{sample}-R_{standard})/R_{standard}] \times 1000$ ‰ with R as isotope ratio referred to the isotope specific standard substance.

ABSTRACT

A potential shared basalt aquifer occurs between Jordan and the Syrian Arab Republic (SAR). Intensive water withdrawal is taking place in Jordan as it furnishes one of the main water supply sources for the Greater Amman, as well as in Southern Syria, affecting the water quality and quantity. Both Jordan and Syria are currently engaged individually in further studying this aquifer, aiming at increasing the respective country's water supply and further groundwater extractions may worsen the situation.

The Energy, Natural Resources and Environment Division of ESCWA has initiated a study on this subregional Basalt Aquifer System, shared by Jordan and Syria, as part of its activities during the biennium 1994/95. The study was implemented in cooperation with competent authorities in both countries, namely the Water Authority (WAJ) of the Ministry of Water and Irrigation of Jordan and the Department of Irrigation and Water Resources of the Ministry of Irrigation of the SAR. The study was conducted within the context of ESCWA-ENRED/BGR (Federal Institute for Geosciences and Natural Resources of Germany) Technical Cooperation Project entitled "Advice to ESCWA member countries in the Field of Water Resources", through the provision of advice in the fields of: hydrogeology, hydrochemistry, remote sensing, isotope hydrology, preparation of digitized thematic maps and the overall assessment of the potential water resources in the Basalt Aquifer System.

The immediate objectives of the present study are:

- to establish an information base on the hydrogeological conditions of the Basalt aquifer region, which is needed for sustainable management of the groundwater resources;

- to formulate proposals for further studies and technical measures for water resources development, management and conservation in specific areas;

- to introduce appropriate methods, such as remote sensing and isotope hydrology, for groundwater exploration and management in the Basalt aquifer area.

The long-term objective of the Project is to achieve an optimized sustainable management of the available water resources in the Basalt aquifer region.

This paper includes a brief account on the main activities that have been carried out during the biennium 1994/95 and presents the outcome of the evaluation and investigations on: geological set-up of the study area (lithology, stratigraphy and geotectonic features), prevailing hydrogeologic conditions in the Basalt Aquifer System (groundwater occurrence, movement and aquifer characteristics) and hydrochemical investigations. The paper also introduces descriptive notes on the thematic maps produced, incorporating all the data and information that are made available about the Basalt Aquifer System in the area. Complementary investigations were conducted during the first quarter of 1996 and the final report on the study was completed in July 1996. This final paper includes, in addition to the

outcome of the initial activities, groundwater balance in the aquifer system; the outcome of the hydrochemical evaluation and isotope hydrologic investigations; the final version of the digitized thematic maps at different scales and plan of action for further investigations.

As per the study, it was indicated that the sequence of basaltic rocks in northern Jordan and southwestern Syria is composed of Neogene plateau basalts and Quaternary (Pleistocene to Recent) basaltic lava flows and shield volcanoes. The basalt complex is underlain, in most of its extent, by Paleogene chalks and marly limestones. In some parts of the western fringe of the basalt field, the volcanics overlie Upper Cretaceous sedimentary rocks.

The major aquiferous sections that occur within the sequence of Upper Cretaceous to Recent sedimentary and volcanic rocks are:

- Upper Cretaceous limestones and dolomites;
- Paleogene chalks and marly limestones;
- various horizons with relatively high permeability within the basalt complex.

Available data on hydraulic aquifer parameters and groundwater balances have been compiled. Further evaluations are necessary to arrive at a quantitative estimate of groundwater resources in the basalt aquifer system. These evaluation will comprise a review of previous groundwater balance assessments and evaluations of the existing hydrochemical, isotope hydrologic and geohydraulic data and will be carried out under Phase II of the study of the Basalt aquifer system.

The available information on geologic and hydrogeologic features of the basalt aquifer system is presented on twelve thematic maps. Computer printouts of the maps have been distributed to the competent national authorities for their review and comments which were incorporated upon finalization of this paper.

The paper ended up with the main findings that could be formulated upon completion of the study. Action programmes towards water resources development, management and conservation in the shared basalt aquifer system, were proposed in Chapter 7 of this paper, to be undertaken either at national or subregional levels.

1. INTRODUCTION

1.1 GENERAL BACKGROUND

The study area is primarily covered by basaltic materials and is about 25000 km^2. It is situated in the southern part of the Syrian Arab Republic and north Jordan (Fig.1). It covers partially the basins of Damascus, Yarmouk and Azraq. Suweida, Deraa (Hauran and Jebel el Arab areas) of Syria and Mafraq, Azraq of Jordan are the main localities in the study area. Population distribution in the area is estimated about 925000 (Hauran area: 500000, Jebel el Arab 248000 and Mafraq-Azraq 177000).

Rainfall which is of irregular and frontal type varies from the highest at Jebel el Arab 500 mm/a to about 300 mm/a and less than 100 mm/a to western and eastern peripheries of the area respectively. Water resources of the area are primarily groundwater and the stored surface water resources behind the existing dams, in addition to the Yarmouk and Azraq spring flows. The total irrigated area in the study region is estimated at 485.000 ha in the major agricultural areas of Hauran, Jebel el Arab, Azraq, Mafraq, Dhuleil and Hallabat areas.

1.2 SCOPE OF THE PRESENT STUDY

The basalt aquifer region in southwestern Syria and northern Jordan has been chosen as a study area for a joint investigation of groundwater resources by ESCWA, BGR experts and national institutions, applying appropriate investigation techniques, considering the particular conditions of the ESCWA region.

Groundwater in the study area furnishes an essential source for urban and rural water supply and for irrigation. In some areas of the basalt region, intensive groundwater exploitation has led to problems of declining groundwater levels, reducing spring discharge and deterioration of the quality of the extracted groundwater.

The study region comprises a complex system of aquifers:

- basalt flows of Miocene to Quaternary age, which are aquiferous in fractures, fissures and in porous layers;
- sedimentary rocks of Mesozoic to Tertiary age underlying and adjoining the basalt;
- Quaternary sediments overlying the basalt in limited areas.

The sequence of basaltic and sedimentary rocks contains various aquiferous sections which are partly interconnected. The complicated hydrogeological setting of the region, the very inhomogeneous aquiferous properties of the basalt sequence and the difficult access to parts of the basalt area are impediments to a reliable assessment of the groundwater resources with conventional methods.

1.3 Objectives

The immediate objectives of the present study are:

- to establish an information base on the hydrogeological conditions of the basalt aquifer region, which is needed for sustainable management of the groundwater resources;
- to formulate proposals for further studies and technical measures for water resources development, management and conservation in specific areas;
- to introduce appropriate methods such as remote sensing and isotope hydrology for groundwater exploration and management in the basalt aquifer area.

The long-term objective of the project is to achieve an optimized sustainable management of the available water resources in the basalt aquifer region.

1.4 Activities

Activities started in August 1994, after representatives of national institutions participating in the study had been nominated by the Ministry of Water and Irrigation, Jordan, and the Department of Irrigation and Water Resources of the Ministry of Irrigation in the Syrian Arab Republic. Activities carried out during Phase I of the project (between August 1994 and February 1996) included:

- Compilation of data and preparation of relevant reports by the cooperating national institutions;
- Field missions to the Syrian Arab Republic and Jordan for discussions and information exchange with the competent government officials in both countries;
- Evaluation of geological and hydrogeological information and data provided by the cooperating national institutions;
- Preparation of a geological map through satellite image interpretation. The map, based on two Thematic Mapper data sets: scene 173/037 of 22/11/1991 and scene 173/038 of 26/10/1991, covers a major part of the basalt province in Jordan and Syria, extending from Azraq in Jordan in the south to Deraa, Ataibe and Zelaf in Syria in the west, north and east (Fig. 2);
- Presentation and discussion of the results of the satellite image interpretation during an expert group meeting (Amman, 12 December 1994);
- Preparation of digitized thematic maps at 1:500,000 and 1:1,000,000 scale, presenting geological and hydrogeological features of the basalt area;
- Evaluation of possibilities of investigating the geohydraulic and regional groundwater flow conditions;
- Compilation of isotope hydrologic data available for the Basalt aquifer area;
- Preparation of a draft report on the preliminary results of the study has been presented for review and discussion during the Expert Group Meeting, Amman, March 1996);
- Evaluation of hydrochemical and isotope data.

Supplementary studies that are to be carried out in the 3rd Quarter 1996 (Phase 2) may comprise:

- Generalized evaluation of quantitative groundwater movement through (a) flow-line analysis; (b) two-dimensional modeling of groundwater flow along a generalized section from Jebel el Arab to Deraa area; (c) consideration of the results of previous groundwater modeling studies for parts of the basalt region in Jordan; and (d) estimates of groundwater balances for various parts of the Basalt region;
- Preparation of geologic and hydrogeologic sections and of additional thematic maps;
- An evaluation of recommendable methods for groundwater exploration and management based on the prevailing conditions of the basalt aquifer area;
- Three-dimensional groundwater simulation modeling of the Basalt aquifer system on a regional scale may be considered at a later stage when an adequate base of hydraulic data has been compiled and definite aims of modeling with regard to groundwater management have been formulated.

The final paper and final version of the thematic maps are planned to be completed by the 4th Quarter 1996.

Proposals for feasibility studies and technical measures may be formulated according to the requirements of the two participating countries.

2. MORPHOLOGY, HYDROGRAPHY AND CLIMATE

2.1 MORPHOLOGY

The study area encompasses most of the area covered by Basalt formation and belongs primarily to Yarmouk river basin in Syria on the north and to Azraq basin in Jordan on the south. In general, the area shows a gentle relief from Jebel el Arab where the highest peak is located at 1800 m above sea level in Syria. The lowest elevation is located at Qa'Al-Azraq and at Yarmouk in Jordan at 440 m above mean sea level. Ground slopes range between 5-10% in the north and 3-5% in other directions, and more than 15% around Jebel el Arab.

The area comprises the Jebel el Arab basalt shield in the north and the basaltic flows continue toward the southeast across the Azraq Oasis (Shihan and Drouz in Jordan) and it continues to the Jordan-Saudi Arabia border then it runs southward for more than 300 km toward Al-Jauf in Saudi Arabia. The basalts start about 15 km east of Mafraq in Jordan and extend for 160 km toward the east. These basalt flows cover about 45,000 km^2 from the southern edge of Damascus basin in Syria down to east of the Wadi Sirhan depression in Saudi Arabia. The Jordanian part of this basalt covers an area of about 11,000 km^2 and about 14,000 km^2 in Syria. The basalt shield known as Harra Ash Shamah (Al-Malabeh, 1993) is interrupted by many hills and volcanoes with altitudes exceeding 1100 m above mean sea level in the north northwest at the north border of Jordan. The land dips to the south southeast over a distance of about 50 km toward the Azraq depression to about 495 m above mean sea level. East of the Azraq depression, the Jebel el Arab basalt lava fields extend southward to join with those of the Uneiza-Tuwala highlands in Saudi Arabia. The basin is occasionally interrupted by small scarps formed by more resistant beds of the Tertiary sedimentary sequence.

The geomorphologic features which prevail in the area play an important role in the hydrogeological configuration of the Basaltic complex. Bajbouj (1982) could recognize three main morphologic patterns as a result of the:

- atmospheric erosion of the paleo-peaks in the area;
- erosional activities by the various tectonic movements which took place in the area; and
- erosional conditions related to the different volcanic activities.

The first and the second types of erosion had affected the Paleogene formation (carbonate rocks) while the third one affected the Basalt complex in the area, giving rise to the creation of Jebel el Arab and the other volcanic cones which occur in a NW-SE trending orientation. In addition to the formation of the highly fractured Basaltic plains as a result of the Basaltic flows that filled the various paleo-topographic depressions render favourable conditions for direct groundwater recharge from rainfall and the resulting annual runoffs in the study area.

2.2 CLIMATE

Mediterranean climatic conditions prevail in the area. It is characterized by a wet and cold winter and a dry and warm summer. Relative humidity ranges from (69-81%) in winter to about (53-61%) in summer. Maximum values are observed in January and the minimum values in May. Potential annual evaporation varies from 1240-1490 mm, while the average monthly evaporation from soil surface ranges from 230-290 mm in the plain area to 300-350 mm in the mountain area, and this range increases eastwards from the study area, in the Syrian territory. In the Jordanian part, the climatological data obtained from the files of the Water Authority of Jordan (WAJ) indicates that the mean annual potential evaporation is 3877 mm, the monthly values range between 449 to 589 mm in summer and 105 to 399 mm in winter. The average wind speed is about 12 km/h. It ranges between 10 to 18 km/h in summer and 7 to 12 km/h in winter. Strong northwesterly winds predominate in summer, shifting to the southwest in winter with the advent of the rainy and cold season during the winter. The annual sunshine duration is 9.0 hours per day in north Jordan and decreases to the north in Syria. The minimum sunshine duration is recorded to be 6.0 hours per day in December and January, increasing to 12 hours per day in June and July. The mean annual temperature is 19°C. The values range between 21°C and 28°C in summer and 5 to 15°C in winter. The coldest month is January and the hottest is August.

Winter season starts from November to March of the following year. Rainfall is generally irregular over the area and range from the highest at Jebel el Arab 500 mm/a including snow fall to about 300 mm/a at the western peripheries of the study area and also decreases eastwards to less than 100 mm/a (map 5).

Table 1 summarizes the meteorological data recorded in the Jordanian part of the study area (Azraq Basin), while table 2 shows the monthly rainfall pattern as recorded during the period 1965/66-1989/90 in the area.

TABLE 1. MONTHLY AND ANNUAL MEANS OF RELATIVE HUMIDITY, WIND SPEED AND DIRECTION, THE CLASS A PAN EVAPORATION AND RAINFALL IN AZRAQ BASIN*

	Months													
Hydrologic Parameters	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual mean	Period
Average relative humidity (%)	79.0	73.0	66.0	58.0	51.2	53.0	55.3	58.0	61.3	62.0	69.0	77.0	64.0	(1965-1990)
Average temperature (°C)	8.9	11.2	13.6	19.1	23.1	26.5	28.0	27.9	26.3	20.9	14.9	10.3	19.0	(1965-1990)
Average wind velocity (km/h) and direction	8.2 SW	9.7 SW	12.0 SW	13.1 NW	12.2 NW	14.2 NW	17.8 NW	17.1 NW	14.0 NW	9.8 NW	7.7 SW	7.4 SW	12.0	(1968-1990)
Average evaporation (mm)	108.5	148.4	232.5	321	449.5	528	589	539.4	399	300.7	156	105.4	3877.4	(1965-1990)
Average rainfall (mm) of 11 stations	31.3	29.5	28.0	13.7	3.1	0	0	0	0	9.1	16.8	28.7	160.2	(1965-1990)

* Water Authority of Jordan files, after University of Jordan (1996).

TABLE 2. MEAN MONTHLY RAINFALL IN (MM) FOR THE PERIOD 1965/66-1989/90[1/]

Station name	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Salhad (S1)*	15.6	38.0	62.5	62.5	69.5	58.6	20.5	6.9	336.4
Imttan (S2)*	5.8	21.5	40.6	40.0	39.8	31.4	13.2	5.1	197.4
K. Awwad (S3)*	4.5	18.2	36.7	44.5	35.0	32.1	11.5	2.7	185.2
Um El-Quettein (F1)	12.2	17.0	32.4	35.3	38.5	37.1	14.0	3.0	189.5
Deir El-Kahf (F4)	12.8	16.5	28.8	28.0	30.1	30.0	24.5	4.1	174.8
Safawi (F2)	10.5	13.2	16.1	12.0	14.9	11.2	6.5	2.6	87.0
Khalidiyeh (AL48)	7.4	17.8	23.0	34.8	27.8	28.8	8.3	1.7	149.6
Aritain (F6)	11.1	13.5	15.7	33.3	18.8	16.5	11.0	4.7	113.6
Azraq Station (F9)	5.0	9.1	12.8	10.3	10.2	12.4	7.4	1.0	68.2
Muwaqqar (CD3)	9.0	16.2	36.8	42.0	34.3	42.0	22.9	1.3	204.5
Umary (F11)	5.9	3.9	7.8	12.5	6.1	8.1	11.1	1.5	56.9
Average	9.1	16.8	28.7	31.3	29.5	28.0	13.7	3.1	160.2
Weighted mean over 12710 km^2									90

*: These stations are located in Syria.

1/ Water Authority of Jordan files, after University of Jordan (1996).

3. GEOLOGY

3.1 GEOLOGICAL MAPPING

A unified geological map of the study area could be constructed making use of the previous investigations carried out in both countries. Satellite image interpretations together with field inspections were undertaken in order to describe and present the prevailing geologic and hydrogeologic conditions in the area.

LANDSAT - THEMATIC MAPPER (TM) satellite imagery was carried out on the basis of different TM-band combinations and ground truth in the basalt area of northern Jordan and southwestern Syria. Two Landsat TM satellite data sets (scenes) are covering the target area (Fig.2). The northern scene (path and row 173/037) was taken from the date of 22.11.1991 and the southern scene (path and row 173/038) was taken from the date of 26.10.1993. With the aid of satellite imagery a synoptic geologic model of the Neogene and Quaternary basalts has been developed at 1:250.000 scale. TM-data gave detailed new information about the distribution and differentiation of the basalt series. Standard processing revealed a high quality suitable for an appropriate visual interpretation. The processing included a topographical standard correction. (More details about satellite imagery interpretations are shown in Appendix 1).

According to image processing the satellite images show a wide range of colours. The colours result from absorption and reflectance properties, image processing and from photographic laboratory work. The colours representing basaltic material in the area are reddish brown, brown, bluish brown, blackish brown, dark blue, black, dark grey and grey. It was also interpreted that the basalt area is composed of Neogene plateau basalt, Quaternary and Recent basaltic lava flows and shield volcanoes. Basaltic dyke feeders extend along NW-SE trending fault systems. Quaternary basaltic lava flows and shield volcanoes are emplaced as point source feeders along NNW-SSE trending lineaments which are crosscutting the Neogene series.

What follows is a brief account on the outcome of the previous geologic investigations together with the satellite imagery interpretations carried out for the study area:

3.1.1 Regional framework

The North Arabian Volcanic Province extends from southwest Syria across Jordan into Saudi Arabia. It is situated in a tectonic frame which is related to the pivot of the NNE-SSW trending Arab-Jordan rift valley system and the NW-SE trending Wadi Sirhan depression: The generally SE-NW trending basalt outcrops of the province are bounded in the northwest in the Lake Tiberias area by the Dead Sea Transform Fault and in the southwest by the Wadi Sirhan Basin. The volcanics constitute an intra-plate continental basaltic succession, representing petrologically an intraplate alkaline and subalkaline single suite series (Krasnov et al. 1966, Ibrahim 1993 a).

The basalts originate from magmatic sources of the upper earth mantle. The emplacement of the first plateau basalts is considered to have occurred during Miocene - Pliocene and volcanic activity continued until the Holocene. The sequence of basaltic rocks in the area is composed of Neogene plateau basalts, Quaternary (Pleistocene - Recent) basaltic lava flows and shield volcanoes.

3.1.2 Neogene basalt

All Neogene basalts, with the exception of Neogene basaltic dikes, occur as plateau basalts which extend over the entire area. The Neogene plateau basalts are composed of single lava sheets of several meters in thickness with intercalated soil or sedimentary layers. No feeder zones are detectable. Relics of volcanic cones of Neogene age (point source feeders) are described from Jebel el Arab area, but from the present study this cannot be certified.

A NNW-SSE trending vertical dislocation along the eastern boundary of Jebel el Arab separates a tectonically deeper situated eastern basaltic field from an uplifted western basaltic field. A dislocation during lower Pleistocene or late Pliocene time is indicated by the first valley filling lava flows of Quaternary basalt into this tectonic relief.

The maximum thickness of about 1500 m of Neogene basalt is assumed beneath Jebel el Arab. The unexposed feeder zones of Neogene basalt are located at the eastern rift-shoulder of a deeply situated basin structure which may represent a prolongation of the Wadi Sirhan basin to the northwest. It is assumed, that the basalt extruded as a result of a subsequent tectonic depression in the northern continuation of the Wadi Sirhan basin which lasted at least from Cretaceous into Tertiary time.

The Neogene basalts are exposed in the southeast and east of the mapped area and the region of Jebel el Arab.

3.1.3 Quaternary basalt

Quaternary series cover the Neogene basalts at Jebel el Arab and vast areas west of it and occur as local events within the eastern Neogene basalt field. Holocene series occur north and south of Jebel el Arab and in the northeast of the mapped area.

Quaternary basaltic lava flows are developed as valley fillings. Depending on the previous relief the lava sometimes is situated in a deeper level than surrounding older basalt units. Proceeding erosion affecting the younger series is transporting debris through the valleys. In some cases the younger series seem to be more affected by erosion than the older ones. Quaternary basaltic lava flows and shield volcanoes are emplaced as point source feeders along NNW-SSE trending lineaments which are crosscutting the Neogene series. Their total thickness varies from few meters to 150 m.

In the area east of Jebel el Arab, which was interpreted entirely as Neogene basalt in earlier maps, several Quaternary basaltic lava flows and shield basalts were discovered on the satellite images. These Quaternary lava flows derive from the NNW-SSE trending escarpment east of Jebel el Arab. Lower Quaternary basalts are developed as shield basalts or thin lava flows forming valley fillings. The thickness of the shield basalts varies. The maximum thickness is probably around 100 m. Each of the individual Middle, Upper Quaternary and Recent shield basalts or lava fields has a total thickness of about 150 m.

3.1.4 Lithostratigraphic units

Lithostratigraphic units were defined through correlation of the results of previous geological studies with new data of satellite imagery. The geometrical position (stratigraphy) of volcanic rocks can often not be determined accurately since they represent more or less restricted local events deriving from dike systems or point source feeders.

The Neogene and Quaternary basalts show no significant differences in structural and textural features. The same varieties occur in both Neogene and Quaternary basalts, e.g.:

- coarse-grained basalt (doleritic type or microgabbroic type);
- porous medium-grained and coarse-grained basalt;
- vesicular basalt (different size of vesicules);-
- fine-grained basalt with olivine and pyroxene phenocrysts;
- fine-grained dense basalt with or without visible phenocrysts;
- very fine-grained vesicular basaltic tuff lava with flattened vesicules.

All basaltic varieties show, depending on the regional setting and climatic conditions, different weathering surfaces. The Neogene basalt is generally more weathered than the Quaternary basalt and does not show point source feeders. The Neogene basalt weathers predominantly into large sized boulders.

Neogene and Quaternary basalts can be easily distinguished in hand specimen: Neogene basalt rocks show highly altered olivine phenocrysts, while Quaternary basalt mainly contains fresh bright greenish (whitish) or yellowish olivine phenocrysts independent on the surface weathering of the rock.

The lithostratigraphic units presented in the study are defined as follows: Basalt rocks of the same feeder zone or the same flow direction are combined to a single suite. Basalt rocks showing the same color on the satellite image, which depends on the grade of weathering, are combined to one group. Further groups are defined according to the regional setting in relation to tectonical features.

The following lithostratigraphic units were defined and are shown on the geological map (Map 3):

(i) Neogene volcanics

- **Neogene (Miocene ?) Plateau Basalt -Nb1-**

The oldest basalt exposed in the mapped area is defined as Neogene Basalt Nb1. It occurs in the southern region of the basalt field in the surrounding of Safawi and in the northeast of the mapped area. Obviously, the plateau basalt occurs in large extent and with great thickness under the Jebel el Arab. It corresponds to the ßN1 (ßN12) of Krasnov et al. (1966), the Safawi Group of Ibrahim (1993 a), probably B4-Basalt of Van den Boom and Suwwan (1966) and partly BII-Basalt of Kruck et al. (1981).

- **Neogene (Pliocene ?) Plateau Basalt -Nb2-**

The Neogene plateau basalt Nb2 crops out in the central part of Jebel el Arab, where it probably reaches its greatest thickness. In the area east of Jebel el Arab the Nb2 basalt covers wide areas.

- **Neogene (Pliocene ?) Plateau Basalt -Nb3-**

In the southeast of the mapped area a basalt unit overlaying Nb2 basalt can be distinguished by satellite imagery. Due to its geometric situation and the color of weathered basalt it is considered as Neogene.

- **Neogene Basaltic Dikes -Ndk-**

Basaltic dike systems are crosscutting the Neogene plateau basalts. Their occurrences are restricted to the Neogene basalt areas. In earlier studies, the basaltic dikes were defined as Upper Pleistocene (B'd unit of Bender et al. 1968 and B6 of Van den Boom & Suwwan 1966). In the present study they are considered older than Pleistocene, since they show typical alteration of olivine phenocrysts which is restricted to Neogene basalts. In some areas the dikes occur as erosional remnants and they can be outlined as morphologic windows piercing through Lower Quaternary basalt of Qb1 and Qb2. The basalt dikes comprise fine-grained dense and coarse-grained porous varieties.

(ii) Quaternary volcanics

- **Quaternary (undivided) Basaltic Lava Flows -Qb-**

Basaltic flows of uncertain stratigraphic position extend over the eastern slope of Jebel el Arab. In outcrops in the area of Safawi this basalt shows slightly altered olivine phenocrysts, indicating early Quaternary or late Tertiary age which correlates direction of the basalt flows appears related to a pre-existing relief. The unit is defined on the map as undivided Quaternary Basaltic Lava Flows.

- **Lower Quaternary until Holocene Cinder and Scoria -Qfe-**

Cinder and scoriaceous cones are restricted to Quaternary (Pleistocene and Holocene) point source feeders. They are emplaced at the final stage of the magmatic activity and are characterized by a high content of iron-oxides. Predominantly, they occur in two parallel NNW-SSE arranged chains of volcanic cones.

- **Lower Quaternary until Holocene Basaltic Tuff -Qt-**

Tuff material is connected to cinder and scoria cones.

- **Lower Quaternary (Pleistocene) Shield Basalt -Qb1-**

Lower Quaternary basalt occurs as flood basalt with preserved surface of pahoehoe-lava (predominantly considered as shield basalt). The basalt shows in places point source feeders which are delineated as cinder and scoria cones (Qfe). Along NNW-ESE and NW-SE trending lineaments pahoehoe lavas occur as shield volcanoes, the feeder zones of which appear indistinct and can be defined in rough outlines only. The basalt corresponds to the hyalobasalt ß1Q1 described from Syria (Krasnov et al. 1966).

- **Lower Quaternary (Pleistocene ?) Basaltic Lava Flows -Qb2-**

Lower Quaternary lava flows occur as valley-filling lava flows. Predominantly, they show point source feeders which are developed in a late stage of eruption as cinder and scoria cones (Qfe). west, southwest and southeast of Jebel el Arab the Qb2 is assumed to extend over large areas although in most parts of the area the basalt is hidden under a thick soil cover. In contrast to plateau basalt and shield basalt, the valley-filling lava flows are restricted to fillings in a pre-existing morphologic relief. Continuing mechanical erosion and related transport of debris through the valleys provides the Qb2 with a dark "unweathered" color in the satellite image.

- **Middle Quaternary (?) Basaltic Lava Flows and Shield Basalt -Qb3-**

The basalt sheet of Leja (maximum thickness of about 15 m) belongs to the well preserved basaltic lava flows of the region. Regarding the typical weathered color in the satellite image and the thick cover of weathered surface obvious in the field, the Qb3 is defined as Middle Quaternary (?). Inside weathered boulders the high vesicular basalt is absolutely fresh, evident by green olivine phenocrysts.

- **Upper Quaternary Basaltic Lava Flows and Shield Basalt -Qb4, Qb4a, Qb4b-**

Lava flows and shield basalt of Upper Quaternary (Holocene ?) are present north and south of Jebel el Arab. They are linked to point source feeders which are characterized by scoriaceous cones Qfe.

- **Holocene Shield Basalt (Flow 1) -Qb5-, (Flow 2) -Qb6- and (Flow 3) -Qb7-**

The last basalt eruptions are restricted to the northeast of the basalt field. They are considered of Holocene age. An alteration crust is totally lacking. The eruption of this series is related to the northern continuation and revival of volcanic activity in Recent times.

(iii) Sediments

- **Volcaniclastics and Sediments -Qvs-**

Undifferentiated volcanic sediments are located in the central part of the eastern Neogene and Quaternary volcanic field. They fill a tectonic window and overlay Neogene basalt Nb1.

- **Mud Pans -Qp-**

Fine-grained sediments (clay minerals) fill morphologic depressions.
Neogene volcanics

3.1.5 Correlation of mapping units

During the course of this study, the following previous investigations and geological maps which cover parts of the Jordanian-Syrian basalt region were consulted:

- Geologic investigations in Jordan and geological map of Jordan (Van den Boom & Suwwan 1966, Bender et al. 1968);
- petrologic investigations in Jordan and mapping of the Azraq area by Ibrahim (1993a, 1993b);
- the geological map of Syria (Ponikarov et al. 1967, Krasnov et al. 1966);
- the geological map of the Hamad basin project by ACSAD (Kruck et al. 1981).

Mapping units used in these previous maps and studies can be correlated only to a limited extent with units applied on the geological map presented here. Previous mapping strategies were based predominantly on large scale lithologic/petrographic observations. The method of satellite imagery interpretation, applied here, has the advantage of giving detailed information on a small scale. Lithological and geochemical features are characterized by very sensitive differences in reflectance properties, from which information on the distribution of individual suites of volcanic rocks can be derived. Table 3 gives an outline on the correlation of mapping units used in different mapping approaches, as far as this is possible considering the above mentioned aspects.

TABLE 3: CORRELATION OF MAPPING UNITS APPLIED BY VARIOUS AUTHORS

ESCWA/BGR 1995	Ibrahim 1993	Ponikarov et al.1967	Van den Boom & Suwwan 1966	Kruck et al. 1981
Qb7		β7 Q4		BVII
Qb6		β6 Q4		BVI
Qb5				BVb
Qb4b	Bishriyya	β1-6 Q4		BVa/b
Qb4a				tuff
Qb4			B6	BIV
Qb3	Rimah	β4-5 Q4	B't	BVa/b, BIII
Qb2	Asfar	β1 Q1	B6/B5	
Qb1				
Qfe	Rimah			
Qt				
Qb	Safawi		B4	
Ndk		βN2b	B4/B6, B'd	
Nb3			B4	
Nb2		βN2/βN2b		BII
Nb1		βN1/βN12	B5	BIII

3.1.6 Thickness of Neogene and Quaternary basalts

Information on the thickness of the basalt sequence is available from BGR-WAJ (1994, Map 10 and 11), Krasnov et al.(1966), ACSAD (1983), Selkhozpromexport (1982), Bajbouj (1982) and borehole logs of WAJ.

The thickness of the basalt sequence and the position of the basalt base is relatively well documented in the southern part of its outcrops, but very scanty data exist for Jebel el Arab and the northern part of the basalt area, where the base of the basalt sequence has been reached by a very limited number of boreholes only (Maps 10 and 11). The following information is available on the occurrence and thickness of basalts of Miocene age:

Kisweh south of Damascus: 500 m (Ponikarov et al. 1967: 165);
Zelaf: 100 m (Ponikarov et al. 1967: 165);
southeastern part of basalt field (Wisad Formation, Ibrahim 1993: 6);
southern and eastern part of basalt field (Nb1, ESCWA/BGR 1994, Map 3).

At Suweida, a basalt sequence of 708 m has been penetrated attributed to Miocene 135 m, Pliocene 415 m, Lower Quaternary 160 m (borehole No. 120). The sequence of Miocene to Pliocene basalts is assumed to reach its greatest thickness in the area of the Jebel el Arab mountain massif. Ponikarov et al. (1967: 19 and 21) state: "it is reasonable to suppose the thickness of the Miocene basalts in the central part of Jabal Ad-Drouz to be very great and reach at least 700-750 m" and "The greatest thickness of Pliocene effusives is observed in the massive of Jabal Ad-Drouz, where it presumably reaches 700-800 m".

The thickness of the Quaternary basalt series ranges from a few meters of valley-filling single flows to more than 200 m in areas covered by several successive shield basalt flows.

The total thickness of Neogene to Quaternary basalts increases from less than 100 m on the fringes and in the southeastern and northeastern parts of the basalt field to more than 700 m on the foothills of Jebel el Arab (Map 10). No direct information is available on the geological structure of the deeper subsurface of the Jebel el Arab mountain massif. It can be assumed that this area comprises the following:

- a sequence of Neogene shield basalt flows with a thickness of several hundred meters, which are covered partly by thin layers of Quaternary lava flows or basaltic tuff;
- the main feeder zone of Neogene basalts, which probably constitute a thick sequence of basaltic rocks as vertical dikes or as sill-type intrusions into the sedimentary rocks;
- interlayers of basaltic rocks and disturbed sedimentary rocks.

3.2 SEDIMENTARY FORMATIONS

The basalt complex of the North Arabian Volcanic Province is underlain by Paleozoic to Neogene sedimentary rocks. The total thickness of sedimentary rocks overlying the Precambrian basement reaches 2.5 to more than 8 km in northern Jordan (BGR-WAJ 1994, Andrews 1992).

The sequence of <u>Paleozoic to Jurassic</u> rocks in northern Jordan and southern Syria is composed mainly of sandstones, siltstones, conglomerates and shales with intercalations of carbonate rocks in Syria. It can be assumed that a comparable sedimentary rock sequence underlies the basalt field at greater depth. The <u>Lower Cretaceous</u> is represented by a sandstone facies in Jordan (Kurnub sandstone) and by detrital to carbonate deposits in Syria

(Aptian-Albian). Upper Cretaceous to Neogene sedimentary rocks are exposed in the surroundings of the basalt field (Map 2). The Upper Cretaceous - Paleogene sedimentary sequence in northern Jordan and southern Syria can be subdivided into three major lithostratigraphic units:

- Upper Cretaceous limestones and dolomites, underlain by an Upper Cretaceous chalk-marl formation in Jordan;
- Upper Cretaceous to Paleogene marls;
- Paleogene chalks and marly limestones.

The stratigraphic range of these units is not uniform over the area of northern Jordan and southern Syria. The deposition of carbonate rocks and of fine grained sediments, related to marine north-south transgressions, generally starts at earlier stratigraphic stages in the north.

Miocene to Recent deposits intercalate, in some areas, with basaltic rocks. Neogene to Recent deposits with considerable thickness extend over the Damascus and Azraq Basins at the northeastern and southeastern margins of the basalt field. Pliocene to Quaternary deposits overlying the basalt in limited areas comprise mud pan deposits and volcaniclastics and sediments in wadis and morphological depressions.

The outcrops of major lithostratigraphic units in the surroundings of and within the basalt field are delineated on Map 2 according to a generalized scheme.

Information on the distribution of sedimentary formations has been taken from BGR-WAJ (1994, Map 4: Surface distribution of hydrogeological units), GITEC & HSI (1995), Bender (1975), Ponikarov et al. (1967), Kruck et al. (1981).

Table 4 shows a generalized scheme of Cretaceous, Tertiary and Quaternary lithostratigraphic units.

TABLE 4: LITHOSTRATIGRAPHIC UNITS OF UPPER CRETACEOUS - QUATERNARY SEDIMENTARY ROCKS IN NORTHERN JORDAN AND SOUTHWESTERN SYRIA, GENERALIZED SCHEME

Pliocene - Quaternary:

Mud pan deposits within and on the boundaries of the basalt complex (from ESCWA/BGR 1994 and above cited geological maps);

Volcaniclastics and sediments in morphologic depressions within the basalt complex (ESCWA/BGR 1994);

Pliocene - Quaternary deposits of the Damascus Basin (Ponikarov et al. 1967).

Tertiary:

Paleogene chalk and marly limestone, corresponding to:

- Lower, Middle and Upper Eocene chalk-like limestone and marl (Ponikarov et al. 1967);
- Umm Rijam (B4) and Wadi Shallala (B5) Formations (BGR-WAJ 1994, GITEC & HSI 1995);
- Ts1 and Ts2, Limestone with chert layers or chert concretions (Bender 1975).

Upper Cretaceous - Tertiary:

Upper Cretaceous to Paleocene marls, corresponding to:

- Maestrichtian - Paleocene marls and limestones (Ponikarov et al. 1967);
- Muwaqqar Formation (B3, BGR- WAJ 1994);
- Ks3, Campanian - Danian chalk, marl, bituminous limestone Bender 1975).

Upper Cretaceous:

Upper Cretaceous limestones and dolomites, corresponding to:

- Cenomanian - Turonian (-Campanian) limestones and dolomites (Ponikarov et al. 1967);
- A7/B2 Unit: Wadi as Sir Limestone Formation, Wadi Umm Ghudran Formation, Amman Silicified Limestone, Al Hisa Phosphorite Formation (BGR- WAJ 1994);
- Ks2, Cenomanian - Santonian limestone, sandy limestone, dolomite (Bender 1975).

Upper Cretaceous chalk - marl (Ajloun Formation), corresponding to:

- A1-A6 Unit, Lower Ajloun Group (BGR- WAJ 1994).

The thickness distribution of Upper Cretaceous to Quaternary sedimentary units can be inferred as follows:

Pleistocene - Quaternary: The filling of unconsolidated deposits reaches several hundred meters in the Damascus Basin and up to 100 m in the Azraq Basin. Sediments in wadis and mudflats are generally a few meters to some tens of meters thick.

Paleogene chalk and marly limestone: The thickness of Paleogene chalks and marly limestones is around 260-300 m north and northwest of the basalt field (Palmyrean mountains, Damascus Basin), 110 m east of the basalt field (Juwef area in southern Syria) and 0-220 m in northern Jordan east and west of the basalt field. In the Yarmouk Valley area, the unit is prevailingly represented by marly sediments. On the eastern extension of the Ajloun Dome, the unit is missing.

Upper Cretaceous to Paleocene marls: The thickness of the marl sequence is reported as 110-270 m in the Southern Palmyrian mountains north of the basalt field, 270- >360 m in the southern Yarmouk basin, and 84-200 m in northern Jordan east of the Yarmouk basin.

Upper Cretaceous limestones and dolomites: The thickness range of the formation was reported as follows:

400 m in the Southern Palmyrides north of the basalt field;
200 m in southwestern Syria increasing to >1000 m in the Anti-Lebanon Mountains;
150 m east of the Jebel el Arab;
390 m in the Yarmouk area;
72-320 m in northern Jordan, up to 450 m in the Yarmouk river - Ramtha area.

3.3 TECTONIC FRAMEWORK AND GEOLOGICAL STRUCTURE

3.3.1 Geotectonic aspects of the Basalt Complex

The basalts of the Northern Arabian Volcanic Province appear related to the regional volcanic activity accompanying the tectonic events of the development of the Red Sea graben during the Tertiary to Quaternary. Volcanic rocks extend over considerable areas in a general NW-SE direction along the eastern shoulder of the Red Sea graben on the Arabian Peninsula.

The tectonic frame of the Neogene and Quaternary basalt field of the North Arabian Volcanic Province is dominated by two tensional systems: a NW-SE system which appears related to the emplacement of basaltic magma during the Neogene, and a NNW-SSE system connected to the Quaternary volcanism. The Neogene NW-SE direction corresponds to the general trend of the basalt extrusions which accompany the Red Sea graben and extends, shifted by about 200 km to the northeast from the Red Sea volcanics, along the eastern flank of the Wadi Sirhan and Azraq Basins into the Damascus Basin.

The entire basalt area is situated in a tectonic frame which is related to the pivot of the NNE-SSW trending Arab-Jordan rift valley system and the NW-SE trending Wadi Sirhan depression.

The Neogene basalts originated from fissure fillings which are connected to major NW-SE and minor E-W trending faults. On the surface, the fissure fillings appear as Neogene basaltic dikes (Ndk). The major NW-SE direction, indicated by the Abu Hussein Fault and the parallel striking fissure fillings in the basalt field, is probably related to tectonic movements of the depression of the Wadi Sirhan syncline. The fissure fillings (Ndk) are predominantly oriented parallel to the depression structure. The Late Cretaceous Fuluk Fault Zone is considered as a northwestern continuation of the Wadi Sirhan graben structure. The Fuluk fault system possibly continues below the basaltic cover west of Jebel el Arab in the area between Bosra and Deraa, but no information is available on the structure of the basalt base in that area.

The magmatic activity of Tertiary appears related to a reactivated fault-system of a Cretaceous NW-trending fault pattern. Probably, the Neogene basalt extruded as an isostatic balance to the vertical dislocation of large continental masses related to the deposition of large amounts of sediments in the area of the Wadi Sirhan basin and in its northwestern prolongation (Fuluk Fault Zone and Hamza Graben).

The Quaternary basalts are linked to two parallel NNW-SSE trending major lineaments (Jebel el Arab and Tell As-Safa). Numerous chains of volcanic cones are arranged parallel to the lineaments. The NNW-SSE trending lineaments may belong to a Pliocene/Pleistocene tensional fracturing which resulted in basaltic extrusions during the Pleistocene. Due to the thick sedimentary cover south and northwest of the volcanic field this tectonic pattern is hidden. Probably, the tectonic direction is related to the Red Sea event of Pliocene/Pleistocene time. Comparable basaltic eruptions are described from the eastern rift shoulder in Saudi Arabia. East of the Jebel el Arab numerous NE-SW and E-W trending short faults reflect a local tectonic pattern which is related to a vertical displacement of the eastern basalt plateau to a lower level along a NNW-SSE trending fault system. The resulting relief is filled by Quaternary lava flows which also reflects a major drainage system. The NNW-SSE tectonic direction dominates the major feeder zone for the Quaternary lava series.

3.3.2 Structure of the Basalt Base

Information on the position of the basalt base is available from BGR-WAJ (1994, Map 11), Krasnov et al. (1966), ACSAD (1983), Selkhozpromexport (1982) and borehole logs of WAJ. Relatively reliable information exists, in general, only for the southern part of the basalt field (Chapter 3.1.6).

The basalt sequence rests apparently over most of its extent on the Paleogene chalk formation, with some exceptions: In the southwestern part of the basalt field near Hallabat, basalts overlie Upper Cretaceous deposits. In the northwest of the basalt field at Kisweh, basalts overlie Miocene marls.

A maximum thickness of around 1500 m is assumed for the basalt sequence in Jebel el Arab (Krasnov et al. 1966: 19, 21). The paleo-relief covered by the basalt flows is largely unknown and not reflected in the map. For construction of the basalt base, a relatively smooth paleo-relief was assumed schematically, dipping radially towards the Jebel el Arab area to elevations around 200 m asl. It can be expected that the contact between basalts and sedimentary rocks is highly disturbed below the mountain area of Jebel el Arab, which comprises the main feeder zone of Neogene basalts.

3.3.3 Structural features of the sedimentary frame of the basalt field

A structural map of the base of the Paleogene chalk formation (Map 13) was compiled using information from BGR-WAJ (1994, Map 9), GITEC & HSI (1995, Fig. 5.15), ACSAD (1983), Technoexport (1961).

The frame of sedimentary formations surrounding the basalt field is dominated by structural highs in the east and west: the Rutba uplift and the Jordan uplift. The Wadi Sirhan - Azraq synclinal structure constitutes a major structural low between the two uplifts. In the northwest, the basalts extend into the young tectonic depression of the Damascus Basin. On its northern margin, the basalt field approaches the anticlinal Palmyrean chains, which are apparently related to a different tectonic system.

In the west of the basalt field, the structure of the sedimentary sequence underlying the basalts appears influenced by the eastern extension of the Ajloun dome and the synclinal element of the Yarmouk Basin. Detailed information on structural features in these areas is not yet available.

The structural map constructed is based on very limited information and indicates the following features: The base of the Paleogene chalks shows synclinal structures in the area between Zelaf and Safawi (east of Jebel el Arab) and in the northwest of the study area with a dip towards the Damascus Basin. The synclinal structures coincide approximately with morphological depressions in the present topography: wadi between Jebel el Arab and Tulul al Ashaqif, Damascus Basin.

An anticlinal structure is indicated in the southwest of the area where the Paleogene is eroded. Upper Cretaceous deposits extend in outcrops in the area around Mafraq - Zerqa and are underlying directly the basalt flows east of Mafraq. The Fuluk fault system appears to have a major impact on the structural contours of the base of Paleogene with a considerable uplift to the southwest of the fault system.

Relationships between other major fault systems and the configuration of the structural contours of the Paleogene base are indicated but cannot be identified in detail from present information.

4. HYDROLOGY

The text presented in this chapter introduces briefly the prevailing patterns related to rainfall, evaporation and surface water resources within the study area. Most of the information and data used to evaluate the hydrologic set-up were obtained from the files of the WAJ and the published and unpublished reports on the hydrologic cycle components prevail in the Syrian part of the study area.

4.1 DRAINAGE

A generalized network of major wadis and mud pans is shown on Map (4), which was prepared from information taken from digital files of Water Authority of Jordan, existing topographic maps and the outcome of satellite images interpretation.

The map shows the main surface drainage systems as follows:

- Westward drainage to the Yarmouk and Zerqa river systems;
- Internal drainage to closed basins: Azraq, the Damascus Basin (former lakes Hijane and Ateibe), seasonal lakes around Braq (Wadi Liwa, Wadi el Fakhta) between the Yarmouk and Damascus Basins, mud flats within the basalt complex (Zelaf) and on the eastern margin of the basalt outcrop.

Several non-perennial streams and wadis are draining the surface runoff from over the basaltic region in both Jordan and Syria. The major drainage areas comprising the study area are those of the wadis: Al-Dahab, Al-Botom, Al-Zeidi and Wadi Al-Khanafes in the north and east of the Yarmouk basin. On the west of Damascus-Deraa Road, Wadi Hreer, Wadi Allan and Wadi Raggad drain the basalt region towards the Yarmouk river on a perennial bases and furnish a major component of the river base flow. The southern part of the study area encompasses the main drainage areas of Wadis: Rajil, Useikhim, Mushash, Hassan, Erratam, and Al-Botom in Jordan.

4.2 RAINFALL

Thunderstorm rainfalls are responsible for most of the precipitation in the study area especially in October, November, April and May. They are characterized by irregularity in intensity and duration. In spite of the prevailing thunderstorms, cyclonic rainfall may reach the area particularly in December, January, February and March. These cyclones cross the Mediterranean Sea and bring cold masses from Europe and form the major precipitations in Jordan and Syria in general.

Precipitation stations are distributed over the three drainage basins underlain by the Basalt Regional Aquifer System, namely the Yarmouk sub-basin in Syria and Azraq and Amman-Zerqa Basin in Jordan. It is worth noting that a major part of the latter basin and Yarmouk sub-basin are underlain mainly by deep carbonate-sandstone aquifer systems that belong to other regional aquifer systems in Jordan.

Average annual or monthly precipitation could be estimated in the Syrian part of the aquifer system using the data compiled from 8 meteorological stations and 22 rainfall stations. These stations are evenly distributed over the watersheds of 4 major wadis, which may allow for estimates of the main components of the hydrologic system. The distribution of these stations within these wadi drainage areas is shown in table 5.

TABLE 5. RAINFALL AND STREAM GAUGING STATIONS IN YARMOUK BASIN (SYRIA)

Catchment	Drainage area (km^2)	Rainfall stations	Dates established	Stream gauging stations
Wadi al Raggad Wadi al Allan	535	7	1959 1966	2
Wadi El Hreer	2550	9	1958 1966	2
Wadi al Dahab	820	8	1959 1960	1
Wadi al Zeidi	146	6	1958 1966	1

The rainfall survey network in Azraq basin consists of 10 daily raingauges, 11 rainfall totalizors and 6 rainfall recorders (Table 6). The evaporation survey network is composed of two evaporation stations one at Azraq in the Qa' Azraq area and the other about 45 km northeast at Safawi (H5). A runoff survey network does not exist in the basin, making it necessary to use empirical formulae to estimate the runoff data.

TABLE 6. PRECIPITATION NETWORKS IN THE AZRAQ, ZERQA AND YARMOUK BASINS IN JORDAN

Basin	Number of rainfall stations		
	Recording	Non-recording	Total
Azraq	16	11	27
Zerqa	7	36	43
Yarmouk (Jordan part)	5	22	27

Based on the information obtained from the available regional maps and from reports, the isohytal map 5 was constructed for the study area. The map shows the general pattern of the mean annual precipitation over the area. It shows relatively high rainfall on Jebel el Arab up to >500 mm/a (rainfall and snow) and in the western part of the area where it is influenced by the Herman mountain. A rapid decrease of rainfall towards east and south with a mean annual precipitation of >60 mm is observed in the southern part of the area. No evaluation of rainfall data from the existing meteorological stations was made for the preparation of the map. The rainfall pattern does not reflect precipitation over any particular period of years. A rough estimate of the mean annual rainfall volume over the study area could be computed from the constructed isohytal map and found to be about 3570 MCM. Rainfall averages in the Azraq basin in Jordan range between 541 MCM in dry years, 1100 MCM in average years and 1600 MCM in wet years. These estimates are based on the evaluation of the data from four daily rainfall stations within the study area in Jordan, No estimates could be made from the available meteorological data on the Syrian part of the study area.

Over the total area of the Yarmouk basin in Syria, the mean annual rainfall volume was estimated at about 3146 MCM of which 1930 MCM is the estimated volume of rainfall over the Syrian part of the study area (Ghadban 1989).

4.3 EVAPORATION

Times series of pan evaporation and data required for the estimation of evaporation is available and fairly reliable in the different areas underlain by the Basalt Aquifer System in Syria and Jordan.

In the Syrian part (Yarmouk Basin) there are three evaporation stations (Tell Chehab, Salkhad, Suweida, table 2). However, they are not uniformly distributed over the basin.

In the Azraq basin there are two evaporation stations [Azraq town and Safawi (H5) stations]. The density (6000 Km^2 per station) is considered adequate according to World Meteorological Organization (WMO) standards. Potential evaporation was estimated by using Penman equation. The highest annual evapotranspiration rate was found to be around 1980 mm in the H5 station and the lowest is about 1700 mm. The evaporation network is also satisfactory in the Amman-Azraq basin.

The mean annual evaporation in the Azraq basin from free water surface is about 3877 mm with monthly values ranging between (450-590) mm in summer and (105-400) mm in winter. In Syria and as recorded from the three stations mentioned above, the mean annual evaporation from soil surface was estimated at (230-290) mm in the plain areas and about (300-350) mm in the mountainous areas. The mean annual potential evaporation ranges from 1240-1490 mm in the Yarmouk basin (Syria) and increases eastwards from Jebel el Arab area.

4.4 SURFACE WATER

Most of the streams in the study area are ephemeral or intermittent that are subject to flash floods (wadi-system). Wadi flow depends on a number of factors, the amount duration and intensity of precipitation, evaporation, permeability of the wadi fill and bad-rock, the size and nature of the drainage basin. In the north, in Syria flow occurs during a period that ranges from 3 to 4 months in Wadi Al-Dahab, Wadi Al-Zeidi and from 4 to 5 months in Wadi Al Raggad and 6 months in Wadi Al Allan. In summer (April-May to November-December) the flow usually ceases except for isolated periods of runoff that result from short intense thunderstorms. The flow in all wadis, except in Al Hreer, is caused by intense rainstorms in winter or spring time and to a limited extent by snow-melting. Groundwater, however, contributes remarkably to the flow of Wadi Al Hreer. The base flow in this wadi is estimated in the order of 3 m^3/s.

In the Azraq basin wadis drain water into the Azraq Playa (Qa' Azraq) where it may remain several months before evaporation. All wadis are ungauged and flow was estimated by applying the "curve number method" developed by the United States. Soil Conservation Service (SCS). Mean annual rainfall was estimated at 1100 MCM or 87 mm as mentioned earlier.

The hydrological observation network of the Syrian part consists of 6 gaging stations (table 6) and observation of 40 springs.

In the Zerqa Basin, eight stations are in operation near the mouths of wadis, two of them were installed in Wadi Dhuleil.

The annual and average runoff volume over the Azraq basin estimated using empherical formula mentioned above was: 35.9 MCM, 13.5 MCM and 1.3 MCM for wet, normal and dry years respectively. The long-term mean annual runoff volume was estimated at 24 MCM for the period (1965-1994), (E. Qanqar 1996).

No flood estimates were made in the Syrian part of the study area particularly to the east of Damascus-Deraa road, as no information was made available.

Surface water resources of the area are primarily originated from the stored surface water resources behind the existing dams and the springs water contributing to the Yarmouk river base flow and the Azraq basin springs in Jordan.

Several small dams were constructed in the basalt region in Syria to make use of the flash floods in the area. Six small earth dams have been constructed in Yarmouk, Zerqa, Azraq and Hamad basins in Jordan. Tables 7 and 8 show the existing dams in the study area. (Fig.3)

TABLE 7. EXISTING DAMS IN THE SYRIAN PART OF THE STUDY AREA

No.	Name	Storage MCM	Use	Mean annual rainfall
1.	Al Ain	1.35	Domestic	275
2.	Hibran	1.95	Domestic & irrigation	500
3.	Sahwa el Khadr	8.75	Domestic & irrigation	390
4.	Sahwa el Blata	1	Domestic & irrigation	340
5.	Rasas	0.03		450
6.	Al Asliha	0.037	Domestic & livestock	450
7.	Jouelin	0.5	Domestic	400
8.	Rum Jouelin	6.4	Domestic	400
9.	Qanawat	6	Domestic	450
10.	Al Batma	2.1	Domestic	
11.	Al Mataiye	0.6		
12.	Ghudair as Sou	0.16	Livestock	
13.	Qarya Sharqiye	5	Irrigation	
14.	Deraa Sharqy	15	Irrigation	
15.	Athman	0.16	Livestock	
18.	Abta Kebir	3.5	Irrigation	
19.	Abta Saghir	0.5	Irrigation	
32.	Shahba	2	Domestic	400
33.	Al Gheida	2	Domestic	400
34.	At Taybe	2	Domestic	450
35.	Al Meshnef	1.26	Domestic	450
36.	Jebel el Arab	19.5	Domestic	500
37.	Qaysame	0.013	Livestock & domestic	450
38.	Salkhad	0.55	Domestic	400
39.	Khazme	0.2	Livestock	450
40.	Zelaf	9.6	Domestic & irrigation	200

TABLE 8. EXISTING DAMS IN THE JORDANIAN PART OF THE STUDY AREA

No.	Dam name	Sequence # for map	Year constructed	Coordinates		Storage (MCM)	Groundwater basin	Associated aquifer
				East	North			
1.	Khaldiyeh	2	1983	276.550	175.250	1.10	Amman-Zerqa	B2/A7, Basalt
2.	Sama Al Sarhan	8	1963	268.250	209.800	1.70	Yarmouk	Alluvian
3.	Ghadeer Al Abyad	9	1963	264.175	200.700	0.70	Yarmouk	B2/A7
4.	Rajil	14	1993	354.200	137.290	3.50	Azraq	Basalt, alluvian
5.	Ruweished	15	1992	433.200	241.100	10.70	Hammad	Basalt, alluvian
6.	Burq	16	1960	428.600	227.600	1.50	Hammad	Basalt, alluvian

As regards the main springs in the area, there are two groups of springs that form the Azraq Oasis. They are located in the central part of the Azraq basin near the well field area. The first group is Drouz consisting of the Aura and Mustadhema springs. The second group is Shishan consisting of the Souda and Qaisiyeh springs. They are recharged through the same resource within the basalt aquifers. These two groups of springs are now totally dry because of low infiltration rates to the aquifers and overexploitation to provide water for the population of north Jordan (Amman, Zerqa and Irbid). Table 9 shows the natural discharge of the two groups for the period 1981-1991. Natural discharge of the Azraq springs in pre-development conditions was 1.700 m^3/h (mean discharge 1965-75, GTZ-NRA 1977).

TABLE 9. MEAN ANNUAL DISCHARGE FROM THE AZRAQ SPRINGS IN M^3/H

Spring Year Name	81	82	83	84	85	86	87	88	89	90	91
Aura	193.0	179.0	138.3	95.5	82.6	13.5	21.6	5.0	5.7	0.0	0.0
Mustadhema	64.1	78.7	70.4	83.9	15.0	15.0	13.5	0.0	0.0	0.0	0.0
Souda	88.0	274.0	256.3	206.4	144.7	122.3	155.6	67.1	84.8	29.7	0.0
Qaisiyeh	278.0	607.0	550.0	505.6	434.5	256.0	276.7	172.8	140.0	57.7	0.0

Table 10 shows the mean discharge of the main springs existing in Hauran plain in Syria.

TABLE 10. MEAN DISCHARGE OF MAJOR SPRINGS IN THE HAURAN PLAIN (AFTER BAJBOUJ, 1982)

Name	Mean discharge (l/s)	Salinity (g/l)	Mean temperature (°C)	Altitude (m asl.)
Mzeirib area, southwestern part of Hauran Plain				
Mzeirib	1,438	0.3	24.0	439
Zeizoun	782	0.4	24.0	399
Chalalate Hreer	1,396	0.4	24.0	380
Sakhneh el Saghira	178	0.3	24.2	420
Sakhneh el Kabira	329	0.3	24.0	420
Ghasouli	238	0.4	24.5	440
Achaari	250	0.4	24.0	440
Ajani	229	0.3	24.5	
Boudah	112	0.3	24.6	440
Ain Abed	305	0.3	24.0	
Northern part of Hauran Plain				
Um ed Dananir	161	0.2	19	
Thouraya	98	0.2	19	572

5. HYDROGEOLOGY

A good deal of previous hydrogeologic investigations were carried out individually by the competent authorities in both countries: Jordan and Syria. These studies encompassed the Basalt aquifer system as well as the underlying carbonate aquifers which occur in the study area, aiming at increasing the respective knowledge about the countries' water resources in order to plan for further groundwater exploitations to meet their respective water demands.

Upon reviewing these studies and assessing, evaluating and correlating the data and information which were made available from both countries, it can be stated that the major aquifers which exist in the study area are the following:

5.1 MAIN AQUIFERS

The sequence of Upper Cretaceous to Recent sedimentary and volcanic rocks comprises major aquifer sections in the following units:

- Upper Cretaceous limestones and dolomites: A7/B2 aquifer in Jordan, Cenomanian-Turonian limestone and dolomite aquifer in Syria;
- Paleogene chalks and marly limestones: Umm Rijam (B4) and Wadi Shallala (B5) aquifers in Jordan, Eocene chalk aquifer in Syria;
- Various horizons with relatively high permeability within the basalt sequence.

The Upper Cretaceous - Paleogene marls (Muwaqqar Formation, B3 in Jordan, Maestrichtian - Lower Eocene marls in Syria) constitute an extensive aquitard between the Upper Cretaceous and Paleogene aquifers.

Paleozoic to Lower Cretaceous formations underlying the basalt field at greater depth can be assumed to contain limited quantities of non-renewable brackish groundwater.

Sections with relatively high productivity in the basalt sequence appear related to:

- the lower part of Quaternary to upper part of Pliocene volcanics in the Hauran plain (Ezraa - Deraa area);
- parts of the Neogene and Quaternary basalts in the foothills of Jebel el Arab around Suweida and in Wadi Liwa and the Leja plateau northwest of Suweida;
- the lower part of the basalt sequence, mainly Neogene basalts, forming a joint aquifer with Upper Cretaceous limestones and dolomites in the Hallabat - Wadi Dhuleil area, the northeastern desert in Jordan and with Paleogene chalks in the Azraq area.

Aquiferous horizons in the basalts with low to moderate productivity are found in wide parts of the basalt field. Of particular local importance are numerous aquifers of limited extent in Neogene and Quaternary basalt of Jebel el Arab.

East of Jebel el Arab, the basalts appear to constitute a regional aquifer of generally low productivity which is hydraulically connected to the underlying Paleogene chalk aquifer. An aquifer with moderate productivity has been explored in the Wadi esh Sham - Zelaf area. Similar wadi aquifers may exist in other areas within the basalt field.

5.2 HYDRAULIC PROPERTIES AND GROUNDWATER MOVEMENT

5.2.1 General hydraulic aspects of the basalt aquifer system

Outlines of the knowledge on hydraulic features of basalt aquifers are given in several references: Domenico & Schwartz (1990:28-28, 70, 255-259), Freeze & Cherry (1979:158-163), Matthess & Ubell (1983:236-243).

Basalt aquifers are, in general, characterized by hydraulic anisotropy and discontinuous heterogeneity. Large contrasts exist in hydraulic conductivity of basalt aquifer systems. Relatively high permeabilities and preferential pathways are related to the boundary layers between individual basaltic flows and to joints and fractures resulting from cooling and tectonic stress.

Lava flows form, after cooling, a solid mass with a coarse crust at the top. Blocky rock masses on the upper surface of lava flows, which are frequently associated with detrital stream deposits, produce a relatively high bulk porosity in most young basalts. Additional differentiations of permeability along boundaries of lava flows may be caused by buried soils and weathering at the top of basalt flows.

Porosity can be high in vesicular lava flows (10-50 %) but the effective porosity is generally less than 1 % in the solid lava flows. Permeabilities of volcanic rocks range from very low values to 10^{-2} m/s. Young basalts have generally a higher permeability than older flows, where permeability is decreased by alterations related to weathering and deep burial and to the influx of cementing fluids.

The main components of groundwater movement in the basalt aquifer system in Jordan and Syria may be described schematically as follows:

- high horizontal flow along the tops of individual basalt flows;
- low vertical leakage through the interiors of basalt flows;
- leakage (vertical flow) along structural discontinuities (fractures and fissures caused by cooling and tectonic stress).

Another general aspect to be considered in the study of the basalt aquifer system in Jordan and Syria is the occurrence and movement of groundwater in mountainous terrain, as altitude differences between main recharge and discharge areas reach up to 1300 m.

In mountainous terrain, the "water table may be considered a free surface whose depth and configuration depends on the interplay between infiltration and permeability distribution" (Domenico & Schwartz 1990:70). Where low-permeability materials alternate with higher-permeability units, downward percolating water in the unsaturated zone may become perched on low-permeability units (Domenico & Schwartz 1990: 28-29).

5.2.2 Information on hydraulic properties of the basalt aquifer system

The basalt complex consists prevailingly of single sheet lava flows. The thickness of individual flows is reported to vary from 3 to 25 m, on average 5 to 7 m. The central parts of the basalt flows are generally constituted by well crystallized massive varieties, the upper and lower parts by coarse bubbled basaltoids. Up to 50% of individual flow sheets may be represented by porous varieties, but the pores are only to a limited extent interconnected. Permeable horizons occur prevailingly on the boundary zones between different basalt flows. Vertical hydraulic interconnections between these horizons are created by cooling or tectonic fractures.

In general, the permeability in the basalt aquifer system may decrease with depth. Water levels at more than 300 m below land surface in boreholes with significant well yields indicate, however, that productive aquiferous horizons extend to several hundred meters depth below surface. Data of hydraulic parameters of the basalt aquifer system are limited. The following information on transmissivity values, all obtained from single well tests, is available for different areas of the basalt aquifer:

Syria (Bajbouj 1982):

Basin Leja - Khil 150 - >10,000 m^2/day
Leja Plateau >1000 m^2/day
Seida, Khil, Alma >1500 m^2/day
Dael >10,000 m^2/day
West of Ibta - Cheikh Meskin - Izra Transmissivity decreases

Jordan: 2 - 44,000 m^2/day (WAJ files, Gibbs 1993). An evaluation of the data has still to be made.

Data of well yield (in m^3/h) and of specific capacity of wells (well yield divided by drawdown: m^3/h/m or m^2/h) are available from digital files of WAJ and from data lists and documents provided by the Department of Irrigation and Water Resources, Syrian Arab Republic. Well yields may not directly reflect hydraulic aquifer properties but depend, to a large extent, on well design, pump capacity and water requirements. Specific capacity values, too, are influenced by the technical design of wells. In highly inhomogeneous aquifers like basalt aquifers, high variations of hydraulic properties (permeability, transmissivity, storage coefficient) have to be expected.

Map 8 shows ranges of well yields and specific capacity.

Wells have, in general, relatively high yields and specific capacities in the Azraq and Wadi Dhuleil areas and in the northern desert of Jordan east of Mafraq: well yields above 40 m^3/h median values of Q/s 32 to 39 m^2/h. In these areas, the basalt and underlying Cretaceous limestones and dolomites or Paleogene chalks constitute a combined aquifer system. The relatively high well yields may be related to a rather high transmissivity of the aquiferous complex with a considerable thickness of carbonate rocks.

In the western part of Wadi Dhuleil and the northwestern part of Jabal el Arab, highly varying well yields are reported: < 10 -- > 40 m^3/h. In the western Wadi Dhuleil area, the basalt constitutes only a thin top section of the aquifer complex constituted mainly by Cretaceous limestones and dolomites. The median Q/s value is moderate with 11 m^2/h.

The northwestern part of Jebel el Arab comprises a complex sequence of aquiferous sections within the basalt with one or two perched aquifer zones above the main basalt aquifer with locally high well yields. Well yields and specific well capacities are low to moderate in the area west of Jabal el Arab (Deraa - Ezra - Bosra). From a number of wells, zero drawdown is reported, indicating relatively high specific capacities.

A comparison of values of specific capacity and aquifer transmissivity available from boreholes in northeastern Jordan (78 data points, leads to the identification of the relationship shown in Fig.4).

- Q/s versus T relationships for data of main aquifers (basalt, carbonate aquifers, Alluvium) scatter, in a rather wide range of variation and with few outliers, around a best fit line of:

$$\text{Log } Q/s = 2.2 + 0.526 \times \text{Log } T \pm 0.07$$

- Values from wells tapping basalt aquifers or basalt and underlying carbonate aquifers are, on average, relatively high.

Horizontal groundwater flow within the basalt aquifer system is generally restricted to horizons with significant permeability on the boundaries of individual lava flowsheets. These horizons may comprise about 10-20% of the total saturated thickness of the basalt aquifer. Assuming permeable layers over 20% of a saturated thickness of 100-300 m, T values of 1000 m^2/d would correspond to permeabilities of $2x10^{-4}$ to $6x10^{-4}$ m/s. From the mean Q/s values ranging from 1 to 40 m^2/h for different areas of the basalt aquifer system (Map 8), transmissivities of about 30 to 1300 m^2/d would be expected. In the areas where the basalts form hydraulically connected aquifers with underlying carbonate rocks, the relatively high well capacities may be related to a high transmissivity of the carbonate aquifers. Further evaluations are required to find explanations for the obvious inconsistency of hydraulic data available for the basalt aquifer system.

5.2.3 Groundwater levels

Information on groundwater levels is available from:

Digital files of WAJ;
Groundwater contour maps: GTZ & NRA 1977, GITEC & HSI 1995, ACSAD 1983, draft maps of WAJ;
Data lists, reports and documents provided by the Department of Irrigation and Water Resources, Syria.

Water levels within the regional basalt aquifer system are related to different types of hydraulic settings:

- water levels of a main basalt aquifer system, in which hydraulic heads represent the water table of regional groundwater movement towards major discharge areas;
- water levels at shallow to intermediate depth (between 0 and 200 m below surface), which are, in a specific area, situated at significantly higher elevation than water levels of the main basalt aquifer system;
- water levels of basalt aquifers and hydraulically connected underlying sedimentary aquifers: Paleogene chalk or Upper Cretaceous limestone and dolomite aquifers.

Water levels of shallow or intermediate aquiferous zones in the basalt complex extend, in particular, over the following areas:

- the mountain area of Jebel el Arab which comprises a complex system of perched aquifers in different basalt flows; the perched aquifers discharge in numerous springs at altitudes between 1000 and 1600 m asl.;
- the slopes adjoining Jebel el Arab to the west including the Leja Plateau, where extensive occurrences of perched groundwater have been explored at depths of 50 to 200 m below land surface; its water levels are situated 100 to 200 m above the water level of the main basalt aquifer system;
- in various parts of the Deraa - Ezra area at depths of <50 m below land surface;
- in the Wadi esh Sham - Zelaf area east of Jebel el Arab (depth to groundwater <50 m);
- in the eastern part of the basalt region: at various locations water levels related to aquiferous zones in the basalt or in Paleogene chalks are situated several meters above the regional water table.

Shallow and intermediate aquiferous zones occur in particular in areas with relatively favorable recharge conditions and with extensive sheet lava flows. The Neogene and Quaternary shield basalts comprise layers with relatively high permeability on the boundaries of successive lava flows, which may extend over several tens of km^2. The poorly developed drainage system on the surface of most of the shield basalt complexes indicates relatively high infiltration rates of precipitation. The following relationships between occurrence of shallow to intermediate aquifers, recharge conditions and extent of lava flows are evident:

- Jebel el Arab mountain area: relatively high precipitation and thick succession of Neogene shield basalts;
- Jebel el Arab foothills at Suweida - Shahba and Leja plateau: extensive Quaternary shield basalts, probably favourable infiltration conditions on the broken surface of Middle Quaternary basalt sheets (Leja plateau) and of surface runoff of Wadi Liwa;
- Wadi esh Sham - Zelaf: Neogene shield basalts, indirect recharge of runoff in extensive wadi system.

No extensive shallow or intermediate aquifers are reported from the areas covered by Quaternary valley filling lava flows, e.g. south and southwest of Jebel el Arab. Individual lava flows of this unit have, in general, limited lateral extent within a pre-existing morphological relief. The well developed surface drainage system indicates a predominance of surface runoff and limited infiltration rates from precipitation.

Depth to groundwater in the main basalt aquifer system (Map 7) ranges from less than

50 m in the morphological depressions of the Yarmouk river basin near Mzeirib, the Azraq Basin and Manqaa ar Rahba near Zelaf and increases to more than 300 m in the mountain areas around Jebel el Arab and Tulul al Ashaqif. In some boreholes on the slopes of Jebel el Arab, water levels are situated at more than 500 m below land surface.

5.2.4 Groundwater movement

Groundwater movement directions are inferred from groundwater contours which have been constructed from available water level data and existing groundwater contour maps of parts of the study area (Map 6):

Digital files of WAJ;
Groundwater contour maps: GTZ & NRA 1977, GITEC & HSI 1995, ACSAD 1983, draft maps of WAJ;
Data lists, reports and documents provided by the Department of Irrigation and Water Resources, Syria.

The contours indicate:

- the generalized altitude of the water table of shallow to intermediate perched aquifers;
- the water table of the main basalt aquifer.

The contours of perched aquifers do not represent a continuous water table. The location of aquiferous horizons in the mountain area of Jebel el Arab is determined from the topography and the sequence of layers with different permeability within the basalt flow sequence.

In most areas with high density of observation points, significant variations of water level values (in m above sea level) are found. These variations may be attributed to:

- inaccuracy of data, in particular inaccuracies of the determination of topographic elevation of the surface (estimations from topographic maps);
- time dependent fluctuations of water levels: available water level data represent random observation over a time span of several years; the water level recordings may be influenced by seasonal or annual water level fluctuations or by water extraction within observed wells or from wells in surrounding areas;
- local inhomogeneities within the basalt aquifer system.

In view of the above, the following approach was used in the preparation of the water level contour map: In areas with variations of water level data in the range of a few meters, average values were considered. Deviations of 5 m or more from the water level of the main aquifer system were ignored (deviations of isolated points) or considered as levels of local or extensive perched aquifers (deviations of groups of observation points).

The basalts in the mountain area of Jebel el Arab comprise a great number of local flow systems which discharge in numerous small springs on the mountain plateau and the western mountain slopes at levels between 1000 and 1600 m above sea level. Perched aquifers in some areas apparently leak into deeper ones in west to northwest of Suweida, the

Hauran plain, the eastern part of Jebel el Arab and in the Wadi esh Sham - Zelaf area.

The main basalt aquifer extends over flow systems of four major groundwater basins: Yarmouk, Zerqa, Azraq and Hamad. Hydraulic gradient in the water table of the main basalt aquifer ranges from 0.5 to 8%.

In the upper Yarmouk groundwater basin, subsurface flow is directed to the discharge area at Wadi Hreer - Mzeirib, comprising a number of springs at altitudes between 400 and 450 m asl. with a total mean discharge of around 5.4 m^3/s. The springs rise mainly on the base of the basalt sequence at the contact with underlying Paleogene sedimentary rocks with low permeability. Quantitative aspects of groundwater movement in the upper Yarmouk basin are discussed in Chapter 5.4. The Yarmouk groundwater basin extends in the north and northeast into the area of internal surface drainage around Braq - Mesmiyeh (Wadi al Liwa) and probably also into the southeastern part of the Damascus Basin.

In the Hallabat - Wadi Dhuleil area, the basalt forms a joint aquifer with the underlying Upper Cretaceous limestones and dolomites. Groundwater moves westward through the deeper carbonate aquifer into the Wadi Zerqa area.

Natural groundwater flow in the Azraq Basin is directed towards the springs area in the Azraq plain, a morphological depression of tectonic origin. The depression, situated at around 500 m asl., acts as discharge area of groundwater from the basalt and the underlying Paleogene aquifer. The springs have dried up because of the extensive groundwater extraction in the Azraq basin.

In the northeastern and eastern parts of the basalt field, groundwater levels in the basalt aquifer appear to be connected to a regional eastward groundwater movement in the underlying Paleogene chalk aquifer. This eastward movement of prevailingly fossil groundwater in the Hamad area is considered as part of the regional groundwater flow towards the Euphrates - Gulf Basin. In the north of the basalt field, eastward subsurface flow from the Damascus Basin into the Hamad area is indicated (Hijane area).

5.3 HYDROCHEMISTRY

5.3.1 Availability and presentation of hydrochemical data

Data of groundwater salinity and hydrochemical analyses are available from:

- Digital files of Water Authority of Jordan (WAJ);
- data lists and documents provided by the Department of Irrigation and Water resources, Syrian Arab Republic;
- reports and publications: Kattan (1995), Almomani (1993, 1994a, 1994b, 1995), ACSAD (1983), GITEC & HSI (1995), Rimawi (1985), Rimawi & Udluft (1985), Drury (1993), Kharabsheh (1995).

A total of 268 water analyses has been included in the evaluation (224 analyses from Jordan, 46 analyses from Syria). For each well in the Jordanian part of the study area, the most recent analysis stored in the WAJ data bank was selected. Dates of sampling of the evaluated analyses ranges from 1981 to 1992.

The evaluations aimed at a general characterization of groundwater hydrochemistry in different areas of the basalt aquifer system, based on concentrations of major dissolved ions. No attempts were made to identify local horizontal or vertical variations of groundwater quality.

Analyses of minor and trace elements are available for very limited areas only (e.g. Drury 1993) and were not considered in the evaluation.

The hydrochemical data of different areas of the basalt aquifer system are presented in Piper diagrams (plot of relative ion contents), Schoeller diagrams (logarithmic plot of ion concentrations) and maps of concentration ranges of major ions. For preparation of the diagrams, the programmes Ground Water for Windows, QuattroPro, Statgraphics and Surfer were used.

A statistical comparison of ion concentrations of samples from different areas is presented in box-and-whisker plots (Fig.14, Fig.20). The box-and-whisker plots (Statgraphic software) divide the selected data set into four areas (quartiles) of equal frequency (Fig.6): A box encloses the middle 50 percent of the data, divided by a line inside the box representing the median. Vertical lines - whiskers - extend from each end of the box to mark the ranges of the upper and lower quartiles, except for extreme data points. Extreme data points are shown as outliers. The statistical mean is shown as a cross.

5.3.2 Distribution of groundwater salinity

Groundwater salinity as shown on Map 9 is generally low to moderate in the basalt aquifer system west and south of Jebel el Arab. Water from springs and boreholes in the shallow and intermediate basalt aquifers of Jebel el Arab and the Suweida - Shahba areas generally has a salinity of less than 250 mg/l. In the main basalt aquifer system between Jebel el Arab, a major recharge area, and the discharge areas at Mzeirib and Azraq, groundwater salinity ranges, in general, from 200 to 400 mg/l.

Higher groundwater salinity occurs in several areas:

- in the southwestern fringe of the basalt outcrop between Azraq, Wadi Dhuleil, Mafraq and Deraa. Some of the production boreholes pump water with elevated groundwater salinity. In Wadi Dhuleil, salinities up to 6000 mg/l of TDS are observed. The sources of the high groundwater salinity in these areas are discussed in Chapter 5.3.4;

- in the northwestern part of the basalt area, groundwater salinity ranges up to 1000 mg/l. The elevated salinity appears partly caused by subsurface inflow from the Damascus Basin. The source of elevated salinity observed in several patches in the area between Suweida and Ezraa has to be further investigated;

- in the eastern part of the basalt region (northeast and east of Jebel el Arab), groundwater salinities are generally in a range between 1000 and 1500 mg/l of TDS.

Lower salinities are found in shallow groundwater in the Wadi Sham - Zelaf area (100-1000 mg/l), where recent recharge occurs from infiltration of wadi runoff. Similar conditions possibly exist locally in the area around Safawi (H5);

- in the southeastern part of the basalt area, high groundwater salinity (1500 - 6000 mg/l) prevails. Most of the groundwater with elevated salinity appears to be related to the Paleogene chalk aquifer underlying the basalt.

5.3.3 Hydrochemical processes in the basalt aquifer system

Contents of substances dissolved in the groundwater of the basalt aquifer system are, under natural conditions, prevailingly derived from:

- atmospheric inputs;
- reactions in the soil zone (pedogenic inputs);
- evaporative enrichment at or near the surface during the recharge process;
- lithogenic inputs: reactions with rock material within the aquifer or the overlying unsaturated zone.

The contribution of atmospheric input to dissolved substances in the groundwater can approximately be estimated from chemical analyses of rainwater from stations in Jordan and Syria (Salameh et al. 1991, Kattan 1994). Mean values of anion concentration are shown in Fig. 7. The rainwater samples from Jordan have, in general, higher concentrations of HCO_3, SO_4 and Ca than samples from stations in Syria. These differences are probably related to the more arid conditions and higher dust content at the Jordanian stations, which are located within or near outcrops of carbonate rocks.

The impact of atmospheric inputs is discussed in Chapter 5.3.4 on the example of the Jebel el Arab area.

Dissolution of soil and rock material in basalt lithology is related, in particular, to reactions of biogenic CO_2 produced in the soil zone with water and silicate minerals and with carbonate deposited from precipitation or dust. These reactions lead to moderate contents of HCO_3 and equivalent cations. The reactions between silicate minerals, water and soil CO_2, which supply lithogenic components to the groundwater, can be formulated schematically on the example of plagioclase dissolution as follows (Appelo & Postma 1993: 204):

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^-$$

$$CaAl_2Si_2O_8 + 2H^+ + H2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+}$$

Ca and HCO_3 go into solution while aluminum silicates (Kaolinite) remain as weathering products. Depending on the mineralogical composition of the basaltic rocks, release of Ca, Na, Mg, K, Si, Al and Fe as ions or molecular complexes is included in the silicate weathering reactions to a varying degree silicate weathering is, in general, a very slow process.

Fe and Al contents in the groundwater are generally low under the prevailing pH and redox conditions. Contents of lithogenic sulfur components are expected to be low because sulphide minerals are not frequent in the basaltic rocks.

The petrographic composition of different basalt rocks, which occur in the North Arabian Volcanic Province, is quite homogeneous. Major mineral components of the basalts are:

> Plagioclase, potassium-feldspar, clinopyroxene, amphibole, biotite, olivine and magnetite. Minor components are: Quartz, zeolite, calcite, epidote, chlorite, sericite, apatite, limonite / goethite and sulphides (pyrite, chalcopyrite). The chemical composition of these minerals is listed in Table 11.

TABLE 11: CHEMICAL COMPOSITION OF MAIN MINERAL COMPONENTS OF BASALTS

Plagioclase:	$Ca\ Al_2\ Si_2O_8$ / $Na\ Al\ Si_3O_8$
Potassium-feldspar:	$K\ Al\ Si_3\ O_8$
Clinopyroxene:	$(Ca, Mg, Fe)_2\ Si_2\ O_6$
Amphibole:	$A_{2-3}\ B_5\ (Si, Al)_8\ O_{22}\ (OH)_2$ $A = Mg, Fe^{2+}$, Ca or Na $B = Mg, Fe^{2+}, Fe^{3+}$ or Al
Biotite:	$K\ (Mg, Fe^{2+})_3\ (Al, Fe^{3+})\ Si_3O_{10}\ (OH)_2$
Olivine:	$Mg, Fe\ Si\ O_4$
Magnetite:	$FeO \times Fe_2O_3$
Quartz:	$Si\ O_2$
Zeolite:	Ca, Na, K - Al, Si - x H_2O (various proportions)
Calcite:	$Ca\ CO_3$
Epidote:	$Ca_2(Al, Fe^{3+})_3\ Si_3O_{10}\ (OH)$
Chlorite:	$(Mg, Fe^{2+}, Fe^{3+})_6\ Al\ Si_3O_{10}\ (OH)_8$
Sericite:	$K\ Al_2\ (Al\ Si_3)\ O_{10}\ (OH)_2$
Apatite:	$Ca_5\ (PO_4, CO_3)_3\ (F, OH, Cl)$
Limonite/Goethite:	FeO (OH)
Pyrite:	$Fe\ S_2$

Additional lithogenic components can be expected in areas, where basalt aquifers are in hydraulic contact with sedimentary carbonate aquifers or aquitards. Anthropogenic inputs, e.g. from infiltration of sewage water or irrigation return flow, may have a significant impact on the groundwater quality. These aspects are further discussed for specific areas of the basalt aquifer system (Chapter 5.3.4).

5.3.4 Hydrochemistry of groundwater in different areas of the basalt aquifer system

5.3.4.1 Jebel el Arab (Fig.8)

Water samples from springs and shallow wells in the Jebel el Arab mountain area are characterized by low ion concentrations and groundwater salinity between 85 and 225 mg/l TDS. According to their hydrochemical composition, the samples are prevailingly of Ca-HCO_3 type waters.

The samples represent perched groundwater in pervious zones of Pliocene basalt sheets or of Quaternary lava flows on the mountain slopes. Tritium contents of 8 - 21 T.U. indicate that the perched aquifers are replenished by recent recharge.

Ion concentrations in rainfall on Jebel el Arab may be represented by values reported from the stations at Suweida and Ezraa (Fig.7). Cl concentrations in groundwater of Jebel el Arab are increased in comparison to rainfall by factors of 2 to 7, SO_4 concentrations by factors of 0 to 3. HCO_3 concentrations in the groundwater are significantly higher than in rainwater.

The hydrochemical composition of the shallow groundwater from Jebel el Arab is similar to the composition of flood waters in the Azraq area (Fig.8, Kharabsheh 1995).

In general, the hydrochemical composition of shallow groundwater in the Jebel el Arab mountain area appears dominated by:

- atmospheric inputs and evaporative enrichment of atmospheric inputs by a factor of around 5;
- reactions between soil CO_2, water and silicate minerals and between CO_2 deposited from precipitation or dust.

5.3.4.2 Hauran Plain (Fig.10-12)

Samples from boreholes and springs from the Hauran Plain and the groundwater discharge area around Wadi Hreer - Mzeirib can, in general, be characterized as Na- HCO_3 type waters with a salinity range of 250 - 800 mg/l TDS.

The Hauran Plain comprises a main regional aquifer system with water levels at 450 to 560 m asl., as well as various local groundwater occurrences at shallow depth (Chapter 5.2.3). No detailed evaluation, differentiating shallow and deeper aquifers, has been made in this study.

A general zonation of the composition of water samples from boreholes is indicated:

- lower salinity (around 350 mg/l TDS) and relative HCO_3 contents of >50 meq% in topographic higher parts of the plain (above 600 m asl., Fig.10);
- moderate salinity of 500 mg/l TDS and relative HCO_3 contents of <50 meq% in the topographically lower parts of the plain around Ezraa - Deraa (Fig.11).

The majority of samples of spring water, including samples from the large springs at Mzeirib, corresponds in the hydrochemical composition to borehole samples from the more elevated parts of the plain (Fig.12).

Concentrations of Na, Cl and SO_4 show a general moderate increase in direction of groundwater flow (Fig.24). The increase may be related to a higher enrichment of dissolved substances during infiltration in the plain areas, where rainfall and velocity of surface runoff are lower than in the mountain area.

Low ion concentrations in some of the spring waters are possibly indications for discharge of regional groundwater flow and recharge in distant areas of the catchment. The samples from Brekeh and Al-Sijen have comparatively high values of EC, HCO_3 and Ca (Fig.10c). Since also NO_3 contents with around 30 mg/l are above the general background value of the area, an anthropogenic source of dissolved ion contents may be suspected: increase of HCO_3 and Ca contents through oxidation of organic carbon - reduction of nitrate. Hence groundwater quality monitoring and a detailed investigation is recommended. The limited available hydrochemical data suggest that a more detailed hydrochemical study, together with evaluations of hydrogeologic and isotope hydrologic data, can considerably improve the knowledge on the regional and local groundwater regime in the Jebel el Arab - Hauran area.

5.3.4.3 Wadi Liwa (Fig.13)

Samples from boreholes in the Wadi Liwa - Mesmiyeh area differ in their hydrochemical composition from groundwater in the Hauran Plain through higher total salinity (600 - 1000 mg/l TDS) and higher contents of Mg, Ca, Cl and HCO_3.

The area constitutes part of the Yarmouk groundwater basin but belongs to the zone of internal surface drainage. The relatively elevated ion contents may indicate the impact of evaporative enrichment in a closed basin. The groundwater may originate from local recharge in the Wadi Liwa - Mesmiyeh Sub-basin or from subsurface inflow from the Damascus Basin.

Several parameters indicate that recharge takes place mainly in more distant carbonate aquifers, probably in the Damascus Basin, and not - or to a minor extent - locally in the basalt aquifer:

- relatively high HCO_3 concentrations;
- absence of measurable ^3H contents, $\delta^{13}C$ values of -8.5, ^{14}C values of around 40 pmc (Chapter 6).

The composition of groundwater in the area comprising the Leja Plateau and Wadi Liwa ranges from Na - HCO_3 type water with low salinity to brackish Na - Cl type water. A more detailed hydrochemical survey is recommendable.

5.3.4.4 Area east of Mafraq (Fig.15)

Numerous boreholes in the area east of Mafraq extract groundwater mainly for irrigation. Most wells tap aquiferous sections of the Pleistocene basalt and the underlying Upper Cretaceous carbonate aquifer (A7/B2 aquifer). The area constitutes part of the Yarmouk groundwater basin. Groundwater movement is directed, in general, from the mountainous area in the northeast towards the extraction area near Mafraq. Depth to groundwater ranges from 100 to 300 m, the thickness of the basalt increases from 200 m towards east to >400 m.

Salinity of samples based on data from 84 boreholes ranges from 340 to 4000 mg/l TDS. 70% of the evaluated water analyses are fresh water samples. The analytical data refer to samples collected between 1982 and 1992 and may not be representative for the present state of salinity distribution of the extracted groundwater.

The fresh water samples are prevailingly Na - Cl type waters. The fresh water is similar in its hydrochemical composition to water samples from the Ezraa area (5.3.4.2). Relative cation contents are somewhat shifted towards higher Na contents in comparison to samples from Syria.

The brackish groundwater is characterized, in particular, by high Cl concentration and elevated Ca, Mg and Na contents. A number of samples shows high deviations from mean ion concentrations (Fig.20). The relative cation contents are not significantly different from the fresh water of the basalt aquifer. HCO_3 concentration in a number of samples is low (<100 mg/l). NO_3 contents reach up to 75 mg/l in some samples; increased NO_3 contents appear to be related to high Cl and SO_4 concentrations (Fig.15g).

The following origin of dissolved substance in groundwater of the area east of Mafraq is indicated:

The aquifer contains fresh water recharged prevailingly at higher parts of the catchment area. The fresh water, which is similar in its hydrochemical composition to groundwater in the Ezraa area and the northeastern desert of Jordan, appears dominated by atmospheric inputs enriched through evaporation and by dissolution of silicate minerals. The composition of the groundwater in the basalt as well as in the underlying carbonate rocks is clearly related to recharge in the basalt outcrop. No relationship to typical carbonate rock water can be seen. A slight contribution of Na and Cl contents from the carbonate aquifer cannot be excluded.

The main source of elevated ion concentrations in part of the wells appears to be irrigation return flow, as indicated by the correlation between NO_3 concentrations with total salinity, Cl and SO_4 concentrations. These effects are discussed in more detail for the Dhuleil area (5.3.4.5).

The occurrence of brackish groundwater appears to be concentrated to certain parts of the area (Fig.15b).

5.3.4.5 **Dhuleil area** (Fig.16)

About 80 production wells are in operation in the Dhuleil area for irrigation and domestic supply. The wells tap mainly the Upper Cretaceous carbonate aquifer (A7/B2 aquifer), which is covered in part of the area by Pleistocene basalt. Depth to groundwater is generally between 50 and 100 m, the thickness of the basalt is < 100 m. Groundwater flow is directed from the northeast to the extraction area.

Only samples from the area with a basalt cover have been considered for this study (18 samples collected between 1985 and 1992). Groundwater salinity ranges from 400 mg/l to 6000 mg/l TDS. Mean concentrations of all major ions, except for HCO_3 are higher than in other areas of the western part of the basalt aquifer system. HCO_3 concentrations are generally low (around 100 mg/l).

The occurrence of fresh water appears to be restricted, at present, to the more eastern -upstream - parts of the area (Fig.16b). Historical water analysis data show that groundwater salinity and concentrations of major ions increased from low levels before groundwater development started in 1961 to brackish water quality in many wells in the nineteen seventies (Fig.16f-16h, Abu-Sharar & Rimawi 1993). The deteriorating quality of the irrigation water together with a diminution in the volume of irrigation water applied led to high soil salinization (Nitsch 1989).

The fresh groundwater in Dhuleil area is, in its hydrochemical composition, comparable to groundwater from the Mafraq area and the northeastern desert of Jordan and apparently originates from groundwater recharged in basalt outcrops. No significant impact of recharge through carbonate rocks can be seen. The main reason for high groundwater salinity and groundwater quality deterioration is apparently irrigation return flow. Increased NO_3 contents are generally correlated with high Cl and SO_4 concentration (Fig.16e).

Samples from some boreholes have very high Cl concentration and low NO_3 contents (AL1007, AL1023). The source of the high salinity in these boreholes (electrical conductivity up to 9000 μS/cm) may be identified through a detailed study of local conditions. The elevated groundwater salinity can be attributed prevailingly to rapid recycling of irrigation water: Part of the water applied for irrigation seeps directly into the subsurface without longer retention in the soil zone. The reinfiltrating water shows no impact of reactions with soil CO_2 and is free of tritium like the pumped groundwater. The hydrochemical composition of the reinfiltrating water is related to the dissolution of soluble salts from the saline soils and possibly to precipitation of less soluble carbonate constituents.

5.3.4.6 Azraq Basin (Fig.17 and 18)

The morphological depression of Azraq constitutes a major regional groundwater discharge area with a total discharge through springs and evaporation in the sabkha (Qa'a Azraq) of around 16 million m^3/year under natural conditions (Chapter 5.4).

The natural groundwater discharge has been highly reduced through intensive groundwater extraction through 15 domestic supply boreholes (AWSA well field, completed in 1981) and through numerous shallow irrigation wells. Major springs have dried up by 1991. (Table 9)

The northern and eastern parts of the Azraq drainage basin are included in the Pleistocene to Quaternary basalt field.

The thickness of the basalts and depth to groundwater increase from the basalt outcrop boundary at Azraq northward to several hundred meters.

The basalt is underlain by Paleogene chalks which constitute an aquifer in hydraulic connection with the basalt aquifer. In the AWSA well field, both aquifers are tapped by the production boreholes. In the Azraq Plain, aquiferous Quaternary sediments are overlying or adjoining the basalt aquifer.

Groundwater from the northwestern part of the Azraq Basin, including the northeastern desert of Jordan and the AWSA well field, is similar in its hydrochemical composition to fresh water from the basalt aquifer in the Mafraq area and shows, in general, the characteristics of groundwater recharge in the basalt outcrop. In the northeastern desert, groundwater is extracted from deep boreholes, some of which have penetrated the basalt sequence and reached the underlying Upper Cretaceous carbonate aquifer. Water samples from the boreholes are prevailingly Na - HCO_3 type waters with salinities of 250 to 550 mg/l TDS and correspond in their hydrochemical composition to fresh water from the adjoining Mafraq area. Cl concentrations and total salinity show a general tendency of increase towards east. Most samples of the water extracted from the AWSA well field at Azraq are Na - Cl type waters with a salinity of 300 to 700 mg/l TDS. The hydrochemical composition is comparable to groundwater in the eastern part of the northeastern desert, situated upstream of the well field. In some areas of the basalt aquifer near Azraq, Na - Cl waters occur with relatively high salinity (around 1000 mg/l TDS) and Cl concentrations of 250 to 300 mg/l.

Water levels in observation wells declined 3 to 7 m over the period from 1984 to 1995 and groundwater salinity in AWSA production wells showed increases of electrical conductivity of 100 to 200 μS/cm over the same period. Short-term increases of electrical conductivity reached 250 μS/cm (Qunqar 1996). One sample reported from well AWSA 14 (F1041, Fig. 18c) indicates relatively high salinity (Cl, SO_4 and HCO_3 concentrations around 200 mg/l each) and does not correspond in its composition to typical basalt water.

Fluctuations of the salinity and composition of water extracted from the AWSA well field may be related to vertical or horizontal differentiation of the natural water quality: Moderately higher contents of dissolved solids in water of the Paleogene chalk or in the basalt aquifer in areas surrounding the well field. Possibly, the groundwater with low salinity extends in tongues along zones with relatively high permeability towards the discharge areas (Drury 1993, Lloyd 1965). The density of observations is, however, insufficient for verifying these conditions in detail.

Samples from Al Urah and Mustadhema springs, now dried up, show the same general hydrochemical characteristics as the water from AWSA boreholes. Groundwater in the Qa'a Azraq has considerably higher salinity. It includes basalt water mixed with water infiltrated in the plain. Recent recharge and near surface groundwater in the plain are affected by evaporative enrichment of dissolved substances. The sabkha area of the Azraq plain contains highly saline groundwater.

A hydrochemical classification of groundwater in shallow aquifers of the Azraq depression has been presented by Rimawi & Udluft (1985). Four major hydrochemical groups have been distinguished:

- Typical basalt aquifer water with a mean salinity of 370 mg/l TDS (group II);
- Groundwater in aquifers surrounding the basalt - carbonate and alluvial aquifers (group I) - and in the main parts of the Azraq plain (group III) with higher Cl contents than the basalt water and mean salinities of 766 mg/l (group I) and 1178 mg/l (group III);
- Hyper-saline Na-Cl water with Cl concentrations of 130 g/l in the central part of the Azraq depression, where pools of surface water evaporate (Group IV).

Increasing groundwater salinity is a threat to many wells in the Azraq Plain, but may also endanger the water quality in the AWSA well field if the flow direction of the groundwater towards the plain is reversed through covering of the depression cone of the well field.

5.3.4.7 <u>**Hamad area**</u> (Fig.19)

The Hamad area extending northeast and east of Jebel el Arab has an arid climate with mean annual precipitation decreasing from 150 mm in the northwest to <70 mm in the southeast. The eastern part of the Azraq Basin catchment (Safawi area) is here included in the Hamad area.

The basalt thickness varies from a few tens of meters near the northern and eastern boundaries of the basalt outcrop to >400 m in the Touloul al Ashaqif area. In considerable parts of the northern and eastern extent of the basalt field, water levels of the main regional groundwater flow system are situated below the basalt base within the underlying Paleogene chalk aquifer.

Groundwater salinity in the discussed part of the Hamad area is generally >1000 mg/l TDS, increasing to several tens of thousand mg/l towards southeast. The hydrochemical composition of groundwater varies in wide ranges over the area. The following characteristics are indicated for different parts of the Hamad basalt field:

- Safawi (boreholes F1212 and F1316) and Zelaf (borehole K2) areas: brackish water with Cl concentrations of 500 to 600 mg/l;
- northern part of the basalt field (boreholes Umm Saad and El Basali): brackish groundwater with elevated Cl and SO_4 concentrations (Cl 350 - 580 mg/l, SO_4 480 - 950 mg/l);
- Muqat and Qasr Burqu areas on the eastern and southern margin of the basalt field: fresh water to slightly brackish HCO_3 or Cl type water.

The groundwater in Muqat and Qasr Burqu areas is possibly related to flood flow infiltration into the Paleogene chalk aquifer. Shallow groundwater with relatively low salinity occurs in the Wadi esh Sham - Zelaf area. No complete chemical water analyses are available. Cl concentrations are reported to vary from 30 to 250 mg/l. Samples from deep borehole NDW1 are fresh water of Na - HCO_3 type. No explanation on the origin of this water can be given, at present.

The available water analyses are insufficient for a reliable assessment of water quality and hydrochemical characteristics over the large area of the Hamad basalt field. Apparently, groundwater in most parts of the area is brackish and receives no significant recharge, at present. Fresh water occurrences appear to be restricted mainly to lenses along major wadi courses.

In general, the elevated groundwater salinity in the Hamad area can be attributed to the prevailing arid climate conditions with very low recharge rates, high evaporative enrichment of the limited quantities of infiltrating water and low rates of groundwater circulation and flushing of aquifers.

5.3.5 Suitability of groundwater for domestic use and irrigation

In the western part of the basalt aquifer system, groundwater quality, according to the organic chemical composition, 18 suitable for domestic supply. Cl and SO_4 concentrations are, in general, below 250 mg/l (Fig. 24e-24f). Water quality problems with respect to domestic use exist in:

- some parts of the Dhuleil area and the area east of Mafraq, where groundwater quality is affected by irrigation return flow;
- the area around Braq (Wadi Liwa Basin) with local occurrences of elevated groundwater salinity;
- the Azraq Plain, outside the basalt outcrop;
- the wide areas of the northeastern and eastern part of the basalt aquifer system, the Hamad area, where brackish groundwater prevails and fresh water occurrences appear to be restricted mainly to major wadi courses.

Nitrate concentrations above acceptable limits for domestic supply occur in the areas affected by irrigation return flow (Dhuleil, Mafraq). The groundwater in these areas possibly contains also residues of pesticides, but no analytical data are available.

The shallow groundwater in Jebel el Arab is vulnerable to contamination from the surface. The bacteriological and chemical quality of springs and shallow wells used for domestic supply needs particular careful sanitary supervision and monitoring. An overview of the suitability of groundwater from the basalt aquifer system for irrigation is given in Wilcox diagrams in Fig. 22a-f. Sodium hazards, according to the hydrochemical composition of the basalt water, are low in most areas. Salinity hazard of the majority of evaluated water analyses is medium. Water samples of shallow groundwater of Jebel el Arab and some springs in the northern part of the Hauran Plain indicate low salinity hazard. Salinity hazards are high to very high in the areas where groundwater salinity is increased by natural or anthropogenic influences: evaporative enrichment in closed basins (Azraq, Braq) and in the arid Hamad area, and inadequate irrigation management (Dhuleil and Mafraq areas). High salinity hazard is frequently accompanied by somewhat increased sodium hazard (medium sodium hazard).

5.3.6 Summary of hydrochemical findings

Groundwater in most of the western part of the basalt aquifer system is fresh water. The hydrochemical water composition in aquiferous layers of the basalt as well as in underlying carbonate aquifers is dominated by processes during the recharge on basalt outcrops. Dissolved substances derive from:

- atmospheric inputs which are enriched in concentration at or near the surface;
- dissolution of silicate minerals through interaction with water and soil CO_2.

These processes produce Ca - HCO_3, Na - HCO_3 or Na - Cl type water with low to moderate salinity, which is generally suitable for domestic use and irrigation.

Groundwater problems in specific areas are:

- Increasing groundwater salinity in aquifers affected by irrigation return flow (Dhuleil area, area east of Mafraq);
- The hazard of flow of brackish water from the Azraq Plain towards the AWSA well field if the drawdown cone of the well field continues to be lowered;
- Wide spread occurrence of brackish groundwater in the arid northeastern and eastern part of the basalt aquifer system, the Hamad area;
- Locally elevated groundwater salinity in the Braq area and some spots of the Hauran Plain.

Suggestions for approaches to deal with these groundwater quality problems are mentioned in Chapter 7.

5.4 Notes on the prevailing hydrogeologic features and groundwater balances in the main water areas within the Basalt Aquifer System in Jordan and Syria

From the satellite imagery, the prevailing hydrogeologic features relevant to the exploration of water resources can be distinguished:

The poorly developed drainage patterns of Miocene-Pliocene plateau basalt and of Pleistocene shield basalt series indicate infiltration of surface runoff and possibly also from in-situ rainfall. The Miocene-Pliocene plateau basalts reach thicknesses of several hundreds of meters intercalated by soil and sedimentary interlayers. Deep vertical fractures (cooling cracks as a result of contraction) are prominent in these plateau basalt and may provide favourable groundwater movement. Unconsolidated Quaternary tuff and scoria volcanoes and tuff and scoria terrains may have relatively high infiltration capacities.

Quaternary valley-filling lava flows and Quaternary weathered tuff terrains show differentiated drainage patterns which give evidence of rapid water transportation into morphologic depressions which are delineated as mud pans. The mud pans are covered by fine grained sediments (clay material) which reduce infiltration and recharge into underlying rocks, sediment or soil layers. Due to evaporation, the salinity increases in the sediment pans.

Basaltic dykes crosscutting the entire area can be deeply situated hydraulic barriers. They can separate areas of different groundwater level and differentiate the basalt aquifers into compartments with different aquiferous properties.

No particular evaluations of groundwater balances have been made, so far, in the framework of the present study. A discussion of groundwater balances is therefore restricted here to general considerations and an outline of information available from earlier reports. These estimates show a high uncertainty with regard to the components of groundwater balances. Without further field investigations, the accuracy of the groundwater budget estimates may be improved, to some extent, through evaluations of isotope and hydrochemical data, a review of the existing groundwater balance assessments, and possibly, through geohydraulic evaluations.

Groundwater balances may be presented here for the main groundwater flow systems of the regional basalt aquifer: the Yarmouk Basin, Azraq Basin, Wadi Dhuleil and Hamad Basin. Special consideration may be given to the Jebel el Arab area, where particular recharge and groundwater flow conditions appear to exist.

5.4.1 Jebel el Arab mountain area

The central part of Jebel el Arab, comprising a high mountain plateau above 1300 m with mountain peaks up to 1800 m, is covered prevailingly by basalt flows of Pliocene age. The outcrops of Pliocene basalts extend over about 400 km^2. The Pliocene basalts are composed of single lava sheets of several meters thickness with intercalated soil or sedimentary layers. In parts of the high plateau, the Pliocene basalts are covered by volcanic tuff related to cinder or scoriaceous cones. Quaternary lava flows extend, in particular, over the slopes of the Jebel el Arab mountain massif.

Numerous springs discharge from the Pliocene and Quaternary basalts, mainly in the western and northern parts of the high plateau and on the western slope of the mountain. The springs are situated at various levels between 1000 and 1600 m asl. In the eastern part of the high plateau, shallow groundwater has been explored at depths of 20 to 50 m below surface (area around Melah - Huya - Keisame, surface elevation 1350 - 1425 m).

The springs issue at the boundary between individual lava flows. According to information from existing maps, about 100 springs are observed in the Jebel el Arab area. Most of the springs have a discharge of <1 l/sec and dry up during summer. The mean discharge of larger springs is in the order of 12 to 20 l/sec with high seasonal fluctuations.

The drainage pattern on the surface of the Pliocene basalts is, in general, poorly developed. This may indicate relatively favourable recharge conditions. The transmissivity of individual aquiferous layers within the Pliocene basalts is probably low because of their limited thickness.

As regards groundwater balance, the previous investigations carried out in the area indicated the following:

- Mean annual precipitation 350 mm/a over an area of around 800 km^2, volume of precipitation 280 MCM/a.

- Western part within the Yarmouk Basin catchment: about 350 km^2, volume of precipitation 122 MCM/a.

- Spring discharge:
  Burdon (1954) 3.6 MCM/a.
- Estimate from available data:
  40 springs with mean discharge 1.5 l/s = 60 l/s
  70 springs with mean discharge 0.5 l/s = 35 l/s
  approximate total discharge 95 l/s or 3 MCM/a.

Spring discharge of 3 to 4 MCM/a corresponds to about 2.5 to 3.3% of the mean annual volume of precipitation over the western part of the Jebel el Arab mountain area. Significant leakage of groundwater in shallow aquifers into deeper aquiferous horizons may occur in the Jebel el Arab mountain area. Groundwater movement from the mountain area towards east and south appears not to be drained significantly by local spring discharge.

5.4.2 Suweida area and Hauran Plain

The foothills of Jebel el Arab around Suweida are situated at altitudes between 800 m and 1000 m asl., and are covered prevailingly by Lower Quaternary basalts which overlie Neogene basalts. In borehole 120 near Suweida, a thickness of 160 m Quaternary basalts and 540 m of Neogene (Pliocene) basalts have been penetrated.

The basalt sequence comprises several aquiferous horizons:

(a) Shallow groundwater discharging in small springs south and northwest of Suweida;

(b) Perched aquifers at intermediate depth in the area southwest and northwest of Suweida with water levels between 50 and 165 m below ground surface. The water table descends from over 900 m asl., south of Suweida to 770 m asl., towards northwest. Well yields range from 6 to > 100 m^3/h. Groundwater salinity is 200 - 450 mg/l TDS. The aquiferous section probably corresponds to the lower part of Lower Quaternary basalts above one or various low permeability horizons approximately at the boundary between Neogene and Quaternary basalts. The water level of the main basalt aquifer is expected in this area at around 520 - 540 m asl. (400 - 500 m below surface);

(c) West to northwest of Shahba, the Lower Quaternary basalt is covered by a basalt shield of Middle Quaternary age, forming the Leja Plateau, which extends over around 300 km^2. The thickness of the basalt sheet ranges from 8 to 20 m (Krasnov et al. 1966: 37-38). The plateau itself has no significant surface runoff and favourable conditions for infiltration of precipitation are assumed (Selkhozpromexport 1982).In one borehole on the western margin of the Leja Plateau (borehole 18), a total thickness of Neogene to Quaternary basalts of 308 m was encountered, overlying Miocene marls.

West and northwest of Shahba extensive occurrences of perched groundwater have been explored with water levels between 20 m and 100 m below ground surface. The water-bearing layers may be assumed to be in Lower Quaternary basalts. Well yields vary from 4 - 25 m^3/h. Drawdown in several wells was very low during testing, indicating relatively high specific well capacities in some locations. Groundwater salinity is 200 - 600 mg/l TDS. Detectable tritium contents in some samples (5.5 - 10.3 T.U.) indicate recent recharge.

The water level of the main basalt aquifer has been reached in a borehole in Rima al Lahf at 367 m below surface (around 510 m asl.);

(d) Surface runoff occurs in Wadi Liwa which borders the Leja Plateau to the east. Along Wadi Liwa, a number of boreholes has reached the main basalt aquifer with water levels between 150 m and 330 m below ground surface (500 - 523 m asl.). Perched aquifers with water levels at 200 to 260 m above the main aquifer occur in the same area.

Well yields of 3 - 40 m^3/h are reported in Wadi Liwa, with some high values of specific well capacity. Salinity is 300 to 1150 mg/l TDS.

Wadi Liwa forms a closed basin, in which surface runoff accumulates during the rainy season in a small lake near Braq. Groundwater flow in Wadi Liwa, as well as deep subsurface flow from part of the adjoining Damascus Basin, is directed towards southwest into the Yarmouk Basin;

(e) The Hauran Plain comprises an extensive main aquifer within the basalt sequence. The water table of the main aquifer descends from around 520 m asl. in the north and east of the Hauran Plain to 450 m in the southwest, where groundwater discharges in several large perennial springs. The main aquifer extends probably mainly over the Neogene basalts and the lower section of Quaternary basalts. The thickness of the saturated main basalt aquifer increases from around 50 m in the southwest to 200 m in the east. Depth to the groundwater table ranges from 50 to around 200 m below ground surface. In various parts of the Hauran Plain, which are covered by plateau basalts of Lower Quaternary and Middle Quaternary age, perched aquifers occur with water levels rest at 50 to 100 m below ground surface.

Reported well yields in the aquifers of the Hauran Plain vary over wide ranges and are, on average, low to moderate (Map 8). According to Bajbouj (1982), the Pliocene -Quaternary basalts of the Deraa - Ezraa hydrogeologic zone form the principal productive aquifer system in the Syrian part of the basalt region. The volume of spring discharge at the lower end of the Hauran Plain in the southwest indicates that the plain comprises a good groundwater basin with considerable quantities of groundwater flow through the aquifer. No distinct picture on the distribution of aquifer permeability and transmissivity can be deduced from the available information.

The basalt aquifer system extends further west over the limits of the study area towards the foothills of Mount Hermon. No investigations of the hydrogeologic conditions of that area and of related groundwater inflow into the Ezraa - Deraa area has been made in this study.

According to the outcome of the previous investigations, the groundwater balance in the area is as follows:

- Mean annual precipitation 250 mm over an area of 4500 km^2, volume of precipitation 1,125 MCM/a.

- Mean spring discharge at Mzeirib - Wadi Hreer:
  Burdon (1954) 170 MCM/a
  Bajbouj (1982) 5.4 m^3/s = 177 MCM/a.

The mean spring discharge would correspond to 15% of the volume of precipitation of 1,125 MCM. Additional contributions to groundwater movement to the discharge area have, however, to be expected from the northwest and from the Jebel el Arab mountain area. Assuming a subsurface flow from the northwest of 20 MCM/a and from Jebel el Arab of 20 MCM/a, recharge in the area between Suweida and Mzeirib, sustaining the spring discharge, would be 130 MCM/a.

Under these assumptions, recharge rates of 11.5% and 19% of precipitation would apply for the Suweida - Mzeirib area and the western part of the Jebel el Arab mountain area, respectively.

The following components of the groundwater balance have been neglected in the above considerations:

- movement of fossil groundwater;
- evaporation losses from groundwater;
- irrigation return flow.

5.4.3 Azraq basin

The Azraq basin forms the northeastern part of Jordan. It furnishes a very important source for drinking water of three major cities in Jordan (Amman, Zerqa and Irbid), in addition to the irrigation water demand of the Azraq area itself.

There are three different aquifers in the Azraq basin. The upper aquifer complex is divided into two subunits, the first is composed of Basalts, Alluvial deposits, Shallala and Rijam Formations in the northern part of the Azraq basin. It is the most important one in the area, because of good groundwater quality and low drilling costs. The second is composed of Shallala and Rijam Formations in the south. The hydraulic connection between these two subunits classifies them as one aquifer. The Shallala Formation is composed of clayey layers and acts as an aquitard, but in the south Azraq, it is more sandy and acts as an aquifer in some places. Depth of aquifer ranges between few meters to more than 200 m. Average transmissivity of the upper aquifer complex is 11000 m^2/d. Permeability of the upper aquifer ranges between less than 0.5 to 115 m/d. Saturated thickness ranges between 50 to 190 m.

The middle aquifer complex is composed of the Amman, Ruseifa and Wadi Essir Formations. Depth to aquifer is more than 600 m. Average permeability is 9.75×10^{-4} m/s. Depth to piezometric heads ranges between 1 to 278 m. Transmissivity ranges between 3800 and 4800 m^2/d.

The lower aquifer complex consists of Kurnub sandstone with depth more than

1000 m. Average permeability is $4.4x10^{-5}$ m/s. Average porosity is 4.6 to 13.1 percent.

The aquifers are hydraulically interconnected by the effect of the major faults and show different flow directions: water of the upper aquifer complex flows from north at Jebel el Arab area toward south to reach the Qa' Azraq; water of the middle aquifer complex flows from west and southwest and from the east (Hamad Basin) to reach the Azraq depression, water of the lower aquifer complex flows from east to west to discharge in its lowest point at the Dead Sea Basin.

The water budget of the Azraq basin shows that the average yearly infiltration is 35 MCM. 1 MCM flows through the Sirhan structure to adjacent areas. About 14 MCM of the infiltrate are lost equally to evapotranspiration and the long term discharge of the springs. This shows that areal recharge to the Upper Aquifer Complex is only 20 MCM.

As already mentioned, two groups of springs form the Azraq Oasis. They are located in the central part of the Azraq Basin near the well field area. The first group is Drouz consisting of the Aura and Mustadhema springs. The second group is Shishan consisting of the Souda and Qaisiyeh springs. They are recharged through the same resource aquifers (Jebel el Arab).

The water quantity and quality have deteriorated in present times in the Azraq Basin, because of overpumpage of the upper aquifer complex to cover increasing demand to water and limited renewable sources (Fig.5). The springs which form the oasis have totally dried up since 1991 (table 9). This means that, searching about new water resources is very necessary for development of the country and to protect groundwater from the probable salt water intrusion from the Qa' Azraq area in the south.

Groundwater budget in the Azraq area can be described as follows:

- Size of catchment:
  between Jebel el Arab and Azraq 2800 km^2
  according to GTZ & NRA (1977) 44000 km^2
  total catchment of Azraq Basin 17,000 km^2 (GTZ-NRA 1977)
  12,700 km^2 (University of Jordan, 1996)

- Recharge estimates: 16-35 MCM/a
  northern half of Azraq Basin (7,350 km^2) 37 MCM/a (Noble 1994).

- Mean recharge in % of rainfall 1963-1993 (Noble 1994):
  in catchment area above 980 m asl. 2.95 - 5.69%
  in catchment area of 3990 km^2 around Azraq 2.18%
  in catchment area of 3660 km^2 around Safawi 2.23%

According to evaluations of isotope data (Verhagen et al. 1991), "the natural groundwater flow into the Azraq basin is fed mainly by the remaining fossil groundwater storage recharged during the last pluvial periods many thousand years ago".

5.4.4 Wadi Dhuleil area

It comprises the area of about 45 km northeast of Amman. Rainfall ranges from 100 - 200 mm/a. The mean annual surface water flow in the main wadi Dhuleil in the area is about 12.7 MCM measured at Sukhneh station, in addition to the Sukhneh spring which used to have annual discharge of about 10 MCM (E/ECWA/NR/L/1/Rev.1), p.103, 1981.

The main aquifer occurring in the area is the basalt which is hydraulically connected with the underlying chert-limestone of the Upper Cretaceous. Its average thickness is about 60 m and has a limited areal extent. Depth to water level in the basalt aquifer ranges from 60-80 m below ground surface. The low hydrostatic gradient in the central part of the area indicate high permeable aquifer with well yields range from 150-400 m^3/hr. A low permeability was observed at the peripheries of Wadi Dhuleil area where the basalt aquifer is thinning. In general, the hydrogeologic investigations carried out indicated that the area can be zoned into three groups with transmissivities range:

Group 1	8.5 - 12.7 m^2/hr
Group 2	82 - 109 m^2/hr
Group 3	1090 - 7100 m^2/hr

The basalt aquifer in the Dhuleil area is recharged directly by natural subsurface flow from the high rainfall (200-500 mm) area of Jebel el Arab in Syria. Natural indirect recharge occurs also from frequent flood water flows along wadi channels, originated from local thunderstorms and/or from regular winter rainfall on the area.

The aquifer is discharging naturally in the form of base-flow near Sukhneh area west, and by vertical leakage to the underlying chert-limestone aquifer in some places.

The aquifer is discharged artificially by pumps installed on existing producing wells. Groundwater from the aquifer is utilized for local agricultural development, industrial needs, and domestic purposes. Overdraft conditions are recognized in the area through continuing water level decline and water quality deterioration attributed mainly to the impact of irrigation return flows.

According to the investigations carried out in the area, the groundwater recharge/discharge computations were as follows:

The basalt outcrops encompass a catchment area of about 1000 km^2.

Recharge estimates:

MacDonald (1965)	40 MCM/a
WAJ (1989)	25-30 MCM/a

The deficit between recharge and groundwater extraction is estimated at 5 to 9 MCM/a (WAJ 1989).

Reliable calculation of the groundwater budget may need an improved understanding of groundwater movement in the basalt and the underlying Upper Cretaceous carbonate aquifer.

5.4.5 Hamad area

The Hamad basin lies in the east of the study area. The basin is underlain by several regional aquifer systems which extend over an arid and extremely arid region. The westernmost of these regional systems is developed in basaltic rocks. It is separated from the regional aquifer system underlying the Yarmouk basin by a groundwater divide which runs in approximately north-south direction along the crests of Jebel el Arab. The Hamad and Yarmouk basaltic aquifer systems belong to the same volcanic province. Higher precipitation on Jebel el Arab have created a regional groundwater mound and consequently a regional flow, which moves westwards and eastwards. A small component of flow moves southward, but the groundwater divide of southwestern and southeastern flow which moves in the area extending to the south of Jebel el Arab is not well defined. The Hamad basaltic aquifer system contains local and perched aquifers above low permeability layers. The main aquifer system is underlain by limestone-dolomite and chert beds of Lower-Middle Eocene age. These carbonate beds create with the basalt a single inter-connected aquifer system. The thickness of the main aquifer was estimated at 100-150 m. The main direction of regional flow is eastward and northeastward.

Recent groundwater recharge in the Hamad area east and northeast of Jebel el Arab appears to be restricted to the eastern slopes of Jebel el Arab and to extended wadi systems, e.g. Wadi esh Sham. No quantitative estimates of groundwater resources in the basalt are available for that area, so far.

6. ISOTOPE HYDROLOGY

6.1 OBJECTIVES AND SCOPE OF EVALUATIONS

An evaluation of isotope hydrologic data from the basalt aquifer system has been made with the following main objectives:

- to improve the understanding of groundwater recharge processes;
- to delineate areas with different origin of groundwater resources;
- to assess ranges of values of regional water balance parameters.

Isotope hydrologic data for the basalt aquifer system are available from various studies carried out in Jordan and Syria between 1973 and 1994 (Almomani 1993, 1994, Arsalan 1976, Kattan 1994, Rimawi 1985, Verhagen et al. 1991). Isotope analyses for these studies have been made in four laboratories:

International Atomic Energy Agency (IAEA), Vienna;
State Geological Survey of Lower Saxony (NLfB), Hannover;
Institute for Radiohydrometry (GSF), Munich;
Water Authority of Jordan (WAJ), Amman.

Data are available from 208 sampling points (Fig.25). The following number of data is available for different isotope parameters:

^{14}C	106 analyses
^{13}C	107
^{3}H	287
^{18}O	359
^{2}H	283

6.2 RESULTS OF EVALUATIONS

6.2.1 Values of $\delta^{18}O$ and deuterium excess

The stable isotope composition of oxygen and hydrogen is particularly useful for the understanding of groundwater recharge mechanisms in arid and semi-arid regions. Stable isotope contents of oxygen and hydrogen in meteoric water are related (Dansgaard 1964) as

$$\delta^2H = s * \delta^{18}O + d.$$

In continental rainwater the slope s is 8 and the deuterium excess d equals 10. In the eastern Mediterranean region, d values deviate from values in continental rainwater and range from 20 to 22‰ (Gat & Carmi 1970). These values are also valid for Syria (Kattan 1993a) and Jordan (Almomani 1993). The stable isotope relationship is represented by the Mediterranean Meteoric Water Line (MMWL)

$$\delta^2H = 8 * \delta^{18}O + 20.$$

Most data of the groundwater samples from the basalt aquifer system do not fit the Mediterranean Meteoric Water Line (MMWL). The majority of data points falls below the MMWL (Fig.26). The histogram of the d values (Fig.27) shows an asymmetric frequency distribution with d values preferentially smaller than 20.

$\delta^{18}O$ values show the following regional distribution: (Fig.28)

The most negative $\delta^{18}O$ values below -7‰ were analyzed in samples of shallow groundwater water from the mountain area of Jebel el Arab. The groundwater from wells situated on the foothills of Jebel el Arab is by about 1‰ isotopically heavier. More negative $\delta^{18}O$ values are observed again in the Hamad area north of Jebel el Arab and along the road between Mafraq and Safawi. $\delta^{18}O$ values of more than -5‰ are found at some sampling points in the Damascus and Azraq areas.

6.2.2 $\delta^{13}C$ values and bicarbonate content

The $\delta^{13}C$ value of the total dissolved inorganic carbon compounds (TDIC) of the groundwater depends mainly on the carbon isotope composition of the CO_2 of the top soil and of the soil carbonate, and on temperature dependent isotope fractionation between CO_2 and HCO_3. The CO_2 in the top soil covered has generally $\delta^{13}C$ values of around -23‰. Soil carbonate of marine origin has $\delta^{13}C$ values around 0‰. The following summary explains the isotopic and hydrochemical situation

chemical reaction:	$CaCO_3$ +	CO_2 + H_2O	<->	HCO_3^- + CO_2	
origin:	marine	plant rain		mixture	
isotope composition:	0‰	-25‰		<-12.5‰	
isotope fractionation:					-8.5 to -9.5‰

The histogram of the $\delta^{13}C$ values of the groundwater samples from the Basalt Aquifer System (Fig.29) has two peaks around -12 and -8.5‰. These values confirm that marine carbonate is the main source of HCO_3 produced during the groundwater recharge process.

The HCO_3 content of most groundwater samples is low and ranges between 50 and 250 mg/l.

Fig.30 shows the regional distribution of the $\delta^{13}C$ values of TDIC from the groundwater samples of the study area, which were dated by the ^{14}C method. The most negative values of -14 and -15‰ are analyzed in samples of shallow groundwater from the mountain area of Jebel el Arab. Towards the foothills of Jebel el Arab, $\delta^{13}C$ values approach -12‰. In the sediment covered areas of the Damascus and Azraq Basins and the Hamad area, higher $\delta^{13}C$ values are found together with high bicarbonate and salt contents.

6.2.3 Radiocarbon and ^3H Values

For the ^{14}C water age determination two main questions have to be answered:

1) What is the initial ^{14}C content of the inorganic carbon ($\Delta^{14}C_i$ of TDIC) ?
2) Does the ^{14}C content in inorganic carbon (TDIC) change during the aging of the groundwater through other processes than radioactive decay?

An answer to the first question is needed if groundwater with different initial ^{14}C content ($\Delta^{14}C_i$)is expected in the study area or if paleohydrological information is required for numerical modelling.

Carbon components participating in the carbon chemistry of the groundwater recharge can be of different origin and may have deviating ^{14}C values. This is reflected by the following relationship:

chemical reaction:	$CaCO_3$ +	CO_2 +	H_2O <->	HCO_3 +	CO_2
origin:	marine	plant		mixture	
^{14}C value:	0 pMC	≈ 100 pMC		>55 pMC	

The initial ^{14}C values of HCO_3 and CO_2 (TDIC) range theoretically from 50 to 65 pMC mainly as a function of the bicarbonate content. The dissolved CO_2 content increases with the third power of the HCO_3 content. In nature the range of $\Delta^{14}C_i$ is wider and has a maximum value of 100 pMC. The actual value depends on the geological and pedologic features of the catchment area, sediment cover, vegetation and climate.

The confidence intervals of $\Delta^{14}C_i$ values estimated through generally applied models result in dating uncertainties of ± 2000 to ±3000 years while the actual ages may be smaller than ± 500 years. The absolute uncertainty in the isotopic composition of the participating carbon components is large compared to ^{14}C values in a regional aquifer. It is therefore difficult, if not impossible, to determine actual regionally valid values of groundwater age.

In the study area $\delta^{13}C_{vegetation}$ may amount to -23‰ on the mountain area of Jebel el Arab. Based on this value, $\Delta^{14}C_i$ values of 85 and 60 pMC are calculated for $\delta^{13}C_{TDIC}$ values of -12.5 and -8.5 ‰, respectively. The water temperature is assumed to be 20°C.

An empirical determination of $\Delta^{14}C_i$ is possible with the ^{14}C value of TDIC of young groundwater which contains ^3H just at the detection limit. One tritiated sample from a well at Dama (Hauran Plain) is available with a ^{14}C value of 93.5 ± 3.0 pMC. Applying an atom bomb correction of -10% we get 85 pMC corresponding to an adjustment of the ^{14}C water ages by -1300 yr. In Fig.31 the conventional and adjusted groundwater ^{14}C ages are compared. They are well correlated with a maximum difference of 5000 yr.

The regional distribution of the conventional ^{14}C water ages (Fig.32) suggests an increase in all directions from the Jebel el Arab mountain area. Towards west (Yarmouk Basin), conventional ^{14}C ages increase to a few thousand years. In the Mafraq, Dhuleil and Azraq areas, ^{14}C ages range prevailingly from 10,000 to 28,000 years. The ^{14}C water ages of samples in the Hamad area (wells Um es Saad and Wadi al Rabia) are exceptional high and may not be related to the Basalt Aquifer System.

6.3 INTERPRETATION

6.3.1 Groundwater recharge

The isotopic composition of oxygen and hydrogen of groundwater are primarily determined by the meteoric origin of the water and the altitude of the catchment area, secondarily by evaporation processes occurring before, during or after the groundwater recharge and finally by admixing of water of different origin and history.

The increase of the $\delta^{18}O$ values from Jebel el Arab mountain area to the foothills may theoretically indicate an altitude effect. A gradient of -0,23 and -1.65‰/100 m for $\delta^{18}O$ and $\delta^{2}H$, respectively, was determined for Syria by Kattan (1994), -0.26‰/100 m was evaluated by Abu Maizer (1993). The value of -0.25‰/100m is reasonable as it is often found worldwide.

The difference in $\delta^{18}O$ values on the Jebel el Arab mountain plateau and on the foothills, situated between 700 and 1000 m a.s.l. and 400 to 800 m below the mountain plateau, should be at least 1.5‰. Differences are, however, generally less than 1‰ (Fig.28). This may indicate that the groundwater resources in the foothills represent a mixture of groundwater recharged on the mountain plateau and of local recharge.

The same $\delta^{18}O$ values would result from effects of partial evaporation of the water. In that case, the $\delta^{18}O$ and $\delta^{2}H$ values fit to a straight line of a slope between 4 and 5 for water evaporated from an open surface. Evaporation from the soil moisture results in slopes of down to 2 (Barnes & Allison 1988). Such lines are termed evaporation lines. Mixing with partly evaporated groundwater results in delta values which fit mixing lines corresponding in their slope to evaporation lines. Similar delta values result from a mixture of irrigation return flow with groundwater. In both cases, d will be smaller than 20‰.

Figs.28 and 29 indicate strong evaporation effects for most groundwater samples from the study area. This rises the question how to differentiate this effect from the altitude effect. The deuterium excess d does not change if groundwater recharged in different altitudes is mixed. d decreases, however, if evaporation occurs.

Fig.33 shows the regional distribution of the deuterium excess values in the study area. In the Jebel el Arab mountain area, the d values exceed 20‰ and correspond to d values of the rainwater. Such high d values are found also in the western and northwestern foothills of Jebel el Arab at elevations of around 800 m a.s.l. Under these conditions, mixture of groundwater recharged at different altitudes cannot be identified. The d values in the Hauran Plain range from 12 to 18‰. That means evaporation took place during the groundwater recharge. The spring water at Soraya and Um ed Dananir with d values of 20.2 and 19.5 may come from a different catchment area in the west.

In two other regions d values of more than 20‰ are found: the area east of Mafraq along the road between Mafraq and Safawi and the northwestern part of the Azraq Basin. In the Dhuleil area and the southern part of the Azraq Basin, d values decrease down to 10‰ or less. Similar low d values are found in the Damascus Plain and the Hamad area.

Most samples appear to be affected by evaporation, masking the expected information from the $\delta^{18}O$ values on the origin of the groundwater. In order to eliminate this effect, a correction of the $\delta^{18}O$ values for evaporation is introduced with the following assumptions: The isotopic compositions of oxygen and hydrogen of the evaporated water may fit an evaporation line in the $\delta^{18}O$ / $\delta^{2}H$ plot with a slope v = 4. The d value of the MMWL may amount to 20‰.

A correction for the evaporation effect can be applied from the following equations:

$$D_o = s * O_o + d$$
$$v = (D - D_o)/(O - O_o)$$

where

O_0 and D_0 = $\delta^{18}O$ and $\delta^{2}H$ values of unevaporated groundwater,
O and D = $\delta^{18}O$ and $\delta^{2}H$ values of groundwater affected by evaporation,
s = slope of the meteoric water line,
v = slope of evaporation line.

It follows for the corrected $\delta^{18}O$ and $\delta^{2}H$ values

$$D_o = (s * O - s / v * D + d) / (1 - s / v)$$
and
$$O_o = (D_o - d) / s.$$

The $\delta^{18}O$ values corrected with these equations are represented in Figs. 34 and 35.

The distribution of corrected $\delta^{18}O$ values shows a clear trend. Water samples from the shallow groundwater from the Jebel el Arab mountain area and of groundwater from the foothills and the Hauran Plain have very uniform $\delta^{18}O_k$ values around -6.5‰. This may correspond to an average recharge altitude of 850 m a.s.l. This tentative altitude value shows that the groundwater is a mixture of water recharged in the mountain area and in the foothills or the Hauran Plain.

Correction of $\delta^{18}O$ values, using the slope value of v = 4, may be exaggerated in some cases. A lower slope in the $\delta^{18}O$ / $\delta^{2}H$ plot of possibly 2.5 may be expected for evaporation from the unsaturated zone (Barnes & Allison 1988).

Anomalous corrected $\delta^{18}O$ values were found in the Dhuleil and Azraq areas. This will be discussed in Section 6.3.3.

In summary, the groundwater in the Basalt Aquifer System appears to have a uniform origin and does not reflect a significant altitude effect. Groundwater partially evaporated during the recharge is found in the foothills of Jebel el Arab and the Hauran Plain. The groundwater from the Hamad area and the Damascus Plain has a different isotopic composition. This will be discussed in another report on the isotope hydrology of groundwater in central Syria (Geyh 1996).

The $\delta^{13}C$ values of TDIC provide another isotope signature of groundwater recharge (Fig.36). Bicarbonate content are generally low in the carbonate free Basalt Aquifer System. A major source of carbonate may be the HCO_3^- content of precipitation. Adopting an enrichment of the HCO3 of precipitation during groundwater recharge by a factor between 3 and 10, the TDIC values observed in the groundwater seem to be reasonable.

Interaction of CO_2, water and silicate minerals may produce HCO_3 contents in the recharged groundwater, but this process is generally very slow and should result in a $\delta^{13}C$ value around -25‰, while observed $\delta^{13}C$ values of TDIC are around -12.5‰.

The $\delta^{13}C$ values of -14‰ and less of groundwater in the shallow aquifer of the Jebel el Arab mountain area can be explained by a fast percolation of precipitation water with minor enrichment. In this case the carbonate load of the rainwater is not sufficient to neutralize the excess CO_2 with its low $\delta^{13}C$ value.

In deep aquifers, HCO_3 can originate from dissolution of silicate minerals if an excess of CO_2 from the soil is present.

In the Damascus, Hamad and Azraq areas the highest $\delta^{13}C$ values are found (Fig.30). The sediments in these areas contain sufficient marine limestone to increase the bicarbonate content. In combination with the occurrence of salt in the soils and associated hydrochemical processes, $\delta^{13}C$ values can become even positive, sometimes associated with changes in the ^{14}C content.

6.3.2 Geohydraulics and paleoclimatic conditions

The slope of the piezometric surface of the groundwater in the Jordanian part of the Basalt Aquifer System (Almomani 1993), and the attempt to construct isochrones around Jebel el Arab may support the hydraulic concept of steady-state groundwater recharge and discharge. Under this assumption a tracer velocity of 6 m/yr is estimated for quasi all directions of the Basalt Aquifer System from Mt. Arab. This yields a K value of 2×10^{-5} m/s (K - hydraulic conductivity) for an assumed total porosity of 10%. The groundwater flow rate from the north through the 250 m thick basaltic aquifer over a width of 125 km towards Azraq amounts to 18.8×10^6 m^3/yr. This result agrees with the natural discharge rate of the Azraq springs of 16×10^6 m^3/yr in the past (Verhagen et al. 1991) and an average water age of about 15,000 years.

This discharge volume corresponds, for a catchment area of 12,700 km^2 (Almomani 1993), to a recharge rate of 1.3 mm/yr or 1.4% of the annual rainfall of 87 mm.

An alternative concept is a non-steady flow system (Geyh et al. 1995). It considers the paleoclimatic changes in the Mediterranean region (Geyh et al. 1985) with presumably widely varying groundwater recharge rates. Morphological evidence comes from the existence of Lake Lisan 15,000 yr BP, the dated terraces of the Dead Sea and the temporarily limited growth periods of speleothem in caves of Galillee and finally from the occurrence of dated fossil groundwater samples from the Syrian desert. A new histogram of the ^{14}C dates of this region is shown in Fig.37.

Groundwater ages of the Dhuleil Region and the southwestern part of the Azraq Basin were excluded in this interpretation, as they may have been affected by irrigation return flow (Section 6.3.3). The similarity of the histogram of ^{14}C water ages derived from mainly Syria (Geyh et al. 1985) and the new data from the Basalt Aquifer System is striking, confirming pluvial phases between 18,000 and 15,000 as well as 8000 years and 4000 conventional ^{14}C yr BP. For this flow concept the constructed hydroisochrones represent lines of different groundwater recharge periods during the mentioned pluvial phases. The fossil head is then the driving force of the groundwater movement rather than recent recharge (Burdon 1977; Lloyd & Miles 1986). Under such circumstances, ^{14}C water ages do not allow the calculation of actual tracer velocities without special conceptional model considerations (Verhagen et al. 1991).

A contribution to the water balance of the large springs in the Mzeirib - Wadi Hreer area can be made by interpreting the isotope results from this area. The question is to what proportion groundwater from the Basalt Aquifer System contributes to the spring discharge. The springs Hreer, Ashaary and Ain Dakar yielded ^{14}C water ages of 6600, 6700 and 3300 yr BP. We assume that the groundwater approaching from the Mt. Hermon has a ^{14}C water age of 3300 yr BP and interpret any increase of the ^{14}C water age of the spring water as indication for an admixture of groundwater from Jebel el Arab with a ^{14}C water age exceeding 6600 yr BP.

According to this model the Hreer and Ashaary springs discharge only water from the basalt region, while Ain Dakar is only fed from Mt. Hermon. ^{14}C water ages of e.g. 5000 yr BP belong to groundwater from both sources. This concept is supported by the $\delta^{18}O$ values. The spring water samples from Hrer and Ashaary have corrected $\delta^{18}O$ values of about -6.8‰ while the sample of Ain Dakar has -5.8‰. This isotopically relatively heavy spring water approaching from the west is recharged on the foothills of Mt. Hermon or is a mixture with groundwater actually recharged in the basin. This differentiation of the groundwater resources in the Hauran Plain has to be compared with the interpretation by Kattan (1993). A decision which of both interpretations is valid can be expected from ^{3}H and ^{14}C analyses of the mayor springs sampled before and after the rainy season.

6.3.3 Anthropogenic effects

In several areas, isotope signatures do not fit into the presented regional picture as described in the previous sections. These deviations can be attributed to admixture of irrigation return flow to the groundwater, indicated by hydrochemical and isotopic data.

The agriculture area of Dhuleil appears to be particularly affected. The ^{14}C water ages of 5800 - 9300 yr are lower than those further north along the road between Mafraq and Safawi. High nitrate contents are observed, total salinity is between 400 and 6000 mg/l TDS. The bicarbonate is low, which may be an analytical effect in the brackish water samples. The $\delta^{18}O$ values reflect high evaporation rates, tritium is not found.

The effect of an admixture of irrigation return flow to the bicarbonate content and related ^{14}C and ^{3}H values are well understood. During flood irrigation, water evaporates and becomes isotopically enriched. Tritium of the atmospheric moisture cannot enter this water as the evaporative moisture flux into the atmosphere is larger than backwards. Therefore, ^{3}H remains below the detection limit of 2 TU. During the seepage of the water through the topsoil, carbon compounds are lost by the consumption of the plants while modern soil CO_2 with a high ^{14}C value from the root zone is taken up and transported into the deep aquifer. As a result, ^{14}C water ages are lower than in the unaffected groundwater.

Based on this model assumption the proportion of the return flow in the pumped water can be estimated. The original ^{14}C water age in the Dhuleil Region might have been in the order of 12,000 yr corresponding to a ^{14}C value of 22 pMC. The water with the measured minimum ^{14}C age of 6000 yr had 47 pMC. Assuming that the CO_2 concentration just corresponds to that of the deep groundwater, a proportion of 30% of irrigation return flow is obtained. A higher proportion of irrigation return flow would be calculated if the carbon concentration of the return flow is smaller than that of the deep groundwater.

In the southern part of the Azraq Basin, similar conditions exist. Irrigation return flow and seepage of isotopically enriched water from the former ponds have changed the isotopic composition of the groundwater.

6.3.4 Temporal variability

Temporal changes in the isotopic composition of the groundwater of the Azraq Basin are evident and thoroughly discussed by Verhagen et al. (1991). The effect of groundwater mining was modelled. According to the results at least 2/3 of the discharged groundwater of the springs is more than 15,000 yr old. Under such conditions it is indispensable to check for every site whether or not the isotope results are representative for the groundwater resource or only a snap shot.

An attempt has been made for a few sites where more than two isotope and hydrochemical data sets were available. From the wells AWSA 1 and AWSA 13 stable isotope determinations were made between 1987 and 1992. During this period the SO_4 and Cl contents decreased and HCO_3 increased. The corrected $\delta^{18}O$ values became more positive, possibly indicating an increasing admixture of water from the underlying carbonate aquifer. The hydrochemical and isotopic results of the wells AWSA 8 and DP 17 did not show any temporal trend.

For the well DP6 the ^{14}C water age increased from 5900 to 8100 years, the $\delta^{18}O$ value became more negative and the mineral load increased by a factor of 3 between 1979 and 1986. This is interpreted as result of irrigation return flow and the admixture of groundwater of different origin due to heavy pumping.

7. CONCLUSION AND RECOMMENDATIONS

7.1 CONCLUSION

In cooperation with the competent authorities in Jordan and the Syrian Arab Republic and the technical support provided by the Federal Institute for Geosciences and Natural Resources of Germany, ESCWA, represented by the ENRED, could conduct an investigation study on the Regional Basalt Aquifer System shared by both countries. The study was undertaken within the context of ESCWA/BGR project entitled "Advice to ESCWA member States in the field of Water resources". Subregional cooperation was proved to be substantive during the course of the investigation to such an extent that made this study possible. The main objectives of the study have been achieved. The outcome of the investigations on the regional basalt aquifer system is presented in this technical publication.

A **geological map** was constructed for the area primarily comprising the basalt aquifer system shared by Jordan and Syria. Remote sensing techniques coupled with groundtruth data and incorporating the outcome of the previous investigations and information that were made available, could lead to the preparation of a unified geological map as a major information base required for groundwater resources assessment and development in the study area. The map presents in addition to the surface geology, correlation of the main lithostratigraphic units, geotectonic framework and the major geologic structures that have direct control on the groundwater occurrence, movement and potentials within the study area.

In addition, **twelve thematic maps** showing the various hydrologic and hydrogeologic parameters prevailing within the study area, were produced.

Data and information provided by agencies of Jordan and Syria in data lists, documents and digital files as well as information available from publications, reports and maps were stored in computer files and processed with commercial computer software. The evaluated data comprise in particular records on various parameters from boreholes and springs, groundwater quality and isotope hydrology. The data evaluation resulted in the preparation of 12 thematic maps at 1:500,00 or 1:1,000,000 scale.

Map 1: Topographic map of the basalt complex and its surroundings

The map shows the general topography of the basalt area and its surroundings and the location of dams.

Maps 2 and 3: **Main lithostratigraphic units of the basalt complex and its surroundings;** and **Geological map of the basalt complex**

The geological map of the basalt complex is a digitized version of a map prepared from satellite image interpretation. Information on the distribution of sedimentary formations surrounding the basalt complex has been taken from existing geological maps and reports. A generalized scheme of Cretaceous, Tertiary and Quaternary formations was applied with a view to the delineation of outcrops of major aquiferous units or aquitards.

Map 4: Drainage system

The map shows the main drainage systems:

- Westward drainage to the Yarmouk and Zerqa river systems;
- Internal drainage to closed basins: Azraq, the Damascus Basin, seasonal lakes around Braq between the Yarmouk and Damascus Basins, mud flats within the basalt complex and on the eastern margin of the basalt outcrop.

Map 5: Mean annual precipitation

The map presents the general pattern of mean annual precipitation: relatively high precipitation on Jebel el Arab (up to >500 mm/year rainfall and snow) and in the western part of the area influenced by the Hermon Mountain, and a rapid decrease of rainfall towards east and south with a mean annual precipitation of < 60 mm in the southeastern part of the area.

Maps 6 and 7: **Groundwater contours;** and **Depth to groundwater level**

Water level contours and depth to groundwater level are presented for the main basalt aquifer system and for shallow or intermediate aquiferous zones in the basalt complex.

Map 8: Well yield

In highly inhomogeneous aquifers like basalt aquifers in Jordan and Syria, high variations of hydraulic properties (permeability, transmissivity, storativity) have been observed. Data of well yields and of specific well capacities were therefore evaluated in a statistical way to determine representative values or ranges of aquifer parameters.

Map 9: Groundwater salinity

The map indicates the general pattern of groundwater salinity:

- Low to moderate salinity in Jebel el Arab and in the basalt aquifer system west and south of Jebel el Arab;
- Higher groundwater salinity in the southwestern fringe of the basalt outcrop and in the northeastern and eastern parts of the basalt field.

Maps 10 and 11: Thickness of Neogene to Quaternary basalt; and **Structural contours of base of basalt**

The maps present an interpretation of available information on the thickness and the position of the base of the basalt complex.

Map 12: Structural contours of base of Paleogene chalk formation

The map, which is based on very limited information and therefore printed on 1:1,000,000 scale, gives an indication on the position of the base of the Paleogene chalk formation, which constitutes an extensive aquifer underlying the basalt complex.

As per the study, it was indicated that the sequence of basaltic rocks in northern Jordan and southwestern Syria is composed of **Neogene plateau basalts** and **Quaternary (Pleistocene to Recent) basaltic lava flows and shield volcanoes**. The basalt complex is underlain, in most of its extent, by Paleogene chalks and marly limestones. In some parts of the western fringe of the basalt field, the volcanics overlie Upper Cretaceous sedimentary rocks. According to characteristic features visible on satellite image interpretation, which was made for the region, the Neogene and Quaternary volcanics can be subdivided into various lithostratigraphic units, as follows:

- Neogene (Miocent - Pliocene) Plateau Basalts of three stages (Nb1, Nb2, Nb3);
- Neogene Basaltic Dikes;
- Lower Quaternary until Holocene Cinder and Scoria;
- Lower Quaternary until Holocene Basaltic Tuff;
- Lower Quaternary (Pleistocene) Shield basalt;
- Lower Quaternary (Pleistocene ?) Basaltic Lava Flows;
- Middle Quaternary (?) Basaltic Lava Flows and Shield Basalt;

- Upper Quaternary Basaltic Lava Flows and Shield Basalt;
- Holocene Shield Basalts of three flow stages;
- Volcaniclastics and Sediments.

The major **aquiferous sections** that occur within the sequence of Upper Cretaceous to Recent sedimentary and volcanic rocks are:

- Upper Cretaceous limestones and dolomites;
- Paleogene chalks and marly limestones;
- various horizons with relatively high permeability within the basalt complex.

The prevailing **hydrogeologic conditions** of the basalt aquifer system can be grouped in brief as follows:

- The Jebel el Arab mountain area with mean annual precipitation of around 500 mm comprises a complex sequence of perched aquiferous horizons related to the boundary zones between different lava flows of Neogene shield basalts. A great number of small springs rise from these aquiferous horizons with a total mean discharge in the order of 100 l/s. It can be assumed that the mountain area contributes significantly to the subsurface flow into deeper aquifers in the surrounding foothills and plains. No extensive aquiferous zones are expected in the deeper subsurface below the Jebel el Arab mountain massif, which is probably occupied by basaltic dikes and sills and highly disturbed blocks of sedimentary rocks;

- The foothills west of Suweida - Shahba comprise a thick sequence of Quaternary sheet basalt flows which contain perched aquiferous horizons at varying depths. Groundwater recharge conditions appear to be relatively favourable on the surface of Middle Quaternary basalts (Leja Plateau) and along Wadi Liwa. A deeper main basalt aquifer system extends from the foothills of Jebel el Arab over the Hauran Plain to the major groundwater discharge area at the Yarmouk River (Wadi Hreer, Mzeirib). The main aquifer appears to be constituted, in that area from the lower part of Quaternary to the upper part of Pliocene volcanics;

- In the southern and southwestern parts of the basalt field, the lower section of the basalt sequence forms a common aquifer together with the underlying Upper Cretaceous or Paleogene carbonate rocks. Well yields are relatively high in some parts of the volcanic - sedimentary aquifer complex. Groundwater flow is directed towards the Yarmouk River in the west, Wadi Zerqa in the southwest and the Azraq Basin in the south;

- In the arid areas east and northeast of Jebel el Arab, the basalts appear to constitute a regional aquifer of generally low productivity. The basalt aquifer is, in general, hydraulically connected with the underlying Paleogene chalk aquifer. A shallow aquifer with moderate productivity has been explored in the Wadi esh Sham - Zelaf area and may exist in other areas within the basalt field.

Depth to groundwater in the main basalt aquifer system ranges from less than 50 m in the morphological depressions of the Yarmouk area near Mzeirib, the Azraq Plain and Manqaa Rahba near Zelaf and increases to more than 300 m in the mountain areas around Jebel el Arab and Tulul al Ashaqif. In some boreholes on the slopes of Jebel el Arab, water levels are situated at more than 500 m below land surface. Water levels in shallow to intermediate basalt aquifers are situated at depths between 0 and 200 m.

The **total thickness** of Neogene to Quaternary basalts increases from less than 100 m on the fringes and in the southeastern and northeastern parts of the basalt field to more than 700 m on the foothills of Jebel el Arab. The saturated thickness of the basalt aquifer system ranges from 100 to 300 m in good parts of the basalt field. Layers with relatively high permeability probably comprise 10 to 20% of the saturated section of the basalt aquifer.

The following approximate ranges of thickness of aquiferous carbonate formations underlying the basalt are inferred according to information from surrounding areas: Paleogene chalks and marly limestones: 0-300 m, Upper Cretaceous limestones and dolomites: 150-400 m.

Groundwater salinity is generally low to intermediate in Jebel el Arab and the basalt aquifer system west and south of Jebel el Arab (200-400 mg/l TDS). Higher groundwater salinities occur in the joint volcanic - sedimentary aquifer on the southwestern fringes of the basalt field, where contents of total dissolved solids of up to several thousand mg/l are observed. In the arid eastern parts of the basalt field, groundwater salinities generally range from 1000 to 1500 mg/l TDS, increasing to 6000 mg/l towards southeast.

Groundwater in most of the western part of the basalt aquifer system is fresh water. The hydrochemical water composition in aquiferous layers of the basalt as well as in underlying carbonate aquifers is dominated by processes during the recharge on basalt outcrops. Dissolved substances derive from:

- atmospheric inputs which are enriched in concentration at or near the surface;
- dissolution of silicate minerals through interaction with water and soil CO_2.

These processes produce Ca - HCO_3, Na - HCO_3 or Na - Cl type water with low to moderate salinity which is generally suitable for domestic use and irrigation.

Groundwater problems in specific areas are:

- increasing groundwater salinity in aquifers affected by irrigation return flow (Dhuleil area, area east of Mafraq);
- the hazard of flow of brackish water from the Azraq Plain towards the AWSA well field if the drawdown cone of the well field continues to be lowered;
- wide spread occurrence of brackish groundwater in the arid northeastern and eastern part of the basalt aquifer system, the Hamad area;
- locally elevated groundwater salinity in the Braq area and some spots of the Hauran Plain.

Aquifer transmissivity is determined by the permeability and thickness of the aquifer. Permeability distribution in the basalt sequence is highly heterogeneous and not known in detail. It may be assumed that layers with relatively high permeability are limited to about 10 to 20% of the total aquifer thickness.

Groundwater movement in the main basalt aquifer is related to extensive groundwater basins. Any large scale groundwater extraction in the individual basins will affect the water balance of the basin and will reduce spring discharge on medium or short terms. Strategies for further groundwater exploration may consider in particular the extraction of limited quantities of water at locations of actual water demand, e.g. for domestic supply, and in areas where groundwater extraction may create only minor immediate effects on the basin-wide groundwater budget.

No particular evaluations of **groundwater balances** have been made, so far, in the framework of the present study. A discussion of groundwater balances is therefore restricted here to general considerations and an outline of information available from earlier reports. These estimates show a high uncertainty with regard to the components of groundwater balances. Without further field investigations, the accuracy of the groundwater budget estimates may be improved, to some extent, through evaluations of isotope and hydrochemical data, a review of the existing groundwater balance assessments, and possibly, through geohydraulic evaluations.

The poorly developed drainage patterns of Miocene-Pliocene plateau basalt and of Pleistocene shield basalt series indicate **infiltration** of surface runoff and possibly also from in-situ rainfall. The Miocene-Pliocene plateau basalts reach thicknesses of several hundreds of meters intercalated by soil and sedimentary interlayers. Deep vertical fractures (cooling cracks as a result of contraction) are prominent in these plateau basalt and may provide favourable groundwater movement. Unconsolidated Quaternary tuff and scoria volcanoes and tuff and scoria terrains may have relatively high infiltration capacities.

Quaternary valley-filling lava flows and Quaternary weathered tuff terrains show differentiated drainage patterns which give evidence of rapid water transportation into morphologic depressions which are delineated as mud pans. The mud pans are covered by fine grained sediments (clay material) which reduce infiltration and recharge into underlying rocks, sediment or soil layers. Due to evaporation, the salinity increases in the sediment pans.

A rough estimate of the **mean annual rainfall** volume over the study area could be computed from the constructed isohytal map and found to be about 3570 MCM. Rainfall averages in the Azraq basin in Jordan range between 541 MCM in dry years, 1100 MCM in average years and 1600 MCM in wet years. Over the total area of the Yarmouk basin in Syria, the mean annual rainfall volume was estimated at about 3146 MCM, of which 1930 MCM is the estimated volume of rainfall over the Syrian part of the study area.

The **mean annual evaporation** in the Azraq basin from free water surface is about 3877 mm with monthly values ranging between 450-590 mm in summer and 105-400 mm in winter. In Syria, the mean annual potential evaporation ranges from 1240-1490 mm in the Yarmouk basin, and increases eastwards from Jebel el Arab area.

As regards **stream flows**, most of the streams in the study area are **ephemeral or intermittent** that are subject to flash floods (wadi-system). In the Syrian part of the study area flow occurs during a period that ranges from 3 to 4 months in Wadi Al-Dahab, Wadi Al-Zeidi and from 4 to 5 months in Wadi Al Raggad and 6 months in Wadi Al Allan. In summer (April-May to November-December) the flow usually ceases except for isolated periods of runoff that result from short intense thunderstorms. The flow in all wadis, except in Al Hreer, is caused by intense rainstorms in winter or spring time and to a limited extent by snow-melting. Groundwater, however, contributes remarkably to the flow of Wadi Al Hreer.

In the Azraq basin wadis drain water into the Azraq Plain (Qa' Azraq) where it may remain several months before evaporation. All wadis are ungauged. The **annual and average runoff volume** over the Azraq basin estimated using empirical formula were: 35.9 MCM, 13.5 MCM and 1.3 MCM for wet, normal and dry years respectively. The long-term mean annual runoff volume was estimated at 24 MCM for the period (1965-1994) Qanqar (1996). No flood estimates were made in the Syrian part of the study area particularly to the east of Damascus-Deraa road, as no information was made available.

Surface water resources of the area are primarily originated from the **stored surface water resources** behind the existing dams and the spring water contributing to the Yarmouk river base flow and the Azraq basin springs in Jordan. Several small dams were constructed in the basalt region in Syria to make use of the flash floods in the area. Six small earth dams have been constructed in Yarmouk, Zerqa, Azraq and Hamad basins in Jordan.

7.2 ACTIONS RECOMMENDED FOR WATER RESOURCES MANAGEMENT

7.2.1 Groundwater exploration

Promising conditions for groundwater exploration are expected in areas with favourable recharge conditions and in areas with relatively high aquifer transmissivity. These conditions may prevail in areas with:

- relatively high rainfall, as around Jebel el Arab and, to some extent, in the Hauran Plain;
- particular features of the surface of basalt flows, indicated by the absence of a distinct drainage pattern, i.e. on outcrops of plateau basalt or shield basalt of Neogene (Nb1 - Nb3), Lower Quaternary (Qb1) or Middle Quaternary (Qb3) age;
- infiltration of surface runoff in larger wadi systems.

Considering the above aspects, a promising potential for exploration of limited quantities of fresh water may be expected in the following areas:

- the area northwest of Suweida covered by Lower Quaternary and Middle Quaternary shield basalts;
- the lower part of the eastern slope of Jebel el Arab covered by Neogene plateau basalts (Nb2), in particular at locations which receive surface runoff from the higher mountain slopes;
- the area south of Bosra where the basalt possibly overlies directly aquiferous carbonate formations.

The above considerations are tentative from a regional point of view. Groundwater exploration in any of the assumed promising areas requires detailed investigation programmes.

A. Groundwater exploration in the Suweida area

The basalt aquifer in the area west and northwest of Suweida, including the Leja Plateau, may comprise a limited potential for additional exploitation of fresh water resources. Fresh water occurs in various horizons at depths between 50 and 400 m below surface within the basalt sequence. The extent and the groundwater potential of the individual aquiferous horizons is, so far, not known in adequate details for a reliable assessment of the exploitable resources. To determine the groundwater potential of the area, an exploration programme would be required. The objectives of the programme may be:

- to determine the extent of productive aquiferous zones at various levels within the basalt sequence;

- to determine the hydraulic properties and exploitable groundwater resources of aquiferous horizons in selected parts of the area;
- to define promising zones or locations for construction of production wells.

The exploration programme can be defined in broad outlines only, at this stage, a more detailed exploration plan may be worked out in cooperation with the competent Syrian institutions.

In general, the programme would have to comprise the following components:

- Compilation and evaluation of all available information on the results of previous exploratory and well drillings through review of reports and documents and through field surveys;

- Drilling of exploratory boreholes: A total of 5 to 10 exploratory drillings to depths ranging from 300 to 500 m may be required. For drilling through basalt rocks to such depths, special drilling equipment will be required (down-the-hole-hammer or similar);

- Performance of geophysical well logging in the exploration boreholes and in existing boreholes which are accessible for geophysical logging equipment. The geophysical well logging has to be considered as a test programme to evaluate the possibilities of identifying and correlating different aquiferous horizons with well logging methods under the local hydrogeologic conditions;

- Application of surface geophysical methods for groundwater exploration in the area cannot be recommended, at this stage, since:

    - it cannot be expected that individual characteristic signals can be received from geoelectric or electromagnetic measurements in the multi-layered and several hundred meters thick sequence of basalt flows;
    - no reliable standard method is known for identifying fracture zones with elevated permeability at several hundred meters depth;
    - costs of seismic investigations to explore geological structures of hydrogeologic importance would probably be prohibitive.

- Performance of pumping tests over several days at the exploration boreholes and at suitable existing wells.

The programme should be accompanied by hydrochemical and isotope hydrologic analyses, which are expected to provide information in particular on recharge conditions of the tapped groundwater.

Successful exploration boreholes may be converted into production wells.

B. Exploration of carbonate aquifers underlying the basalt in the Syrian Arab Republic

In most parts of the extent of the basalt in the Syrian territory, the basalt appears to be underlain by Paleogene chalks, Upper Cretaceous to Paleocene marls and Upper Cretaceous limestones and dolomites. No detailed knowledge on the aquiferous properties of this sedimentary sequence below the basalt field is available.

The Paleogene chalks are generally poor aquifers at greater depth.

The Upper Cretaceous limestones and dolomites are probably, in most parts of the basalt field in Syria, covered by a thick sequence of marls with low permeability and situated at depths of several hundred meters. The chance of tapping a significant potential of fresh water in the Upper Cretaceous carbonate aquifer appears therefore not promising, in general. Groundwater recharge may be very limited and the groundwater may be brackish after leaking through the overlying marls.

In the Mafraq area, the hydraulically connected basalt and Upper Cretaceous carbonate rocks provide an aquifer with moderate to high productivity. The formations of Paleogene chalk and Upper Cretaceous marls are missing in this area, which comprises a structural high and considered to be an extension of the Ajloun Dome. That geological structure is probably delimited in the northeast by a major fault related to the Fuluk fault - Hamza graben system. The extent of the fault into the Syrian territory is not known. Its alignment cannot be traced on satellite images because of a thick cover of soil and weathered basalt.

It appears possible that the structural high extends over a limited area of the Syrian territory south of Bosra. The top of the Upper Cretaceous limestones and dolomites may be situated at a depth of 300 to 400 m below surface, overlain directly by Neogene basalts or by Upper Cretaceous marls and/or Paleogene chalk in reduced thickness. Depth to groundwater is expected to be between 100 and 200 m.

To identify the geological sequence and the potential of the basalt and Upper Cretaceous carbonate aquifers in the area south of Bosra, drilling of deep exploratory boreholes will be necessary with depths range from 400-500 m.

The extent or absence of the Upper Cretaceous marls aquitard may, in principle, be investigated through surface geophysical methods, since the electrical resistivity of the marls may be significantly different from the resistivity of basalts and of the limestone and dolomite formation. In view of the probable deep situation of the basalt base (several hundred meters), surface geophysical prospecting may not be cost efficient.

C. Groundwater potential in the Hamad area

The fresh water potential in the northeastern and eastern parts of the basalt field, the Hamad area, are limited because of the arid climate conditions and very low recharge rates. Fresh water lenses are known to occur in the basalt or underlying Paleogene chalks along major wadi courses, where infiltration of wadi runoff creates some groundwater recharge. Unexplored fresh water lenses with limited extent may exist in some wadis. Promising areas for exploration of fresh water lenses may be identified through hydrographic analysis, using topographic maps and satellite images, and hydrologic observations.

Deeper groundwater related to the regional aquifer flow system is generally brackish and non-renewable. In wide areas, the water table of the deeper groundwater is situated below the basalt cover in the Paleogene chalk aquifer.

Exploration of limited quantities of brackish groundwater, which can be used for watering of livestock, or even fresh water (e.g. borehole NDW1) appears possible. For that purpose, it is recommended to conduct a detailed survey of all existing boreholes in the northeastern and eastern parts of the basalt field, including:

- compilation of available relevant information, such as drilling records and data of well tests;
- collection of water samples for chemical and isotope analysis;
- measurement of water levels, determination of the topographic altitude of well heads;
- performance of pumping tests, where possible.

An evaluation of the data obtained through the survey may provide an improved basis for the planning of further groundwater exploration measures.

7.2.2 Water quality rehabilitation in Dhuleil and Mafraq areas

Groundwater quality has deteriorated in the Dhuleil area and is also threatened in the area east of Mafraq through the impact of irrigation return flow.

To avoid increasing water quality problems and to restore an adequate water quality in the aquifers of these areas, irrigation practices have to be improved. Measure for rehabilitation of saline soils in the Dhuleil area have been recommended by Nitsch (1990). In applying these measures, impacts on the groundwater quality have to be considered. The necessary leaching of saline soils will introduce dissolved salts into the groundwater. Methods of and water quantities applied for the soil leaching should be adjusted to the requirements of groundwater quality conservation and improvement: The salinity of the water percolating into the aquifer should preferably not exceed the natural background level of groundwater salinity, which is around 700 mg/l TDS.

The following approach to restore the soil and groundwater quality may be considered:

- Rehabilitation of saline soils with adequate quantities of fresh water from the Khaldiya reservoir;
- Introduction of irrigation practices and crop pattern through which further soil salinization can be avoided;
- Stopping of application of water with elevated salinity directly for irrigation: e.g. through:
  - mixing of brackish water with fresh water from the Khaldiya reservoir;
  - disposal of extracted brackish water for other purposes;
  - closing of wells yielding brackish water.

The measures should be accompanied by a water quality monitoring programme.

7.2.3 Surface water management

A. Surface water impounding and artificial groundwater recharge

Most of the streams in the study area are ephemeral or intermittent and subject to flash floods depending on the amount, duration and intensity of precipitation, evaporation, permeability of the wadi fill and bedrock, the size and nature of the catchment area. In the Syrian part of the study area, good progress has been achieved in surface water impounding for domestic use, irrigation, livestock and artificial groundwater recharge (table 7). Currently, construction of additional dams in the country is underway; 23 dam sites are proposed including Yarmouk and Damascus basins.

In Jordan, the most promising area which has favourable conditions for surface water impounding, particularly for artificial groundwater recharge to the basalt aquifer system, is in north Azraq basin. The annual average runoff volume over the Azraq basin in normal years was estimated at 13.5 MCM.

Geotectonics and scorieous basalts play an important factor in the infiltration rates in addition to prevailing soil texture and topography for a positive relation between the amount of floods and the amount of water that infiltrates into the basalt aquifer system in Azraq area. This indicates that making use of the flood water for artificial groundwater recharge projects, if executed in the Azraq basin, would be of vital importance for addressing problems of aquifer depletion, ceasing of spring-flows and/or deterioration of groundwater quality particularly adjacent to the Qa' Azraq.

Conjunctive use of flood water and groundwater in the lower reaches of the main subcatchment areas where the private and AWSA well fields exist may provide an optimal solution by implementing artificial groundwater recharge projects via constructing small earth dams, check dams or spreading dikes after thorough investigations to justify and identify possible sites for such water works. Also, surface water impounding to level the flood hydrograph (increasing the life span of runoff) will create possibilities to utilize the stored surface waters under different climatic conditions for conserving runoff and flood water supplementing available groundwater resources, preventing salt water intrusion near and adjacent to Qa' Azraq and may mitigate the impacts of rainfall variability on crop production.

Kharabsheh (1995) has carried out hydrologic investigation on five main subcatchment areas in north Azraq (950 km^2). It was found that the annual flood volume stored behind the proposed dams at the lower reaches of the subcatchments is in the order of 12.8 MCM which is almost equal to the Azraq spring flows before they dried up by 1991. The annual recharge to the basalt aquifer system from the stored flood water is estimated at 8.5 MCM.

B. <u>Rainfall harvesting</u>

A rough estimate of the mean annual rainfall volume over the study area could be computed from the constructed isohyetal map (5) and found to be about 3570 MCM. Rainfall average in normal years in Azraq is estimated at 1100 MCM. Over the total area of Yarmouk basin in Syria, the mean annual rainfall volume was estimated at about 3146 MCM of which 1930 MCM is the estimated volume of rainfall over the Syrian part of the study area. Therefore, rainfall harvesting is of vital importance to supplement the water resources in the area for rainfed agriculture, livestock and increasing the infiltration water to recharge the regional basalt aquifer in Jordan and Syria.

In order to identify favourable sites for executing rainfall harvesting projects it is recommended to undertake the following:

- Water harvesting schemes must make sure that adequate and reliable data and information on rainfall and stream flow or runoff in general are available so as to design with less costly and safety margins against unknown or uncertain risks;

- It is essential for intensifying rainfall and surface runoff measurement networks to be established ahead of time to provide the data required for water harvesting project planning and design. Small experimental water sheds would provide more realistic data on estimation of surface runoff from rainfall data, and would provide significant input towards successful water harvesting projects;

- Detailed hydrometeorological analysis of rainfall data (daily and storm by storm) as well as probability and risk analysis of intra storms drought periods, rainfall intensities and durations of single rainfall events is required for better designs;

- Field investigations on the prevailing hydrogeologic conditions and geotectonic structure of the area where water harvesting projects may be executed have to be carried out before designing such projects;

- Research works are needed to identify the hydrologic response of the main catchments to water harvesting and farming practices, particularly on the catchment water and sediment yields as well as water quality evolution;

- As regards the aquifers occurring in the catchment area, research works have to be conducted to identify the impact or the possible adverse effect on the productivity of the aquifers as a result of catchment water and the rate of suspended solids or sediment yields and soil erosion.

7.2.4 Isotope hydrology

A. Geohydraulics and paleoclimate

It is still not clear to which extent groundwater resources in the Basalt Aquifer System are related to recent recharge or to recharge during pluvial periods. An improved knowledge of these recharge conditions is needed for a reliable interpretation of the isotope hydrological data and for the numerical modelling and assessment of the water budget.

To get an answer, a dense ^{14}C mapping is recommended including high precision ^{3}H measurements and stable isotope determination. A suitable study area would be the section between the AWSA well field at Azraq and the Syrian border. This part is not affected by irrigation return flow and many WAJ and private wells exist with depth down to 400 m. About 20 - 40 samples should be taken within a strip of about 20 - 30 km width. TDIC contents are extremely low, but ^{14}C analyses can be performed at the laboratory of NLfB, Hannover, which is ready to carry out a joint scientific research with competent institutions.

This study may be supplemented by sampling of deep and shallow groundwater on the southern slope of Jebel el Arab up to the mountain plateaus.

B. Groundwater mining

In the Azraq Basin the groundwater gradient is low and the exploitation of the groundwater resources may result in a mobilization of saline water in the south and a contamination of the fresh water resources. The hazard of salt water intrusion from the sabkha Azraq (Almomani 1993) can be at least partly assessed from results of existing and additional isotope hydrological analyses.

^{14}C determination on the inorganic carbon (TDIC) of groundwater and other isotope analyses from various sites in the Azraq Basin have been carried out since 1969. The time series of results are unique in the world and allowed to develop a preliminary conceptional model on the geohydraulics of the local system and an explanation of the hydrochemical changes as a result of the groundwater mining (Verhagen et al. 1991). The last ^{14}C analyses were done, however, in 1986. Since then, significant changes in the hydrochemical composition of the groundwater occurred and major springs ceased to discharge.

In order to confirm, improve or even reject the conceptional mining model, the time-series should be updated through re-sampling and additional analyses.

7.2.5 Hydrogeologic and hydrologic monitoring

The observation networks in the Syrian and Jordanian parts of the study area need to be further improved. Streamflow gauging stations are usually installed to measure surface runoff and provide information on runoff characteristics. However, records from gaging stations and periodic streamflow measurements could be used to determine water losses and gains in mountain and alluvial channels of the principal wadis. Such information is significant for understanding the recharge mechanism and for the integrated management of surface and groundwater systems. Watershed management, artificial recharge, rainfall harvesting, rainfed agriculture and construction of water works require more information on rainfall, runoff, flood reoccurrences, water levels, water quality and aquifer characteristics.

A. Groundwater monitoring network

Groundwater is characterized by relatively small time variability and pronounced spatial or areal variability. Although time-series measurements such as water level and water quality observation form essential part of groundwater investigations, network design should place a major emphasis on regionalization of hydrologic parameters that govern the occurrences, movement and storage of groundwater.

The design of groundwater networks is usually made through an implicit evaluation of existing and potential problems and hydrogeologic heterogeneity. The first reflecting the economic interest and the second the amount of effort that might be required to define the geohydrologic framework.

Data that are useful in defining the regional geohydrologic framework are abundant in both the Syrian and Jordanian parts of the aquifer system. However, updating of information on recharge and discharge, and improving the groundwater data collection system is necessary in order to obtain adequate data and information for the development of groundwater simulation modelling.

Time series data which need to be collected comprise:

(a) Water levels;

(b) The amount of abstractions and well discharge;

(c) Springs discharge;

(d) Quality of groundwater.

Data computed from groundwater networks include:

(a) Aquifer parameters determined from pumping tests;

(b) Potentiometric surfaces, flow directions, ... etc.

The groundwater network in the Syrian part of the Yarmouk basin underlain mainly by the Regional Basaltic Aquifer System, was set up in 1978 within the context of a water resources project implemented by SELKHOPROMEXPORT. The network consisted of 69 boreholes and 40 springs, data collection lasted three years (1978-1981). In 1981, the groundwater network was extended to include private wells and wells drilled by other institutions. Monthly periodical measurements were conducted and they comprised water levels, water quality, well discharge and temperature. Since 1981 the observation programmes became discontinuous and important gaps existed during the last decade.

Some 519 wells have been drilled in the Azraq basin of which 327 well were operational in 1989.

Total withdrawal increased from 19.3 MCM in 1982 to 48.4 MCM in 1994. Systematic monitoring of public and private wells commenced in 1982. Data collection from the groundwater observation networks (observation wells and springs) during the period 1982-1991 demonstrated that spring discharge decreased, during this decade, from 8.35 MCM until it dried up in 1991 as a response to a continuous decline in water levels.

What is crucial, however, with regard to the effects of development is the degradation in water quality. In 1971 initial TDS in Wadi Dhuleil groundwater was about 300 mg/l. Salinity increased since then and total mineralization reached 3400 mg/l in 1986. Groundwater quality network has received particular attention in this area and quality data is now available in table, maps or in the WAJ data bank.

Monitoring on water levels, water quality and well discharges have to be continued and assessed in both Jordan and Syria.

B. Aquifer parameters

The fundamental aquifer parameters of transmissivity and storage coefficient are needed for the evaluation of the water resources of the aquifer system and its development planning. The most reliable test by pumping test analysis is costly and in the case of a multi-aquifer sequence as such occurs in northern Jordan, presents considerable problems of interpretation in consequence of the practical limitation of the test procedures.

Knowledge of storativity in all areas underlain by the Regional Basaltic Aquifer System is scarce, and difficulties are expected to be encountered when attempts are made to assign specific values for simulation modelling.

No adequate information could be obtained about the aquifer parameters from the well pumping tests carried out in the study area in both Jordan and Syria. Therefore, long-term pumping tests have to be programmed in an evenly distributed manner to secure good knowledge about the aquifer performance to facilitate the development of an acceptable simulation modelling which will provide guidance for optimal utilization of the available groundwater resources in the area.

The test pumping of each well shall be carried out in two stages. The first stage shall comprise a varying discharge step-drawdown test of duration not exceeding 36 hours and a recovery test. The second stage 96 hours. Constant yield test shall follow when the water in the borehole has recovered to or close to its original level after completion of the first stage. Throughout the duration of these tests, measurements of the drawdown should be carried out following normal procedures for such tests. Immediately, upon completion of the constant discharge test, a recovery test shall be carried out for a minimum period of 48 hours.

7.2.6 Establishment of a groundwater data base

A great number of hydrogeological data has been obtained from groundwater investigation and observation programmes in various parts of Syria. These data provide highly valuable information for future activities of assessment, development and management of the national groundwater resources. The data are contained in project reports and in files of various government authorities. Accessibility of the data and data security could be greatly improved through a national computerized groundwater data base, as it exists, e.g. in Jordan.

With presently available computer technology and specialized software, development and installation of a national groundwater data base would be achievable with relatively limited efforts. Financial resources would be required for computer hardware, software and training.

The currently issued version of "UN/Groundwater Software for Windows" provides a user-friendly tool for storage, processing and retrieval of groundwater data, including the following applications: hydrochemistry, well logs and lithology, pumping tests, hydrographs, grain size curves, mapping, and fence diagrams. This software has been developed by the United Nations Natural Resources Environment Planning and Management Branch, New York, and is disseminated for the purpose of promoting and assisting groundwater studies in governments and research institutions.

The ESCWA/ENRED may support the development and installation of a national groundwater data base in Syria through technical advice and mediation of international experience, if this should be requested by the Syrian authorities.

7.2.7 Institutional arrangements

Mutual cooperation and coordination for developing and managing the shared water shed comprising the basalt aquifer is extremely beneficial for Jordan and Syria. The ultimate goal of shared basin development is a comprehensive and many-sided plan dealing with all measures to ensure rational development, utilization and conservation of the water resources taking into account the socio-economic factors prevailing in both countries.

It is needless to say that unilateral development of the common water resources will never reach its ultimate usefulness and totality without full knowledge of the shared water sheds' main parameters, which include: geomorphology, hydrology, hydrogeology, hydrometeorology, agrometeorology, climate, soil and vegetation. The knowledge of these parameters will render the shared basalt water resources development much easier, more realistic, possible and reliable on a long-term basis. Moreover, unilateral development will inevitably be guided mainly by the interest of the country taking the action, with little regard for the other country involved, and this may give rise to undesirable problems which can be so intractable that they stop all forms of joint actions.

Bearing in mind the preceding discussion, the following course of actions is recommended to be considered by both countries to develop their shared water resources, surface and groundwater:

- Set up joint advisory steering committee responsible for coordinating, following-up and exchange of information regarding water shed investigations. This committee may be composed of representatives of the governments' authorities concerned;

- Constitute national teams of experts to operate collectively, where possible, to standardize and establish technical basic data on all relevant water shed parameters. A representative of these national teams delegated by his government should be a member in the steering committee mentioned above;

- Formulate of joint programmes for basic data collection, inventory, publications, required mapping, appraisal of existing projects, research and its mechanism, basin development and management and design and executing relevant pilot projects of common interest;

- Formulate of subregional plans and designs including alternative schemes for water resources development and allocation policies;

- Follow-up the implementation of the recommended actions, mentioned earlier, for the development, management and conservation of the shared water resources within the basalt field in Jordan and Syria either at national or subregional levels;

- Prepare analytical papers and substantive reports as required by the competent water authorities in Jordan and Syria on the water resources activities being carried out or planned in the area.

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APPENDIX 1

INTERPRETATION OF LANDSAT THEMATIC MAPPER IMAGES OF THE BASALT AREA

LANDSAT - THEMATIC MAPPER (TM) satellite imagery was carried out on the basis of different TM-band combinations and ground truth in the basalt area of northern Jordan and southwestern Syria.

With the aid of satellite imagery a synoptic geologic model of the Neogene and Quaternary basalts has been developed at 1:250.000 scale. TM-data gave detailed new information about the distribution and differentiation of the basalt series.

For this study images of the LANDSAT 5 satellite were chosen because of the favorable spectral and spatial resolution of the Thematic Mapper (TM) multispectral scanner. The LANDSAT 5 satellite is a sunsynchronous polar orbiter which passes all parallel latitudes always at the same time, e.g. the equator at about 10:00 am. One scanned full scene has a size of 160x160 km on the earth's surface. The scene comprises about 240 Mb of data. The scanner records 7 spectral bands, 3 in the visible, 3 in the infrared, and 1 band in the thermal infrared section of the spectral range. The spatial resolution is about 30 m, e.g. one picture element (pixel) covers 30x30 m on the earth's surface. LANDSAT TM data reveal the best conditions for geological research, e.g. for lithologic discrimination inclusive of alteration zones and of the recognition of structures.

Standard processing revealed a high quality suitable for an appropriate visual interpretation. The processing included a topographical standard correction.

The TM-band 1 (0.45-0.52 μm) combined with a blue filter which is in the spectral range of the visible light (VIS, the visible blue part of the VIS) shows high reflectance of bright material which has a high albedo, e.g. clay minerals and shows strong absorption of vegetation and minerals, rocks or soil which contain bivalent and/or trivalent iron (Fe^{2+} and/or Fe^{3+}).

The TM-band 4 (0.76-0.90 μm) combined with a green filter which is in the near infrared spectrum (NIR) shows high reflectance of chlorophyll, intermediate reflectance of clay and shows absorption of Fe^{2+} and Fe^{3+}.

The TM-band 5 (1.55-1.75 μm) and TM-band 7 (2.08-2.35 μm) which are in the range of the short-wave infrared (SWIR) show high reflectance of Fe^{2+} and Fe^{3+} containing material.

Additionally, the TM-band 7 shows absorption features of anions and molecules such as OH^-, CO_3^{2-} and H_2O resulting from lattice overtone and bending-stretching vibrations of the fundamental modes occurring at these longer wavelengths. Contamination of organic material or opaqe accessories reduce the diagnostic absorption feature in the range of 2.3 μm.

Two Landsat TM satellite data sets (scenes) are covering the target area. The northern scene (path and row 173/037) was taken from the date of 22.11.1991 and the southern scene (path and row 173/038) was taken from the date of 26.10.1993. Data processing was carried out by the Gesellschaft für Angewandte Fernerkundung (GAF, München) and by the BGR (Hannover) in TM-band combinations (7-4-1), (7/1-4-1), (5/7-4-1) colour coded red, green and blue. All hardcopies (colour photo prints) were carried out by the BGR (Hannover).

The hardcopies are in the scales 1:100.000, 1:250.000, 1:500.000 and 1:1.000.000.

According to image processing the satellite images show a wide range of colours. The colours result from absorption and reflectance properties, image processing and from photographic laboratory work. The following colours are typical of the mineral groups mentioned before:

- Phyllosilicates (e.g. kaolinite, montmorillonite, mica incl. sericite, chlorite; also calcite). The colour in the image using the red filter in band 7 is blue to green because low reflexion "reduces" the red in the resulting colour.

- Iron hidroxides (goethite, limonite). The resulting colour using the same red filter is red, because the high reflexion in band 7 intensifies the red in the resulting colour.

The TM-band combination 7-4-1:

According to absorption and reflectance properties the TM-band combination 7-4-1 colour coded red-blue-green creates an image with characteristic features:

Red colours are displayed by iron-rich rocks or soil which have a low albedo (dark coloured volcanic ash, weathered basalt surface, ... etc.).

Green colours predominantly represent vegetation.

Blue and cyan colours represent alteration zones, clay minerals and carbonates which are free of impurities.

The colours representing basaltic material in the basalt area are reddish brown, brown, bluish brown, blackish brown, dark blue, black, dark grey and grey.

The present TM-band combination shows fresh basalt in dark black. Depending on the different climatic conditions the reflection properties of the basaltic rocks differ. Especially in the western area weathering processes with soil production increase the reflectance into shorter wavelength due to increasing content of mica and clay minerals (TM-band 1). It results in bluish-blackish and greyish basalt because the red-component (TM-band 7) is overtoned. In the eastern area increasing oxidation and precipitation of iron oxides and lower production of clay minerals and soil increases reflectance in the SWIR-range (TM-band 7). At this stage the basalts reach more brownish colour.

To the outermost W and SW of the southern scene Cretaceous limestone is exposed near the City of Mafraq and south of Amman (The city of Amman is not displayed on the image). Predominantly, the limestone is free of organic impurities which is evident by its whitish colour.

South of the basalt field Cenozoic sediments are exposed in brownish, white, yellow, red and cyan colours. The brownish colour derives from chert sediments which contain some amounts of iron oxides. The white and yellow colour reflects quartz-rich eolian and fluviatile sand. The cyan (or bluish-greenish) colour which occurs in the Wadi Sirhan depression is assumed to be caused by kaolinitic-carbonatic evaporitic sediments with a distinct sodium salt content. The reason for the cyan colour are bending-stretching vibrations of OH-anions in evaporites with resulting absorption of TM-band 7 (red). The trace of cyan coloured sediments can be followed up through the Wadi Sirhan until the Azraq well field area. Directly in the area of Azraq two red coloured fields occur. The red colour indicates absorption of TM-band 1 and TM-band 4 and reflectance in TM-band 7, due to lack of vegetation and occurrence of bivalent and/or trivalent iron. Obviously, this area is covered by dead or dry vegetation and plenty of iron oxides.

In an area south of the two Azraq springs the blue and the red colour receive less radiation. A homogenous green field extending in that area is assumed to be a dry pond of anomalous chemical composition. Probably absorption occurs in the visible wavelengths, especially in TM-band 1, due to charge transfer of iron-bearing minerals or soils, as well as absorption in the SWIR-range of TM-band 7, due to bending-stretching vibrations of OH-anions.

The TM-band combination 7/1-4-1:

The TM-band combination 7/1-4-1 colour coded red-green-blue was used to enhance the signal of reflectance of bivalent and/or trivalent iron for TM-band 7 in favour of fading over the absorption of bivalent and/or trivalent iron for TM-band 1. This effect is caused by the mathematical quotient calculated by TM-band 7 divided by TM-band 1 digital data. This method is called "iron-factor".

Intensive red colours indicate iron-rich volcanic cones and scoriaceous material. Predominantly, the Quaternary volcanic cones show this peculiar feature. A dense cover of volcanic cones is evident in the area of Jebel Al Arab.

Red colour overtone exists overall in the Neogene basalt fields, whereas the Quaternary/Recent basalt flows are free of red colours and appear in bluish black colours.

The TM-band combination 5/7-4-1:

The calculated quotient of SWIR-bands, in which values of TM-band 5 are divided by TM-band 7, enhances rocks which contain mica, calcite and gypsum. According to the absorption properties of the minerals in the spectral range of TM-band 7 distinct areas are delineated by red colours.

Generally, high reflectance in TM-band 5 and strong absorption in TM-band 7 is known from mica and clay minerals, e.g. chlorite, kaolinite and montmorillonite.

The top of the Tell As-Safa volcano and also two basalt fields bordering the center of the volcano in the NW and SE show a higher response in red colour in comparison to the rest of the volcano. The red coloured areas represent the latest volcanic eruption in the entire basalt field.

The basalt area is composed of Neogene plateau basalt, Quaternary and Recent basaltic lava flows and shield volcanoes. Basaltic dyke feeders extend along NW-SE trending fault systems. The Neogene plateau basalts reach a thickness of about 1500 m in the area of Jabal Al Arab. Quaternary basaltic lava flows and shield volcanoes are emplaced as point source feeders along NNW-SSE trending lineaments which are crosscutting the Neogene series. Their total thickness varies from few meters to 150 m.

From the satellite imagery, hydrologic features relevant for the exploration of water resources can be distinguished:

The poorly developed drainage patterns of Miocene-Pliocene plateau basalt and of Pleistocene shield basalt series indicate infiltration of surface runoff from highly developed drainage systems of valley-filling lava flow terrains and possibly also from in-situ rainfall. The Miocene-Pliocene plateau basalts reach thicknesses of several hundreds of meters intercalated by soil and sedimentary interlayers. Deep vertical fractures (cooling cracks as result of contraction) are prominent in these plateau basalts and may provide favourable groundwater movement. Unconsolidated Quaternary tuff and scoria volcanoes and tuff and scoria terrains may have relatively high infiltration capacities.

Quaternary valley-filling lava flows and Quaternary weathered tuff terrains show differentiated drainage patterns which give evidence of rapid water transportation into morphologic depressions which are delineated as mud pans. The mud pans are covered by fine grained sediments (clay material) which reduce infiltration and recharge into underlying rocks, sediment or soil layers. Due to evaporation the salinity increases in the sediment pans.

Basaltic dykes crosscutting the entire area can be deeply situated hydraulic barriers. They can separate areas of different groundwater level and differentiate the basalt aquifers into compartments with different aquiferous properties.

FIGURES

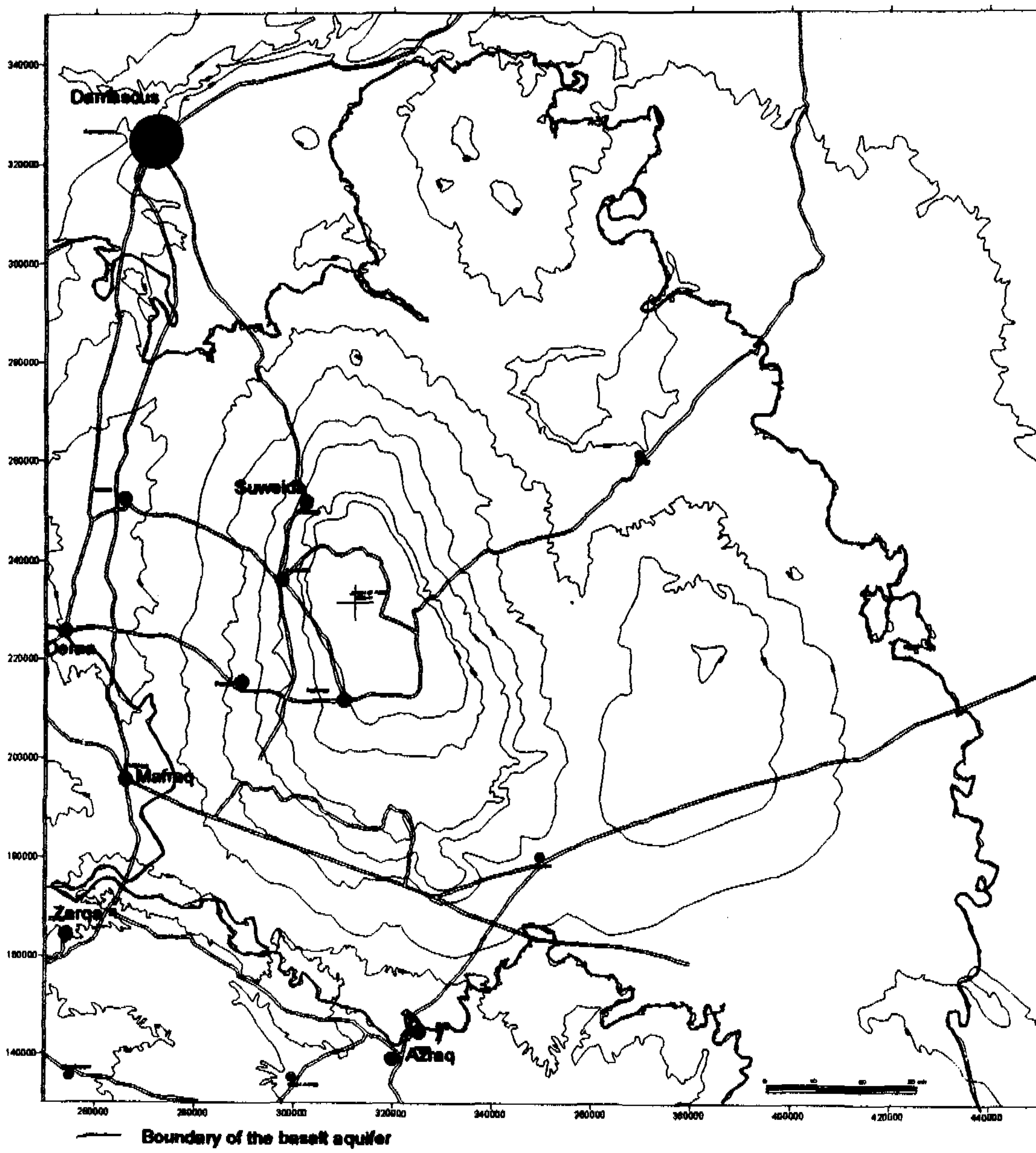


Figure 1: Basalt Aquifer Region in Jordan and Syria

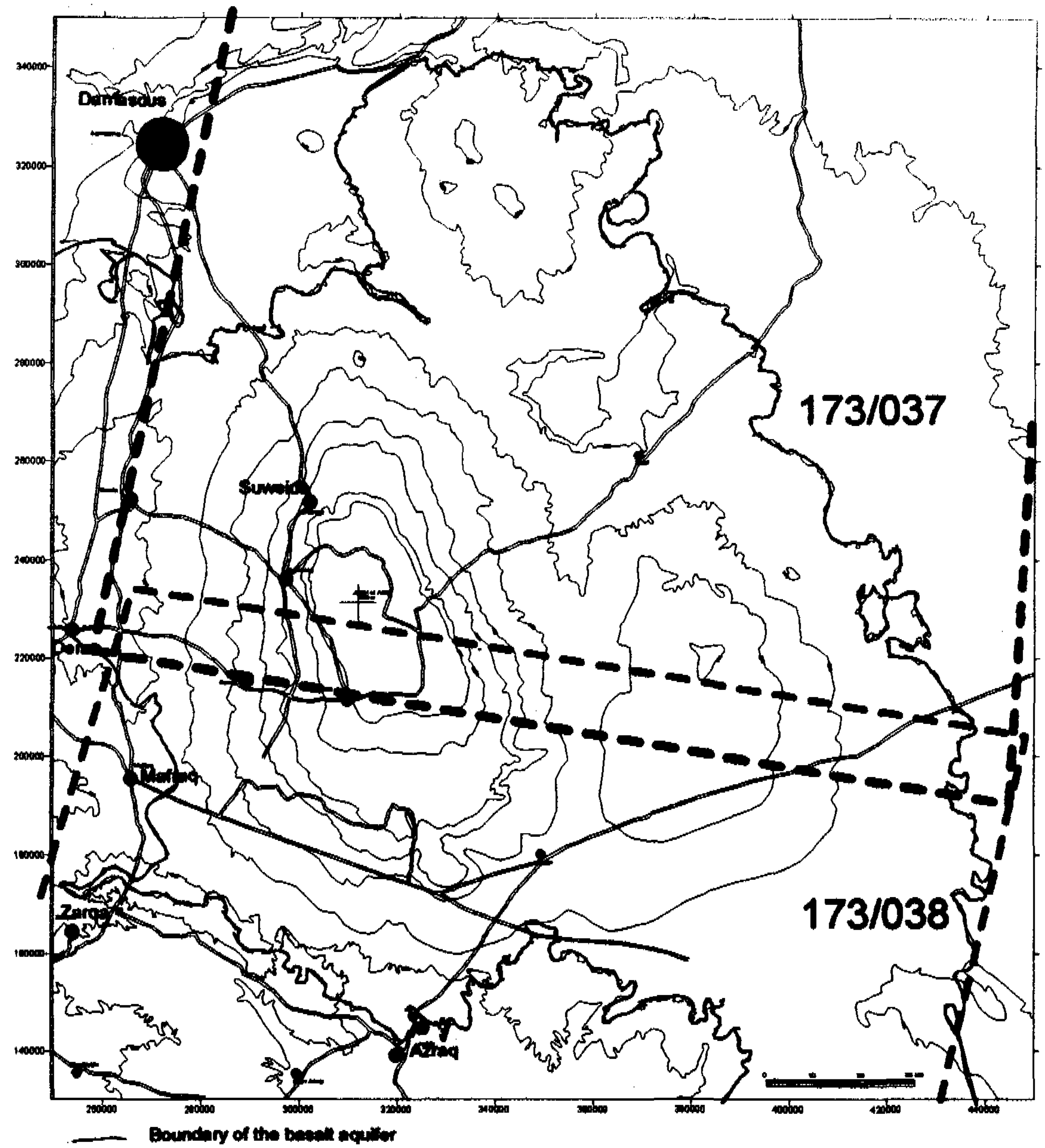
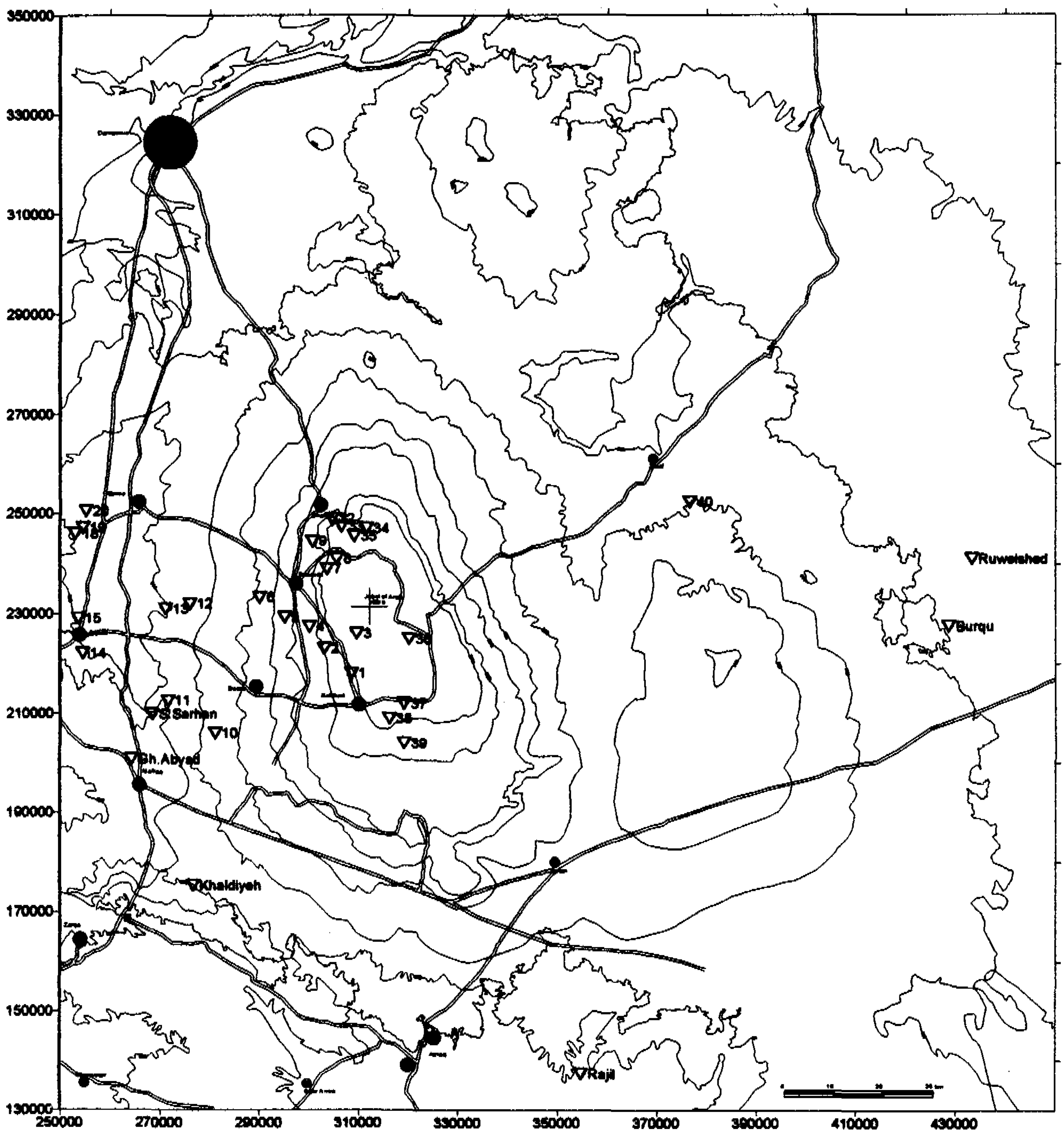


Figure 2: Location of satellite image scenes TM 173/037 and 173/038



Numbering of dams in Syria see Tab. 7

Fig. 3: Location of dams

Fig.4: Specific capacity against transmissivity, northeastern Jordan

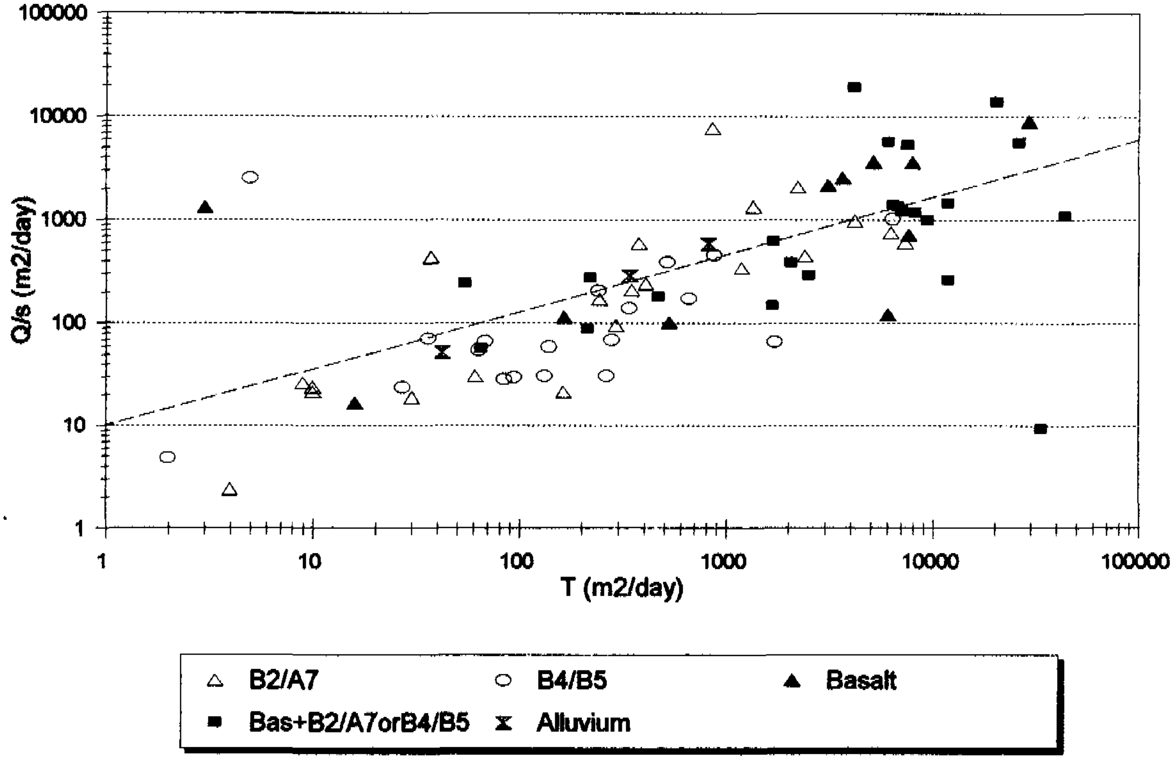
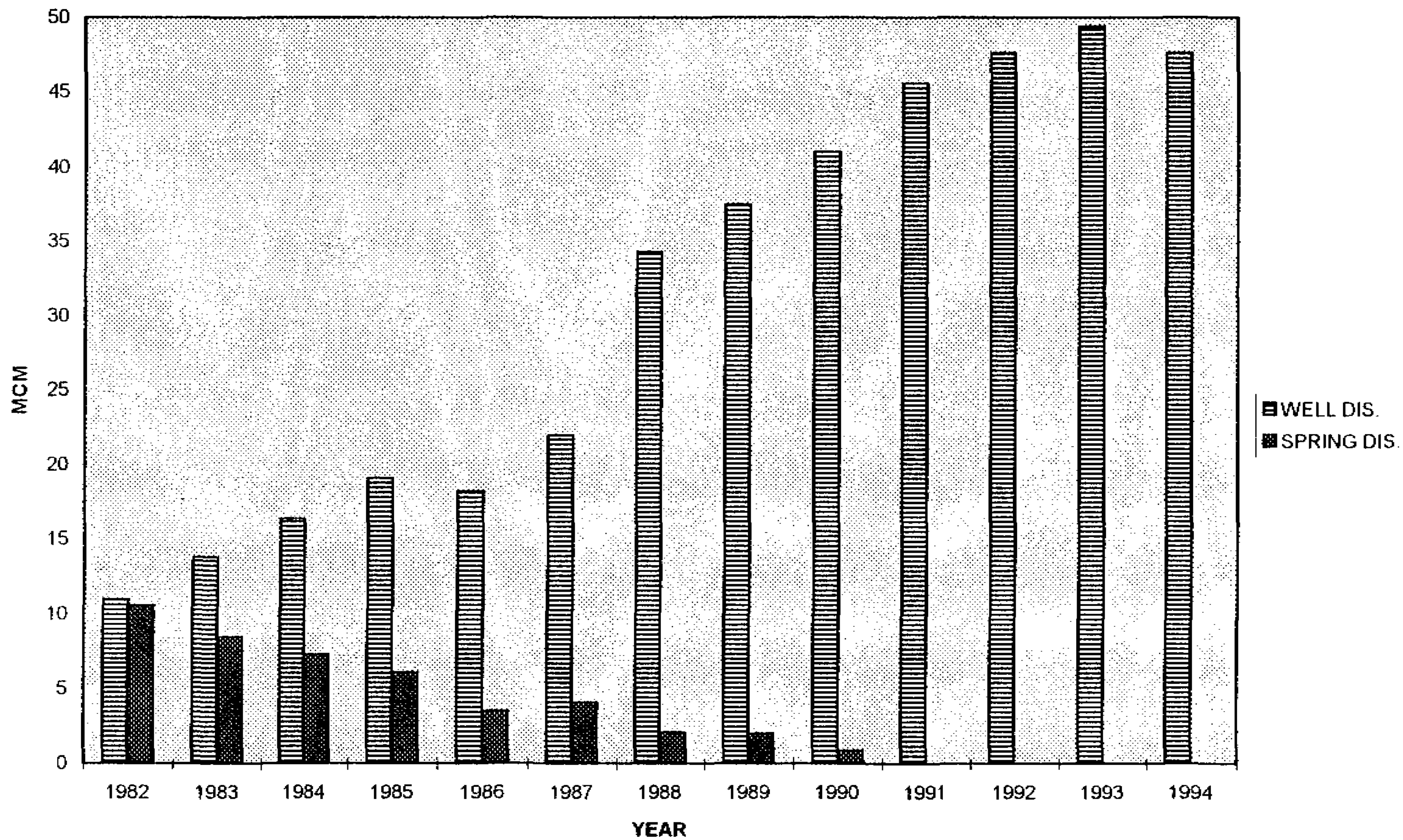


Figure 5. **WELL DISCHARGE & SPRING DISCHARGE (MCM)**



SOURCE: E. QUNQAR, 1996 (AZRAQ BASIN)

Figure 6: Box- and- whisker diagrams, explanation

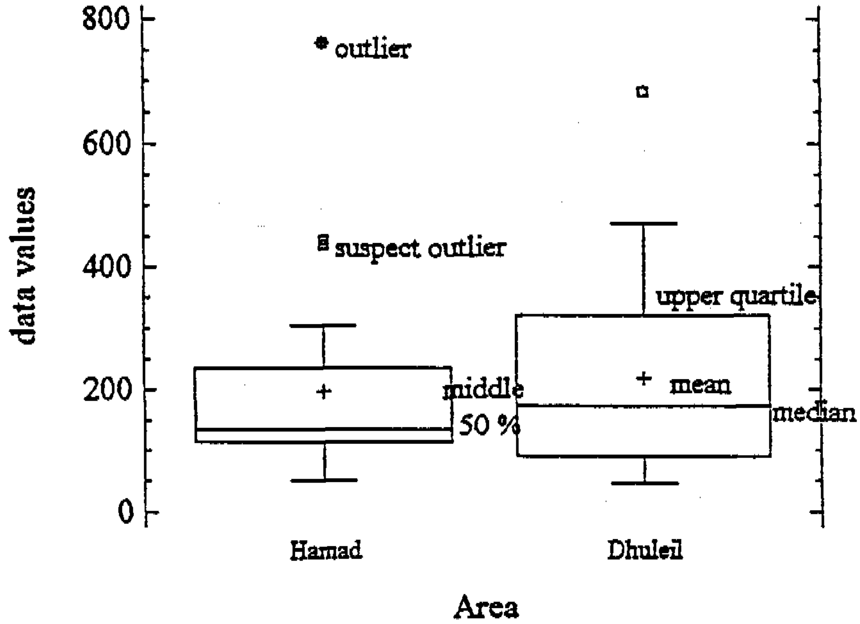


Fig. 7: Mean anion concentrations in precipitation in N Jordan and S Syria

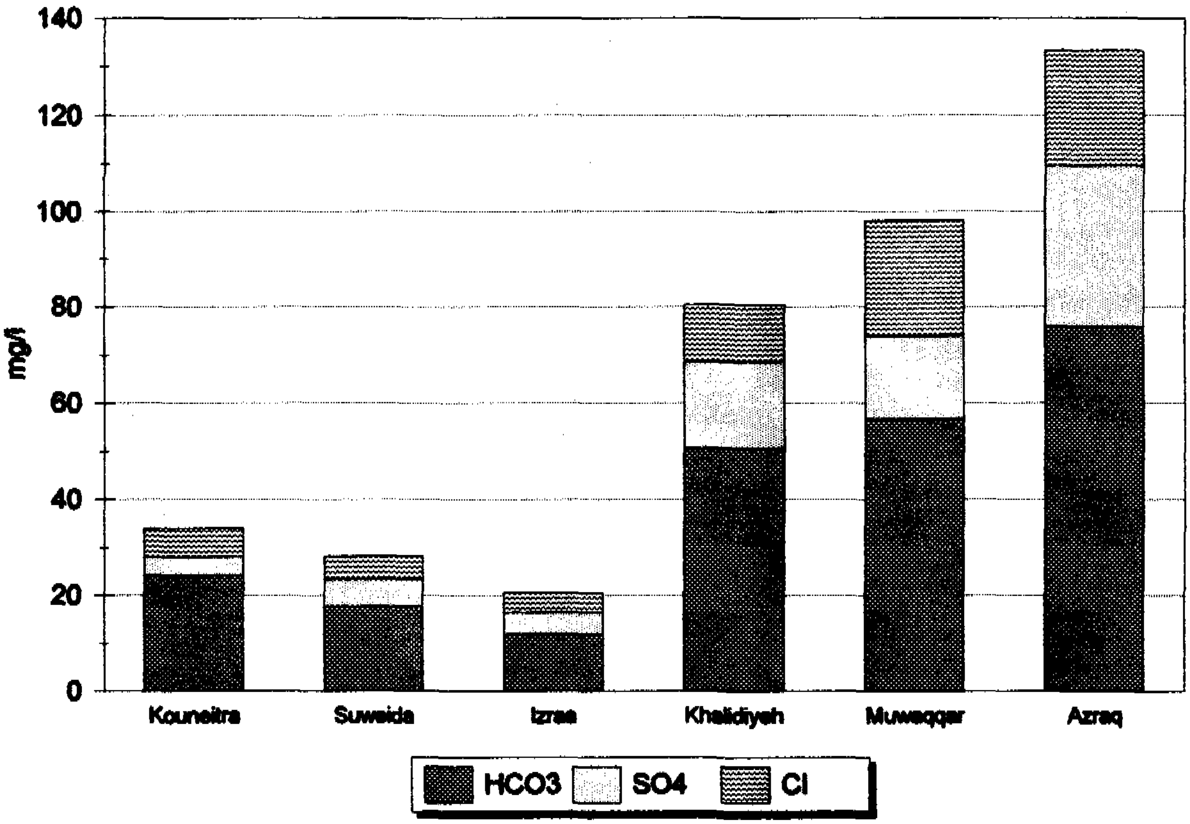


Fig. 8: Mean anion concentrations in rain, flood and ground water

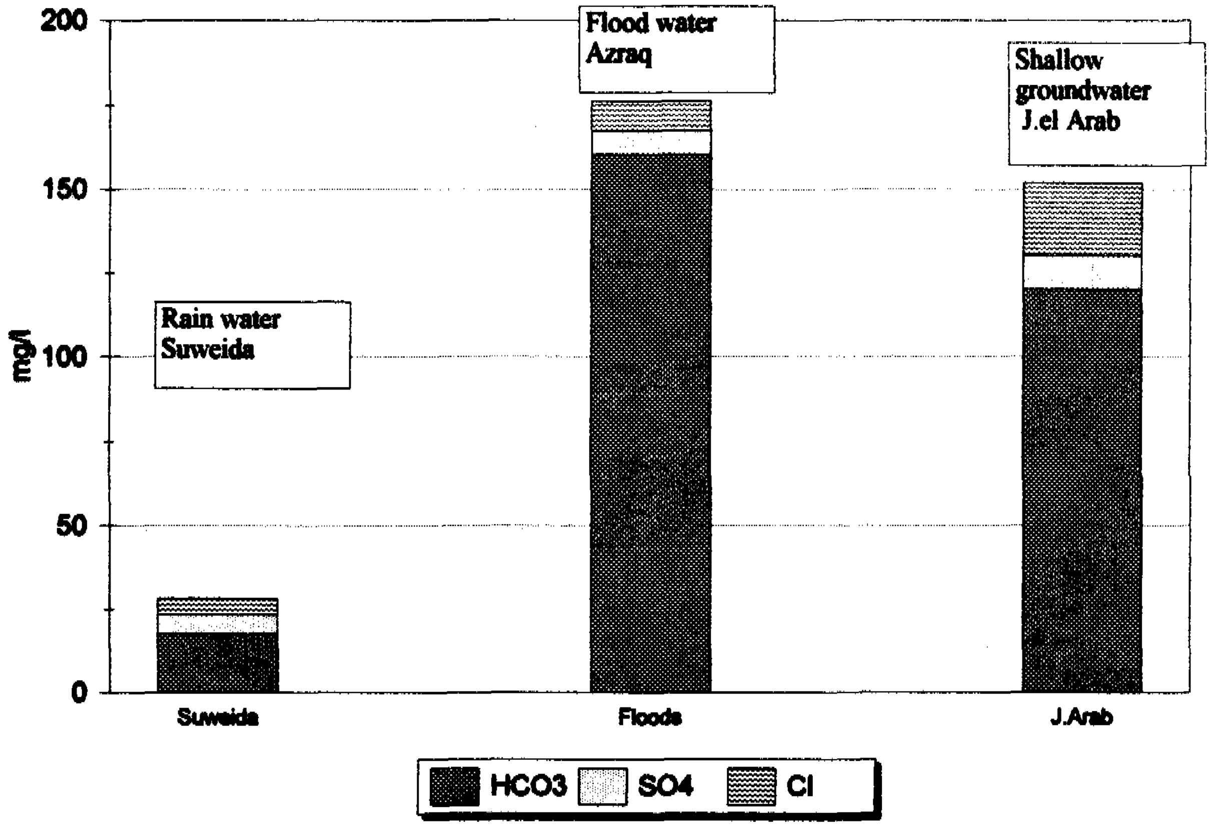


Figure 9: Shallow groundwater of Jebel el Arab
a) Location of sampling points
b) Piper diagram
c) Schoeller diagram

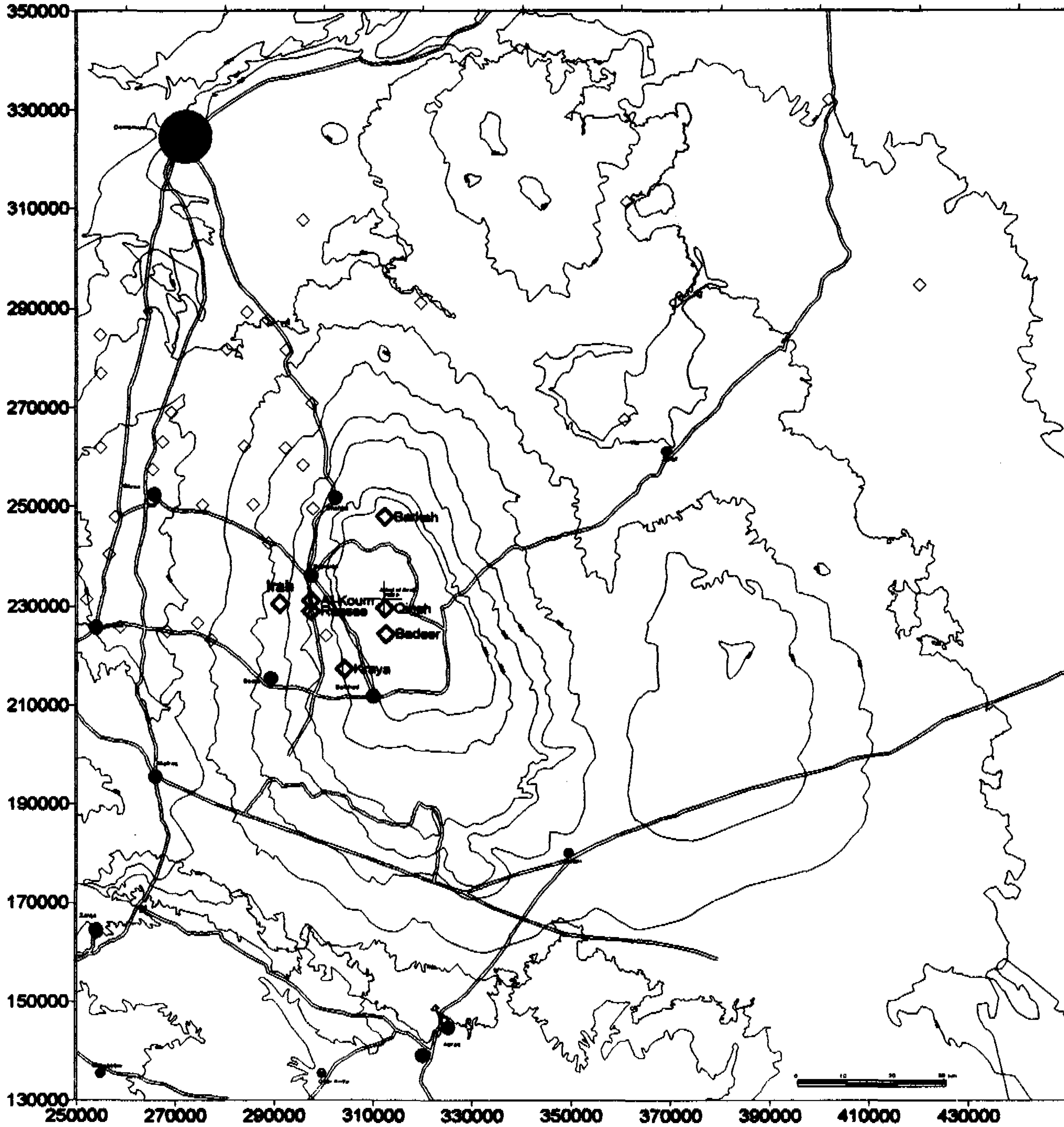


Fig. 9a: Shallow groundwater of J. Arab, location of sampling points

Fig. 9b: Piper Diagram .. Shallow groundwater of J.Arab

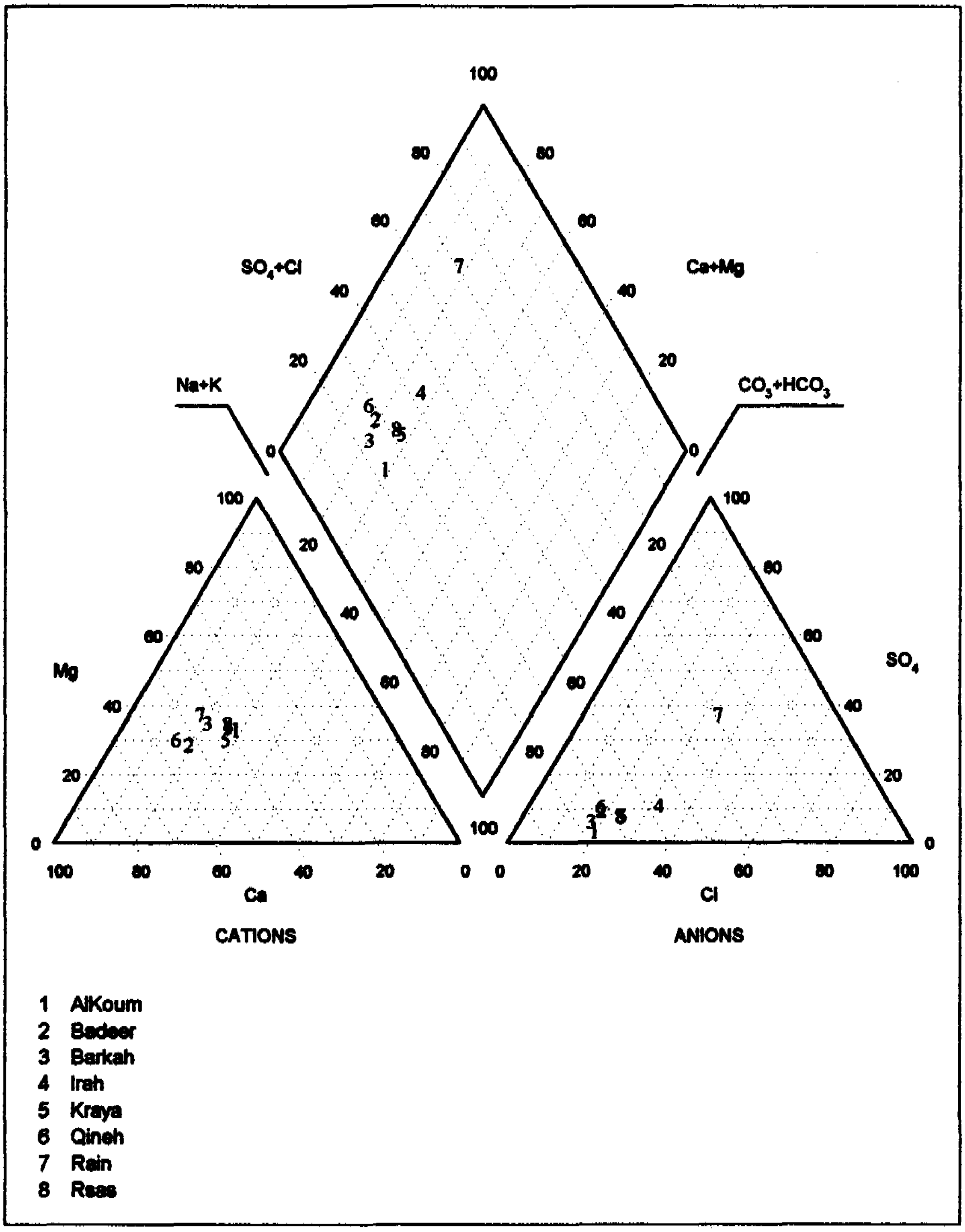


Fig. 9c: Schoeller Diagram .. Shallow groundwater of J.Arab

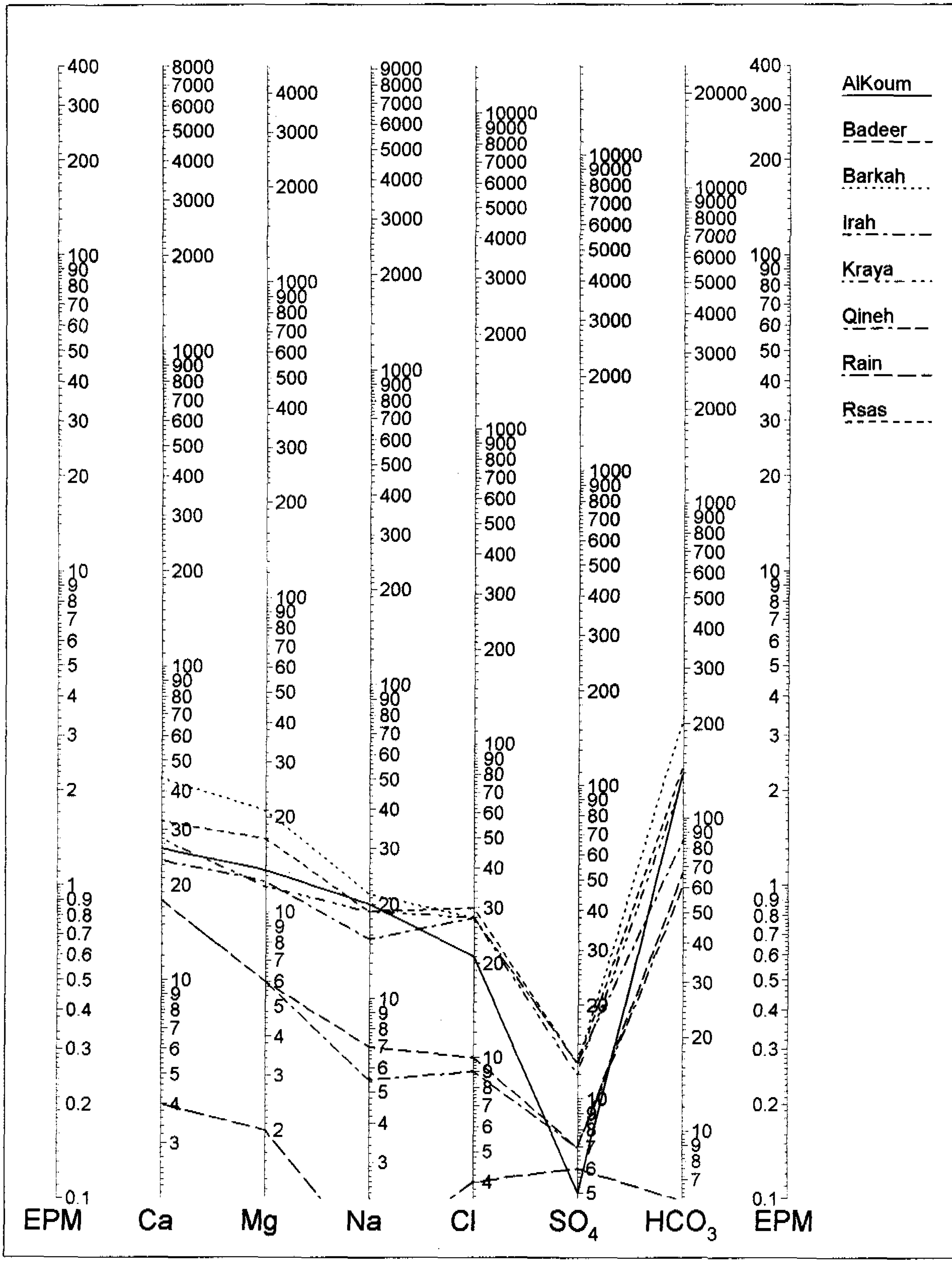


Figure 10: Hauran Plain, Al Museifra - Khabab area
a) Location of sampling points
b) Piper diagram
c) Schoeller diagram

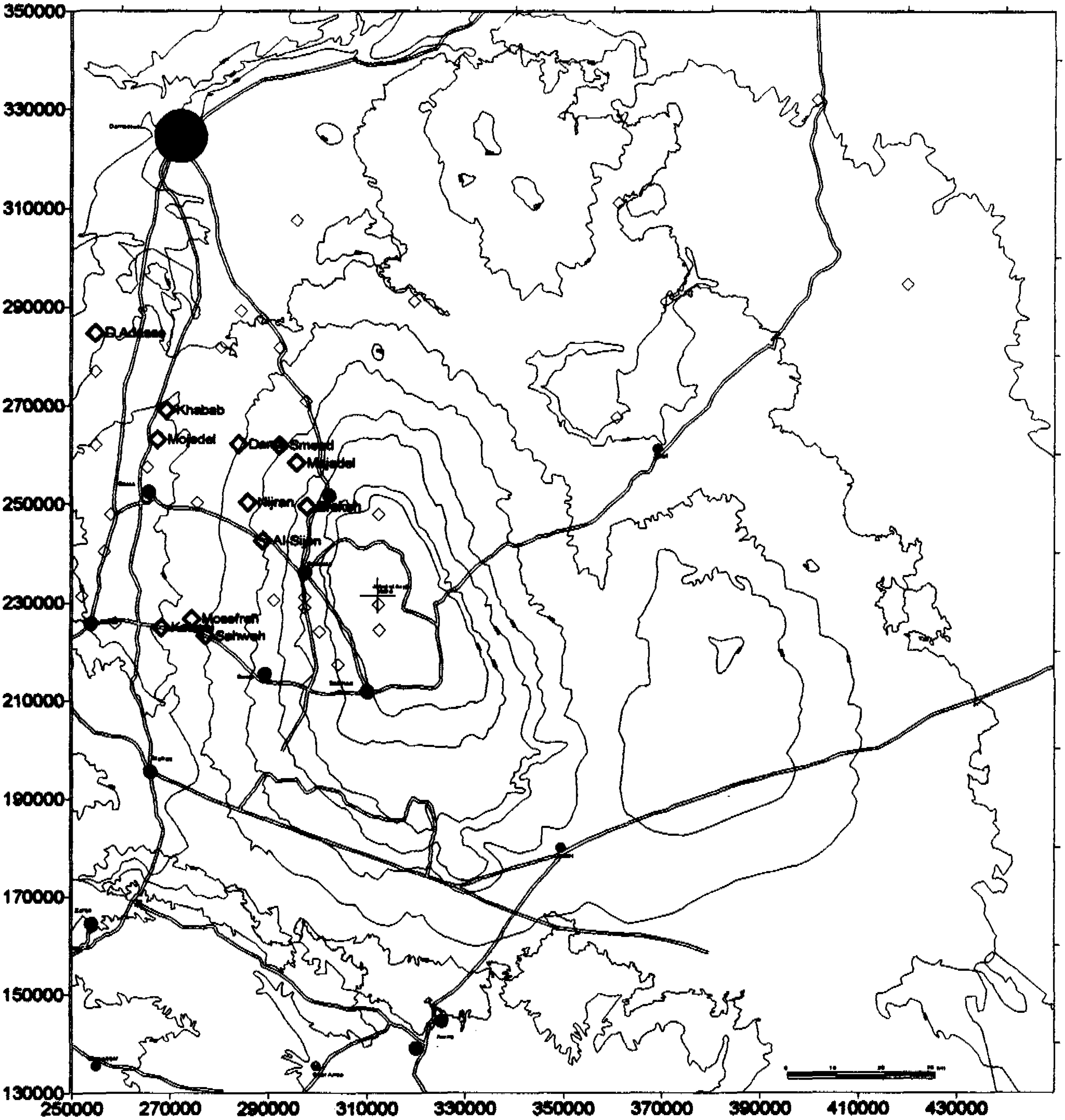


Fig. 10a: Location of sampling points, wells in Al Museifra - Khabab area

Fig. 10b: Piper Diagram .. Wells, Al Museifra - Khabab area

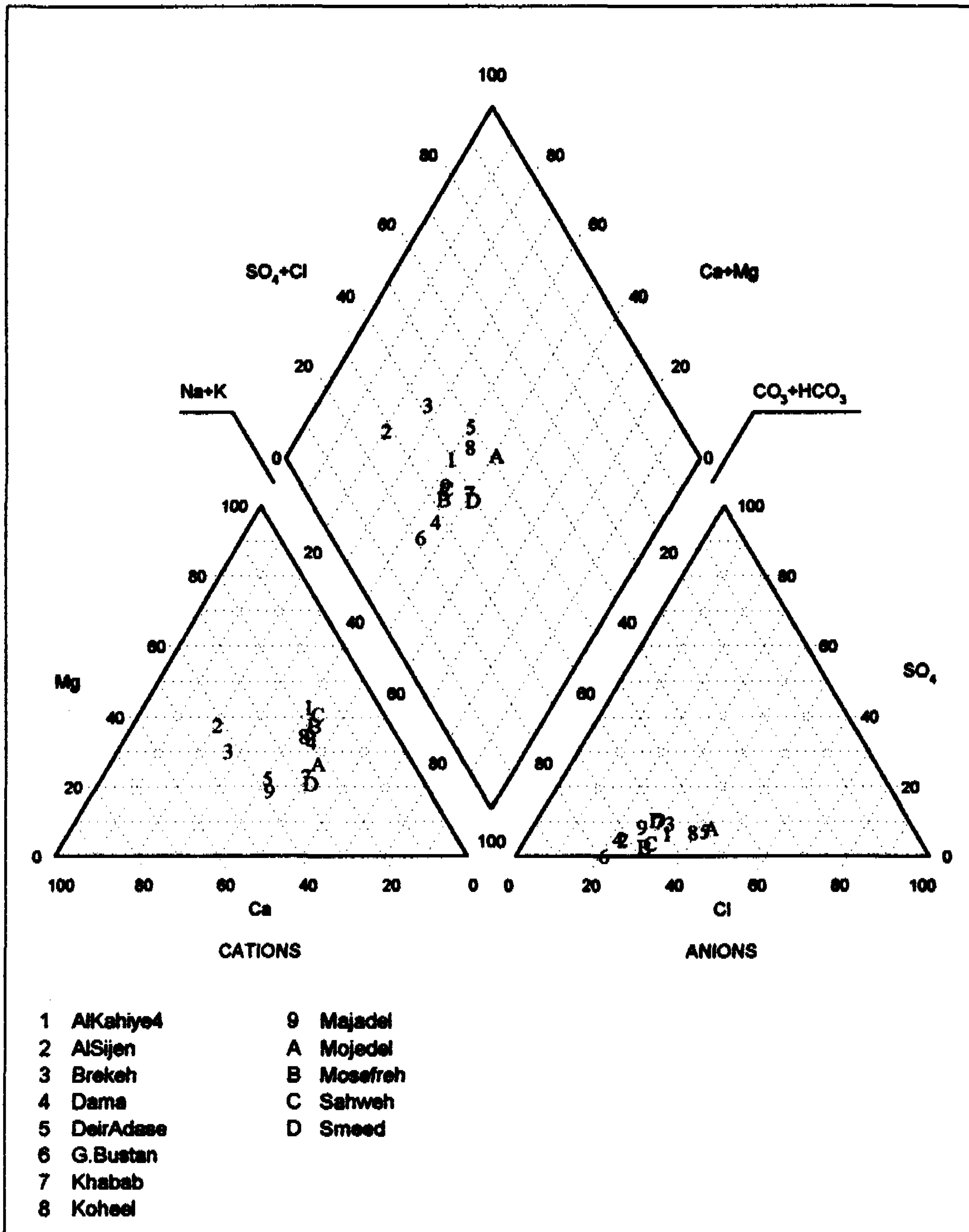


Fig. 10c: Schoeller Diagram .. Wells, Al Museifra - Khabab area

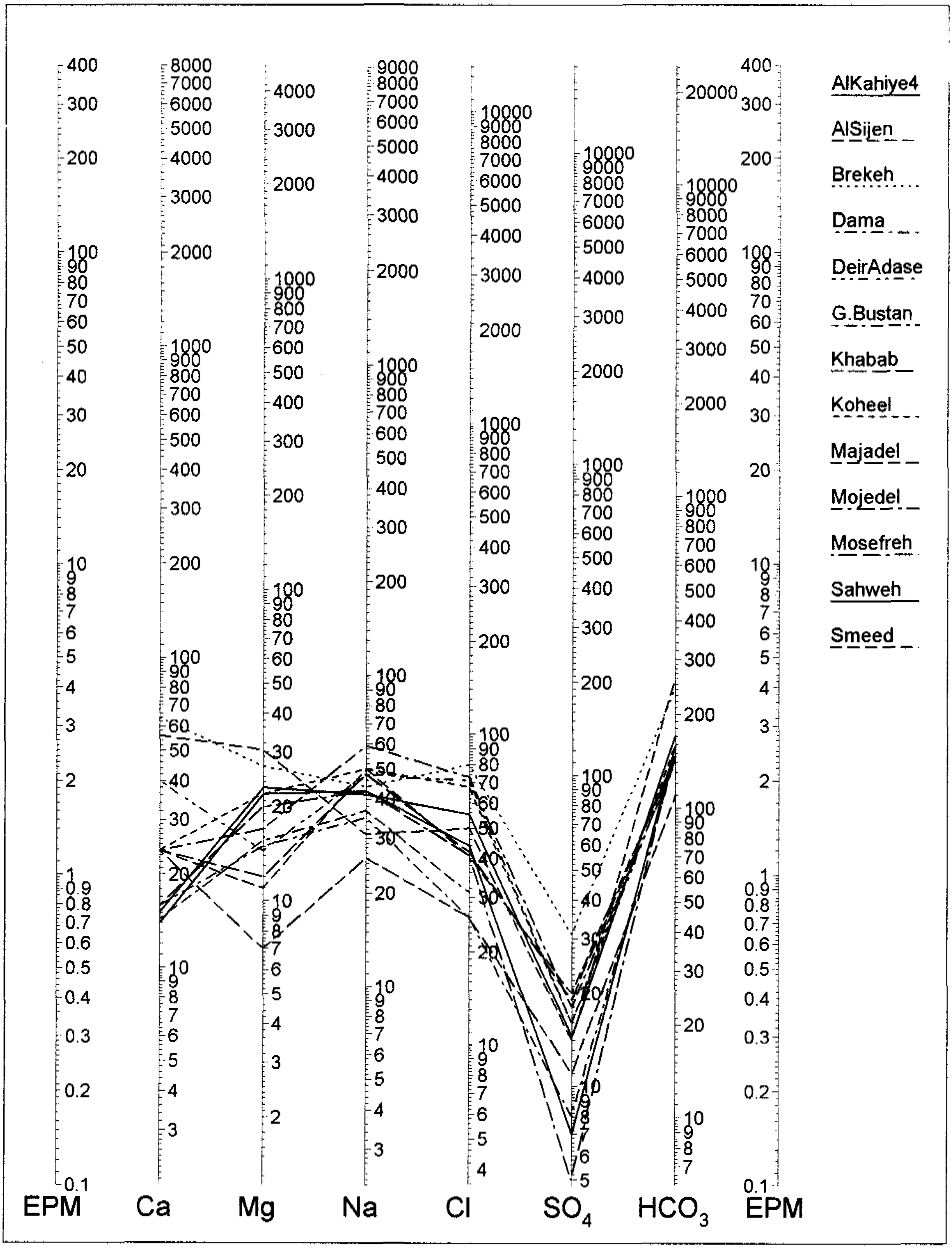


Figure 11: Hauran Plain, Ezraa area

a) Location of sampling points

b) Piper diagram

c) Schoeller diagram

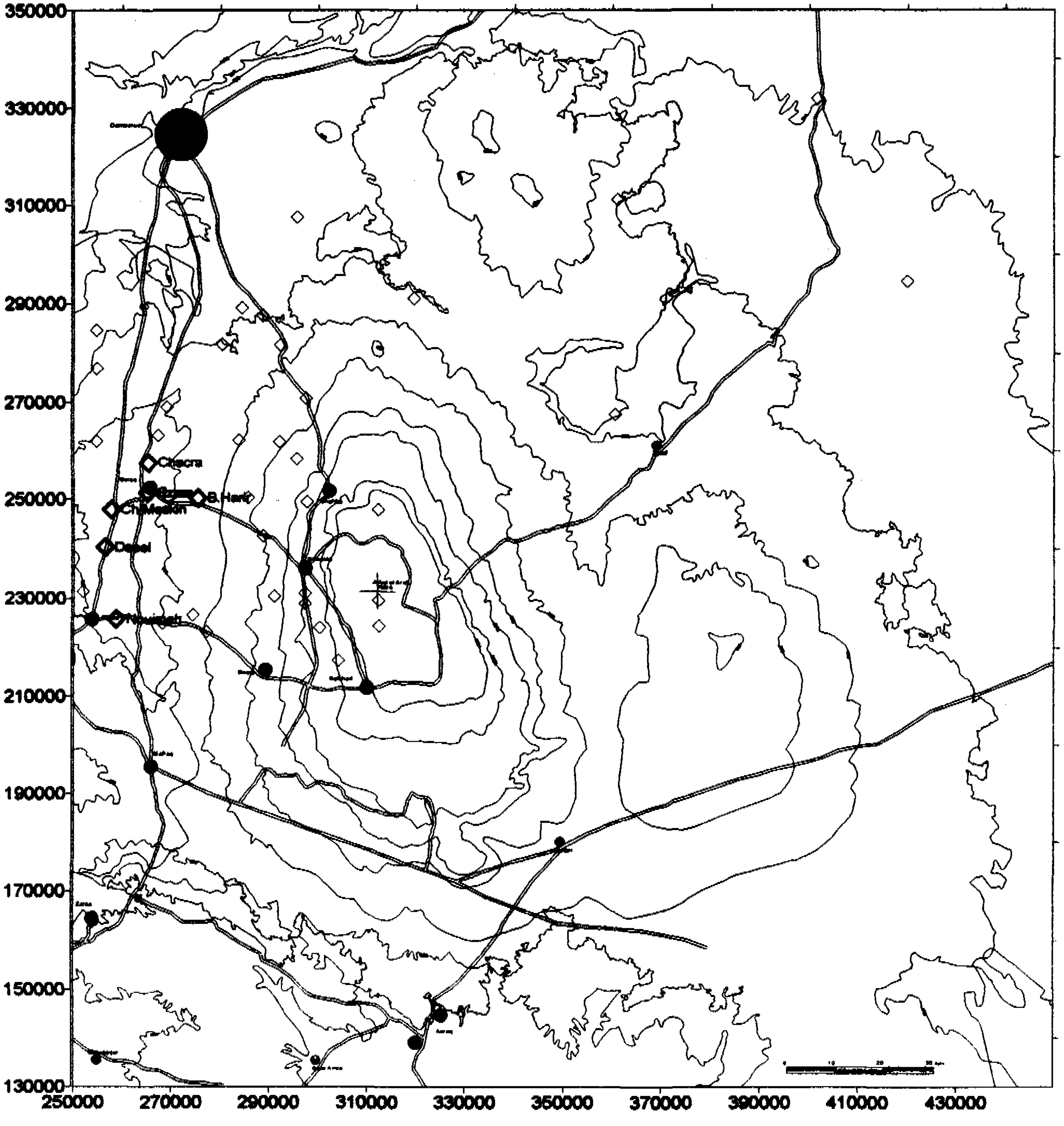


Fig. 11a: Location of sampling points, wells in Ezraa area

Fig. 11b: Piper Diagram .. Wells, Ezraa area

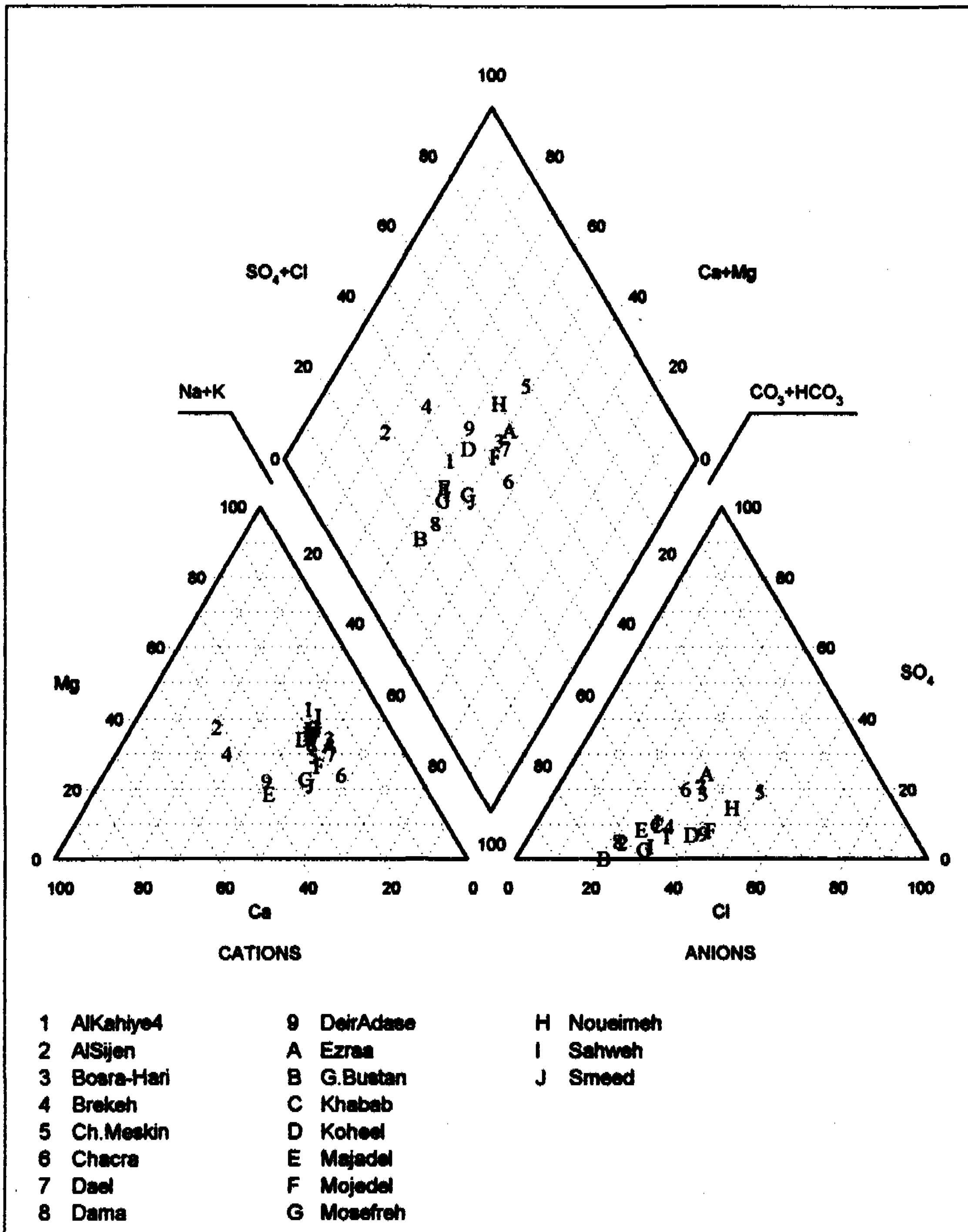


Fig. 11c: Schoeller Diagram .. Wells, Ezraa area

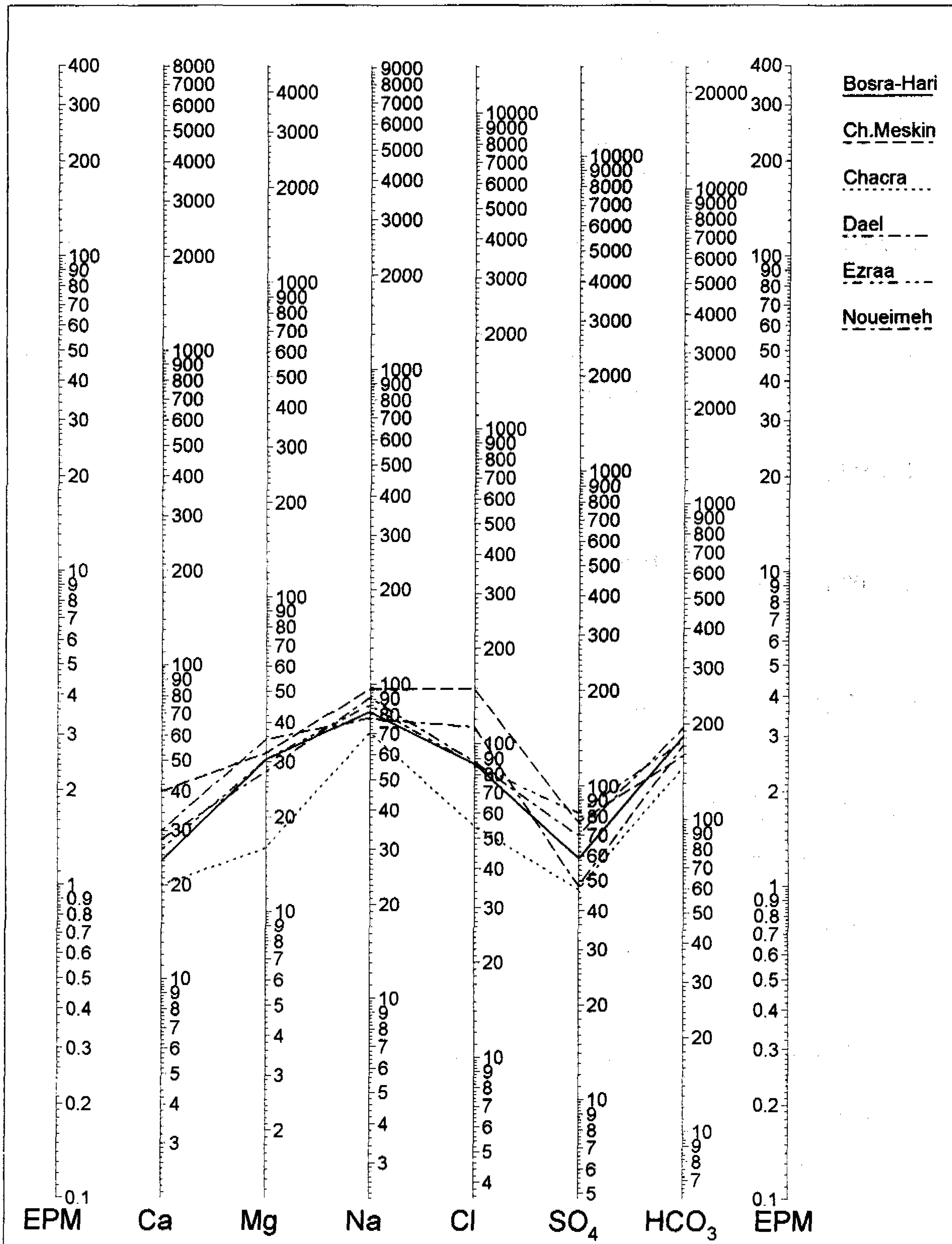


Figure 12: Springs in Wadi Hreer - Wadi al Aram - Mzeirib area

a) Location of sampling points

b) Piper diagram

c) Schoeller diagram

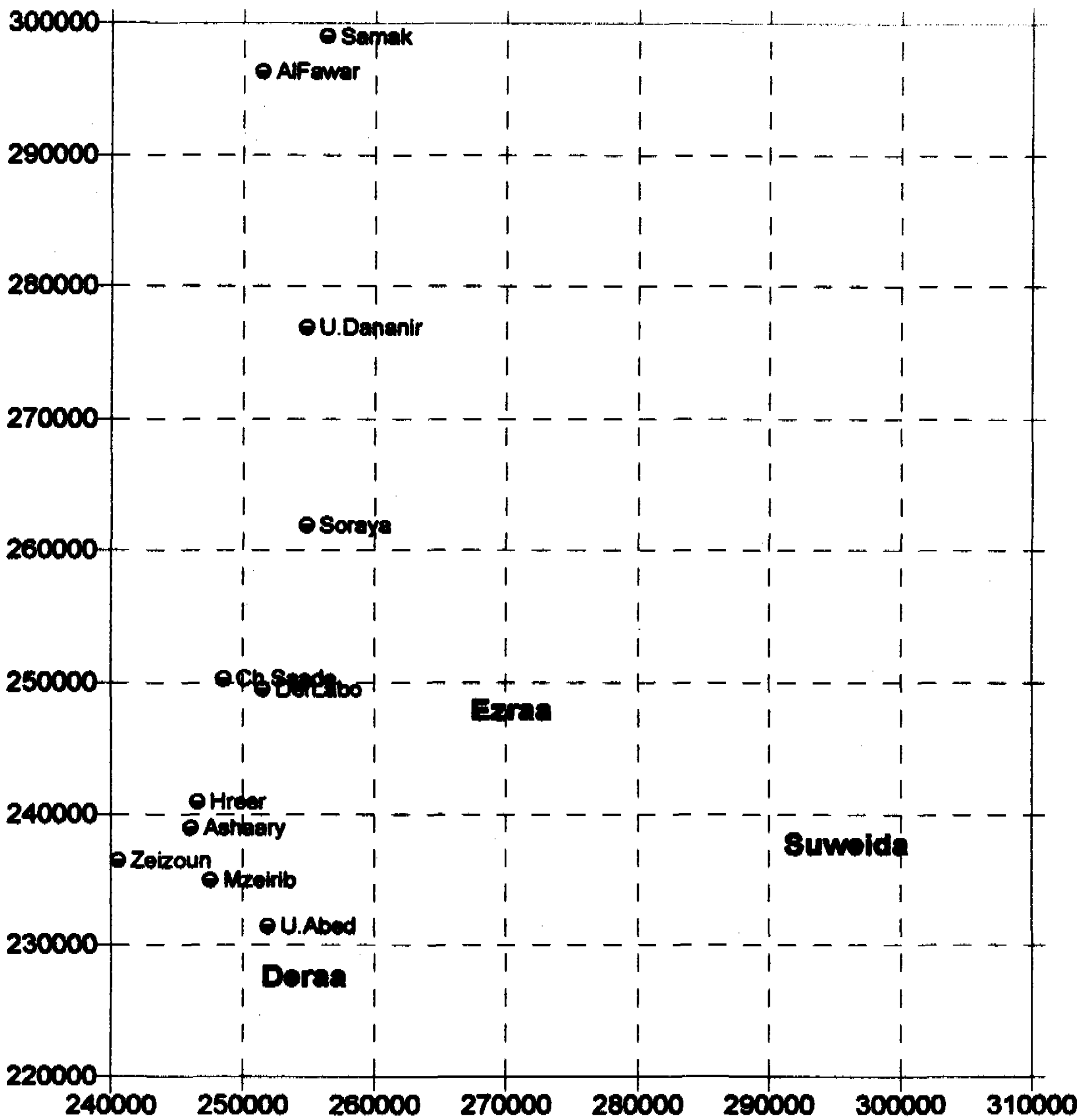


Fig. 12a:

Location of sampling points, springs W. Hreer - W. al Arram - Mzeirib

Fig. 12b: Piper Diagram .. Springs, W. Hreer - Mzeirib

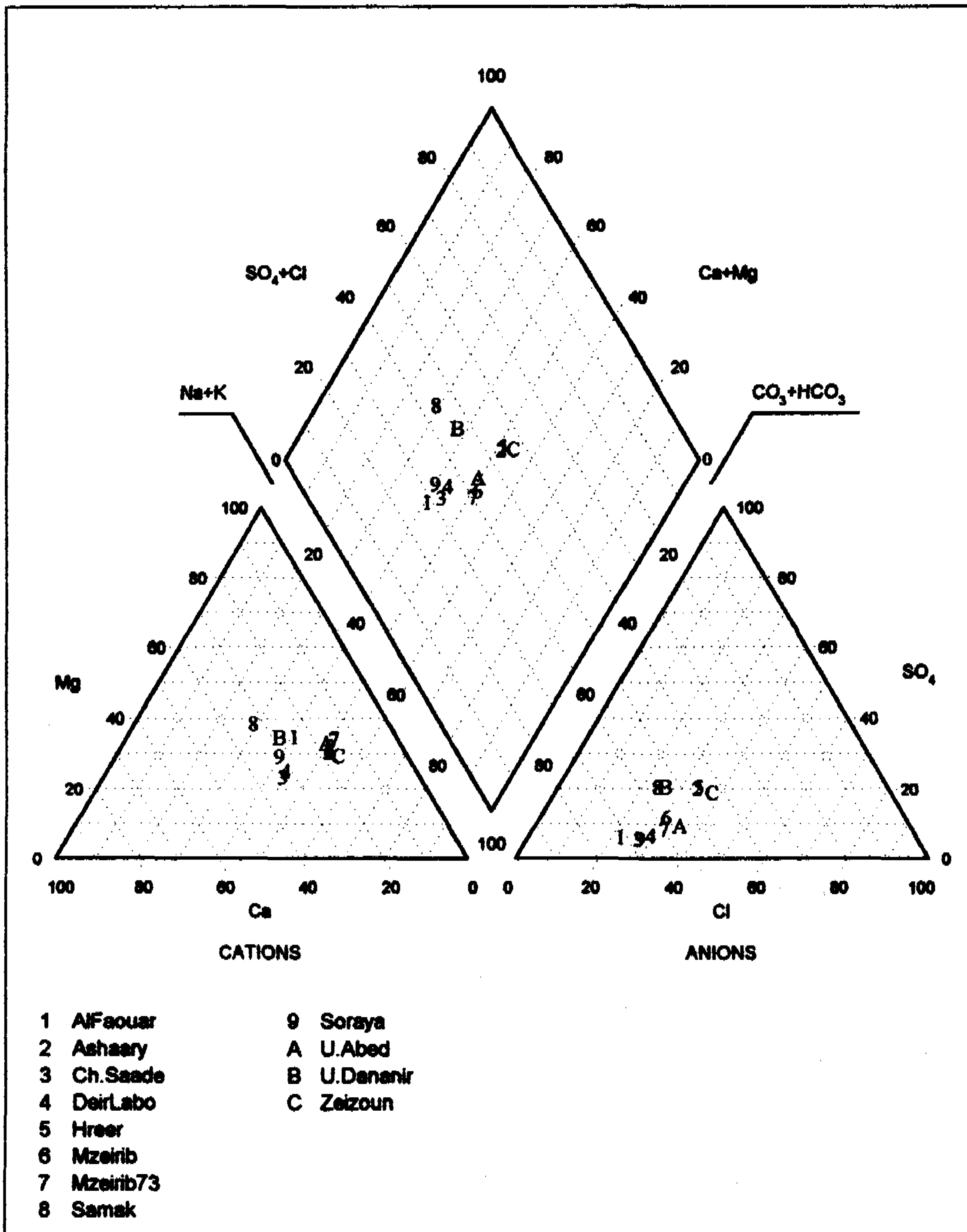


Fig. 12c: Schoeller Diagram .. Springs, W.Hreer - Mzeirib

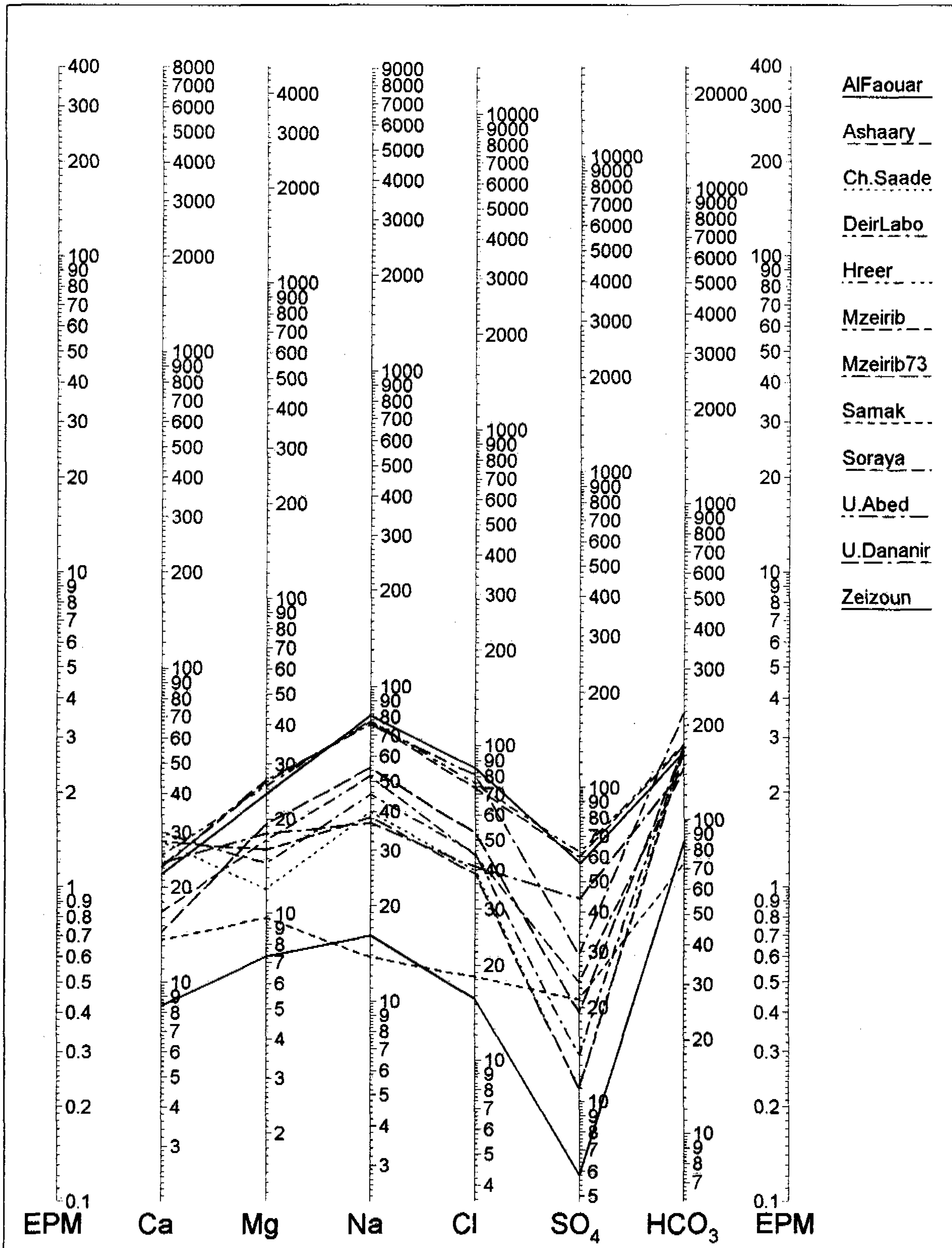


Figure 13: Wadi Liwa

a) Location of sampling points

b) Piper diagram

c) Schoeller diagram

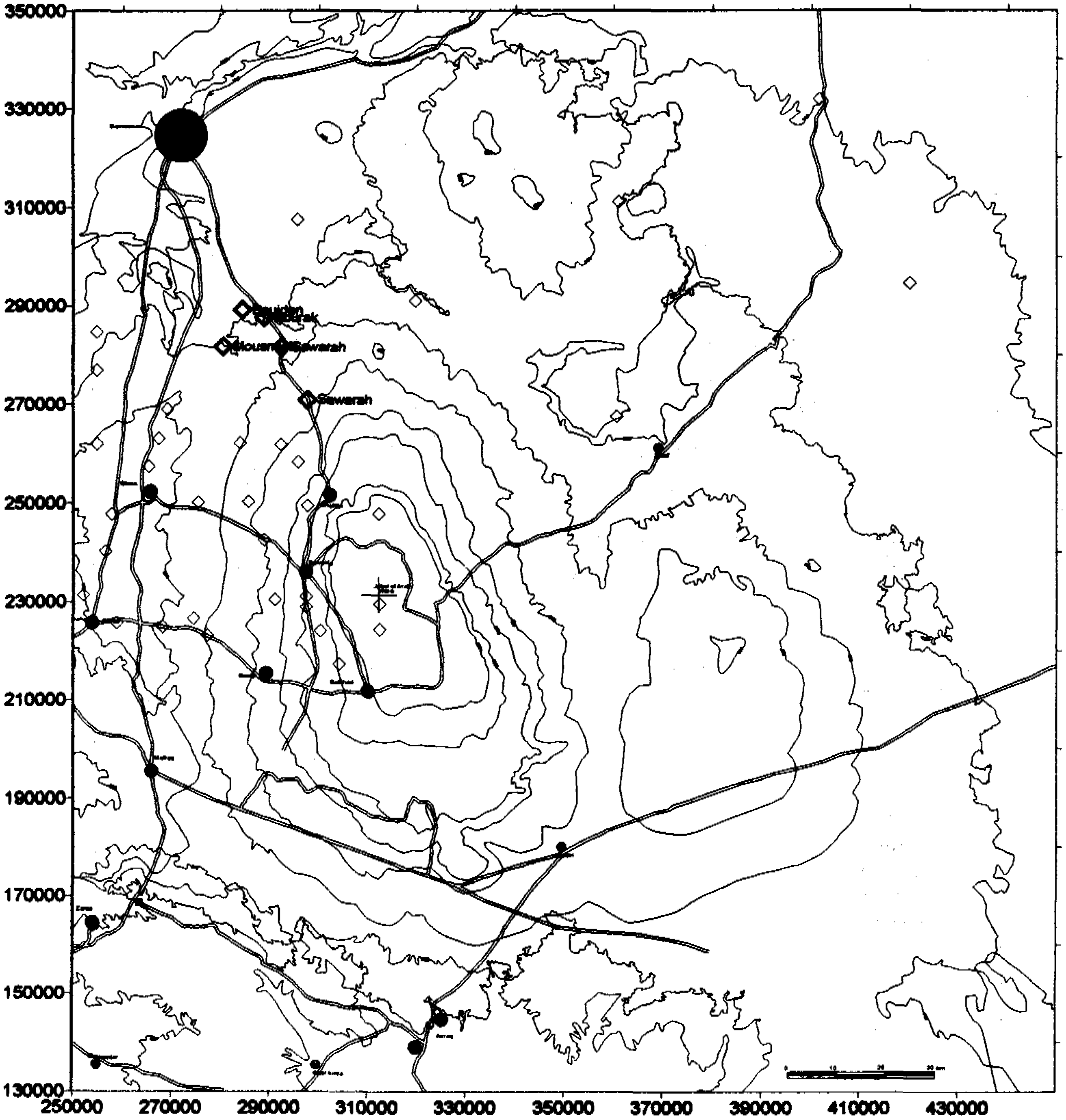


Fig. 13a: Location of sampling points, wells, Wadi Liwa

Fig. 13b: Piper Diagram .. Wells, Wadi Liwa

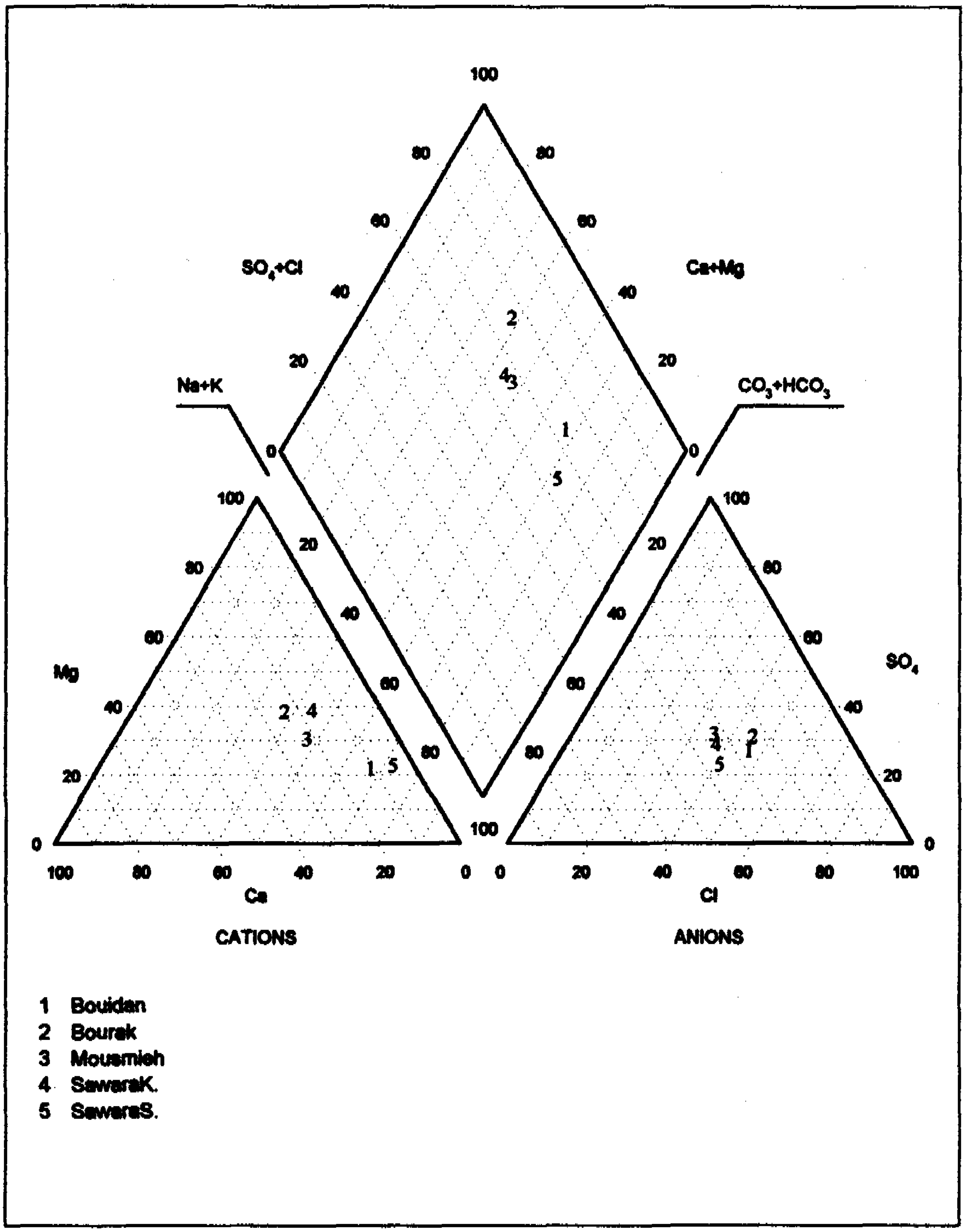


Fig. 13c: Schoeller Diagram .. Wells, Wadi Liwa

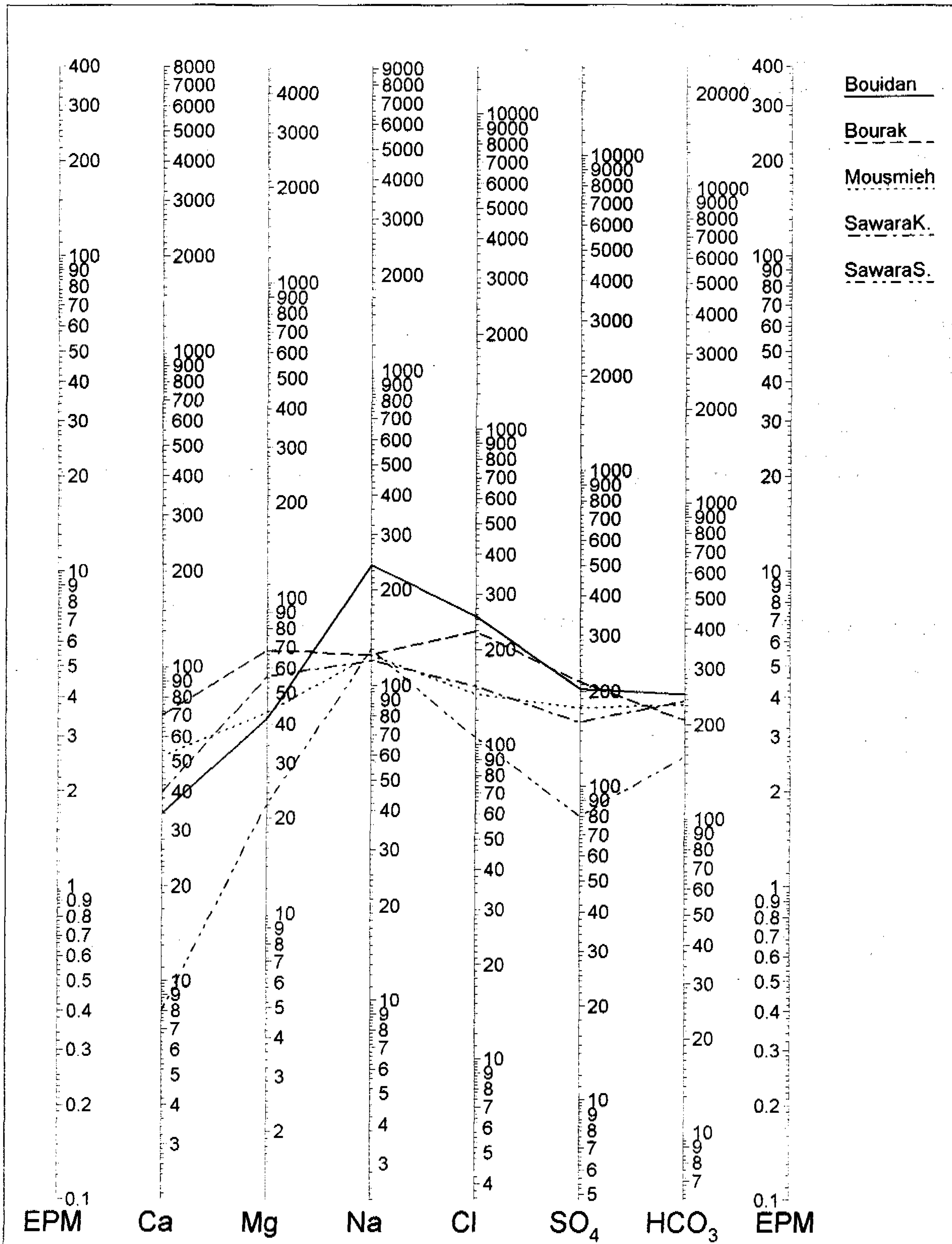


Figure 14: Statistical comparison of water analyses from different areas of Jebel el Arab - Hauran, Box- and- whisker plots

a) Electrical conductivity, b) Ca, c) Mg, d) Na, e) HCO_3, f) SO_4, g) Cl, h) NO_3

Fig. 14a: Box-and-Whisker Plot, Electrical conductivity

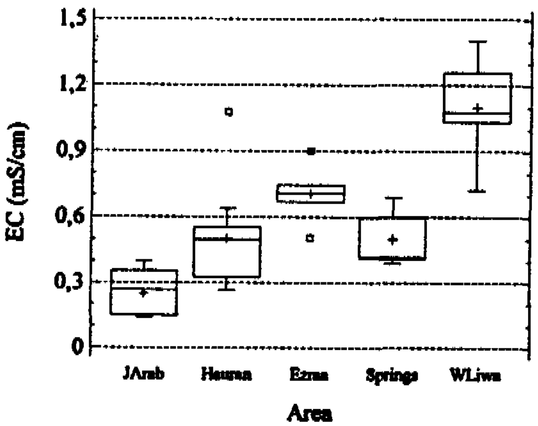


Fig. 14b: Box-and-Whisker Plot, Ca concentration

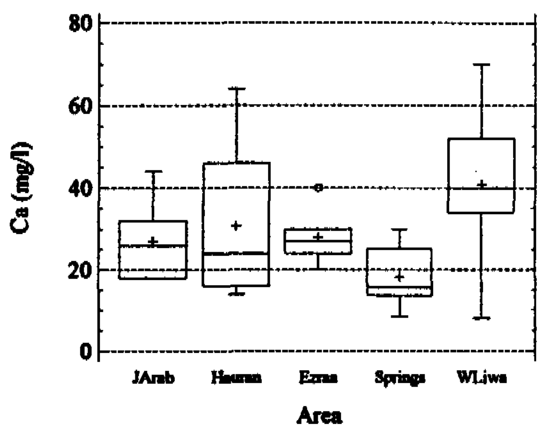


Fig. 14c: Box-and-Whisker Plot, Mg concentration

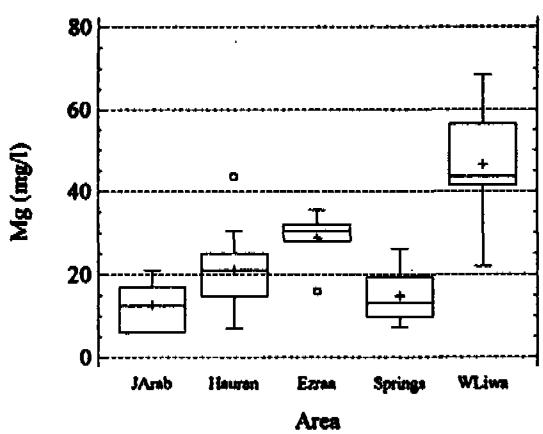
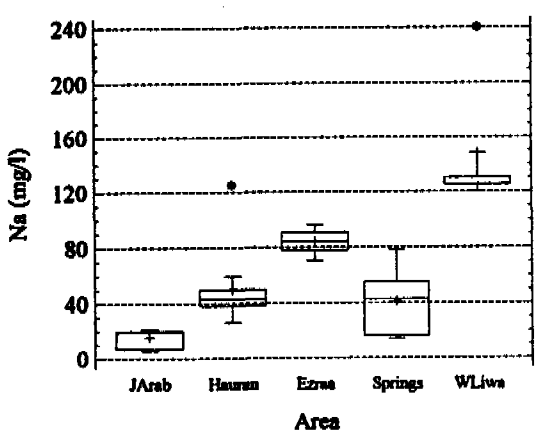


Fig. 14d: Box-and-Whisker Plot, Na concentration



Statistical comparison of water analyses from different areas of Jebel el Arab - Hauran,
Box- and- whisker plots

Fig. 14e: Box-and-Whisker Plot, HCO3 concentration

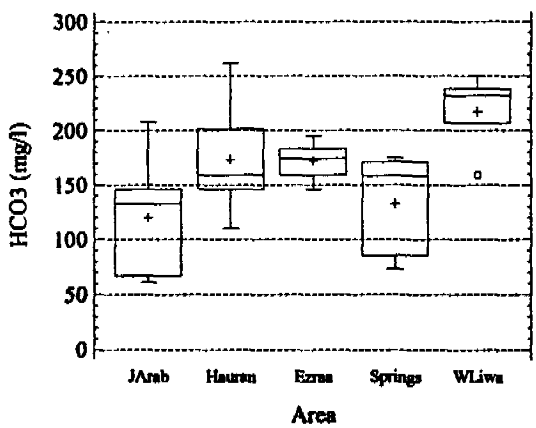


Fig. 14f: Box-and-Whisker Plot, SO4 concentration

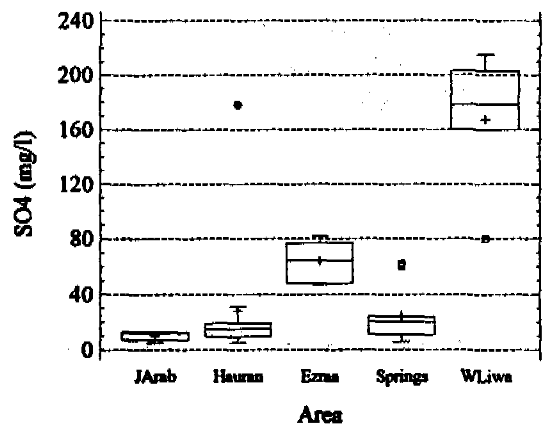


Fig. 14g: Box-and-Whisker Plot, Cl concentration

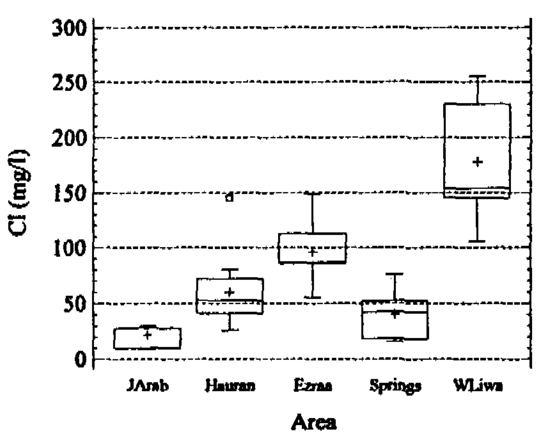


Fig. 14h: Box-and-Whisker Plot, NO3 concentration

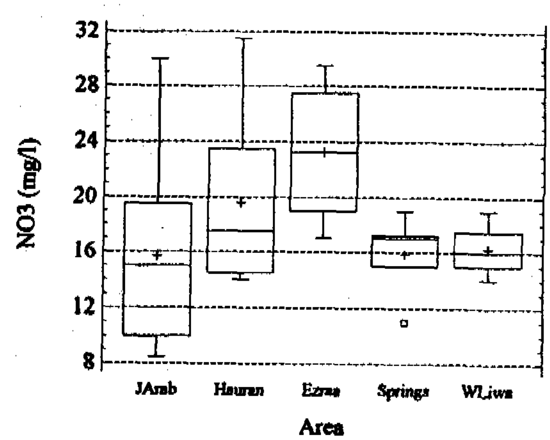


Figure 15: Area east of Mafraq

a) Location of sampling points
b) Distribution of electrical conductivity
c) Piper diagram. fresh water
d) Schoeller diagram, fresh water
e) Piper diagram, fresh water
f) Schoeller diagram, brackish water
g) NO3 / Cl plot

Fig. 15a: Location of sampling points

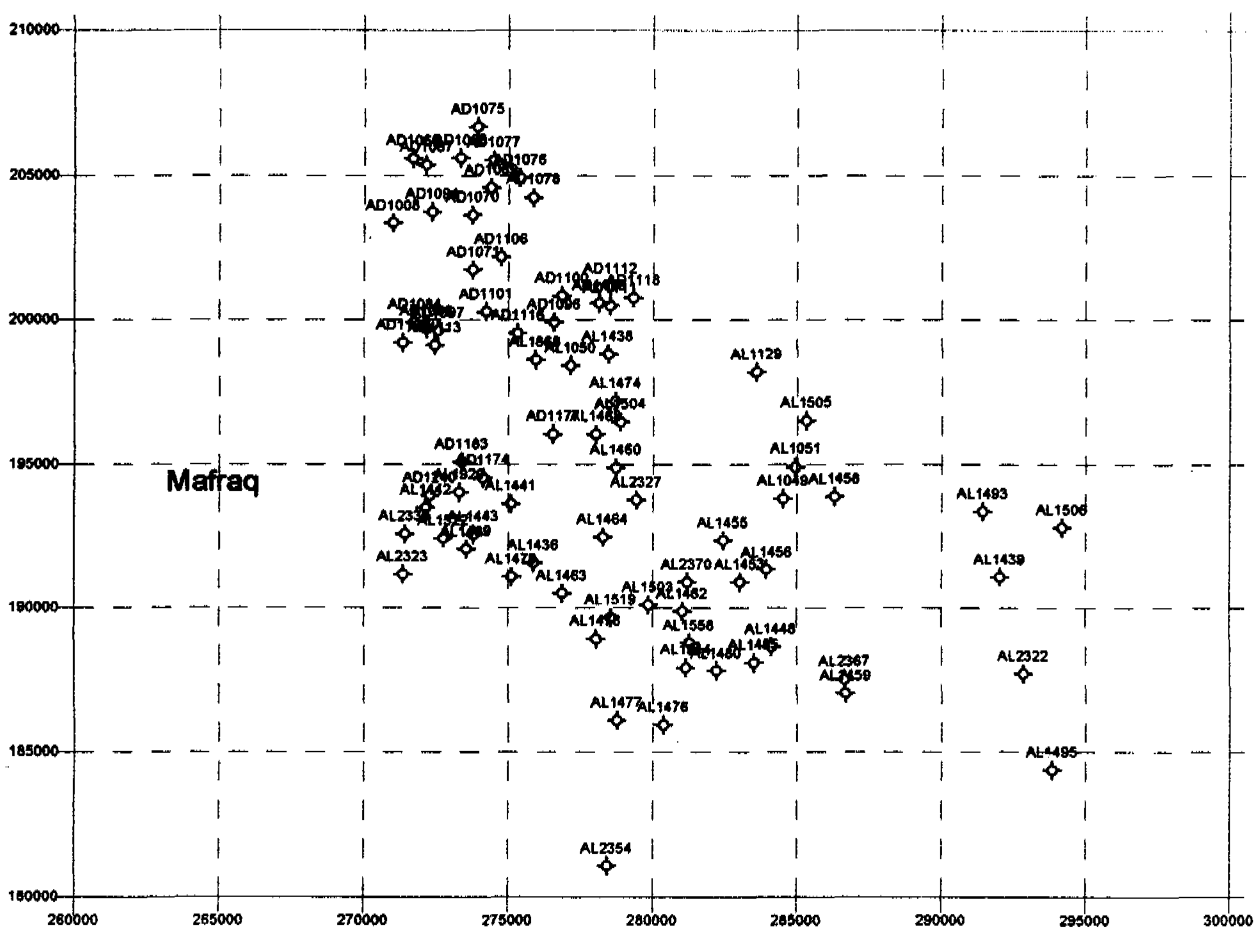


Figure 15b: Mafraq area
Electrical conductivity of groundwater samples

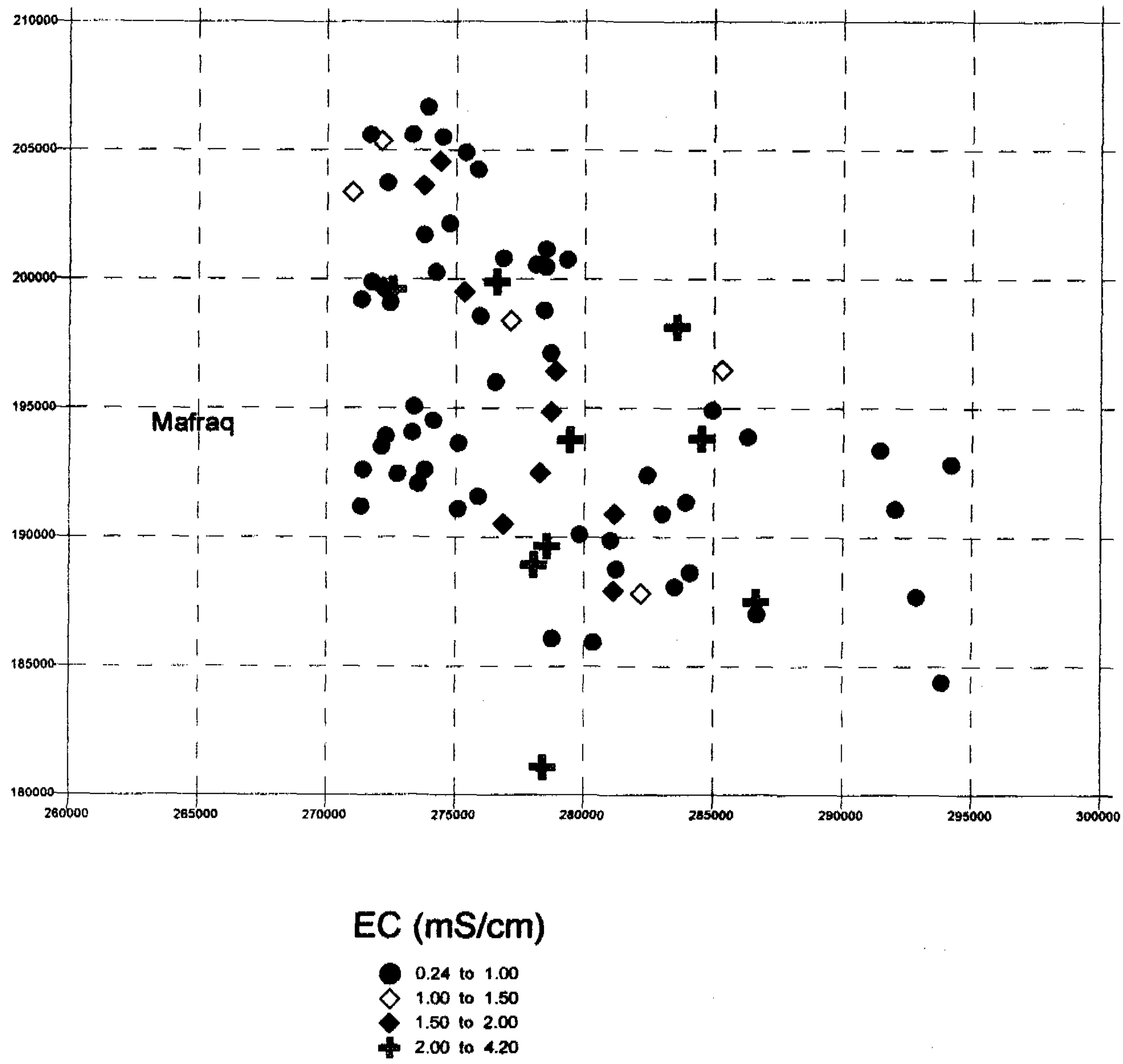


Fig. 15c: Piper Diagram .. Mafraq area, fresh water

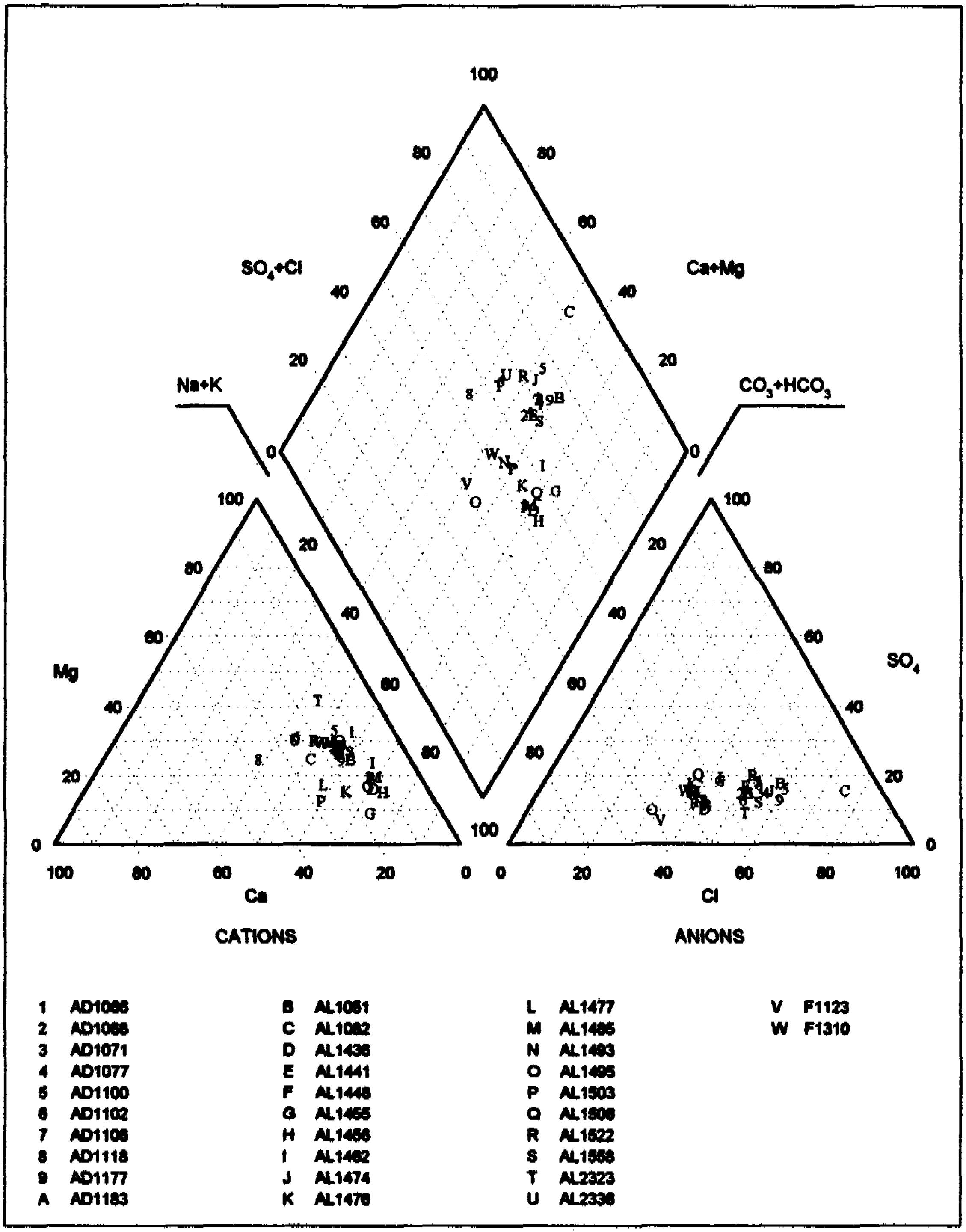


Fig. 15d: Schoeller Diagram .. Mafraq area, fresh water, selected samples

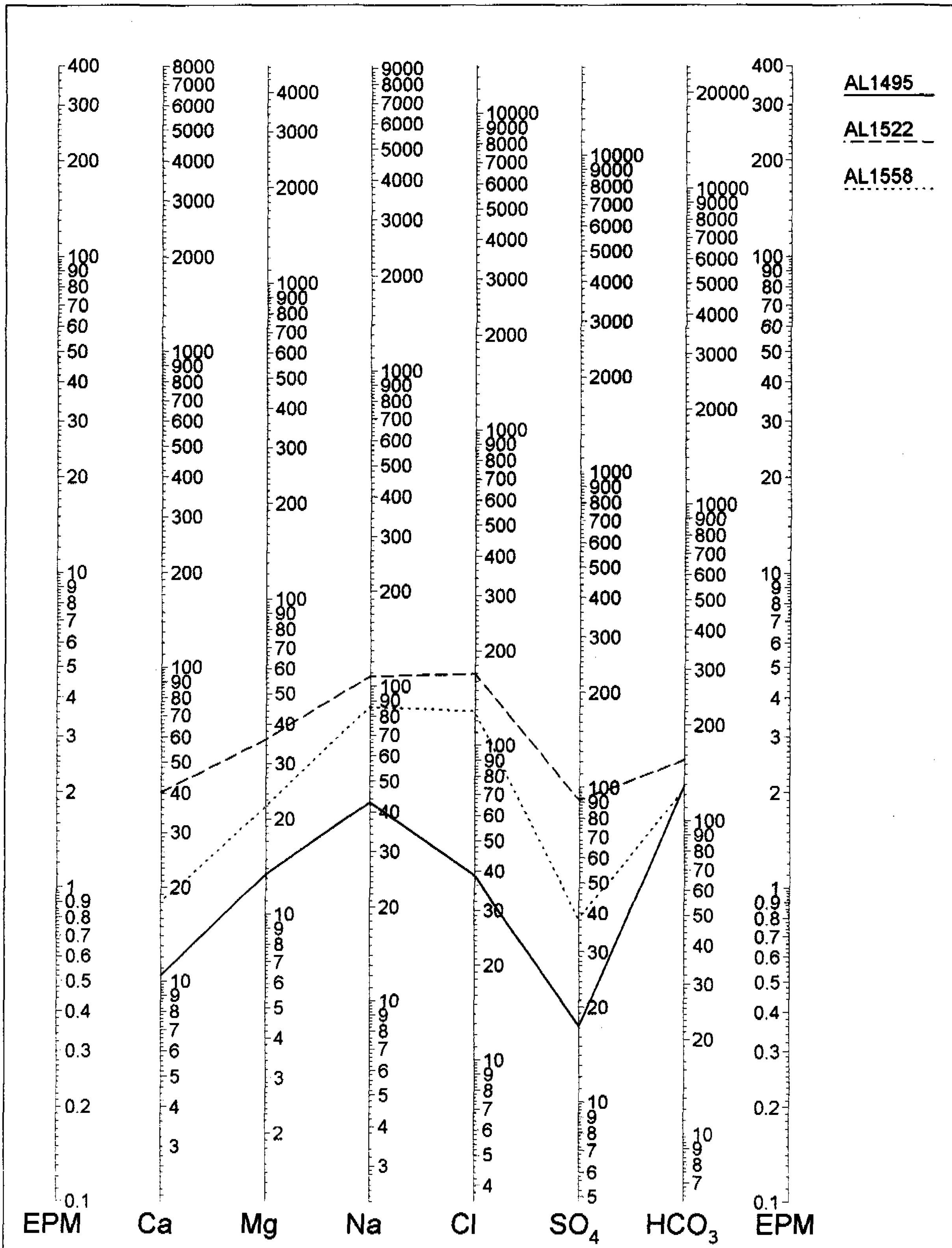


Fig. 15e: Piper Diagram .. Mafraq area, brackish water

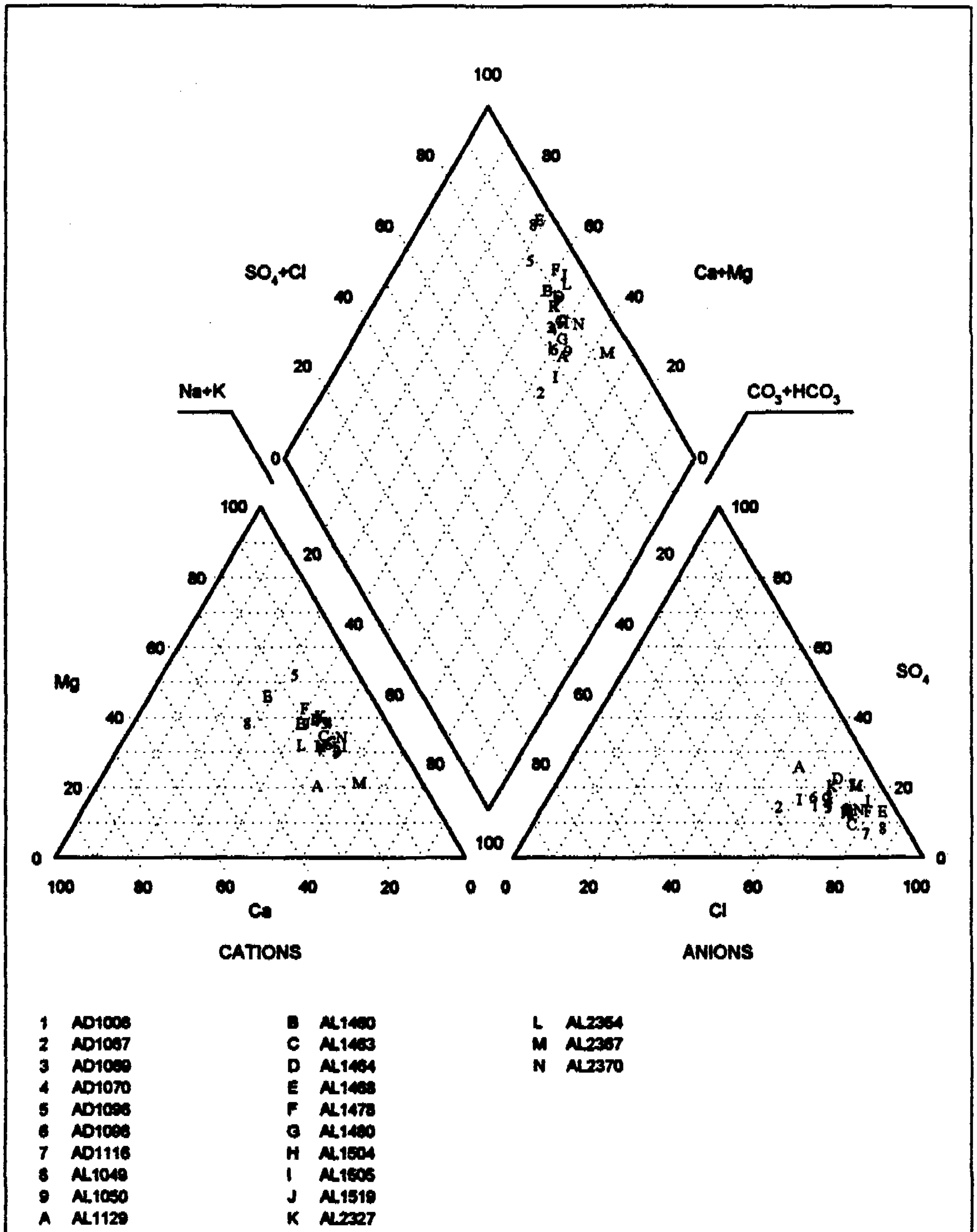


Fig. 15f: Schoeller Diagram .. Mafraq area, brackish water

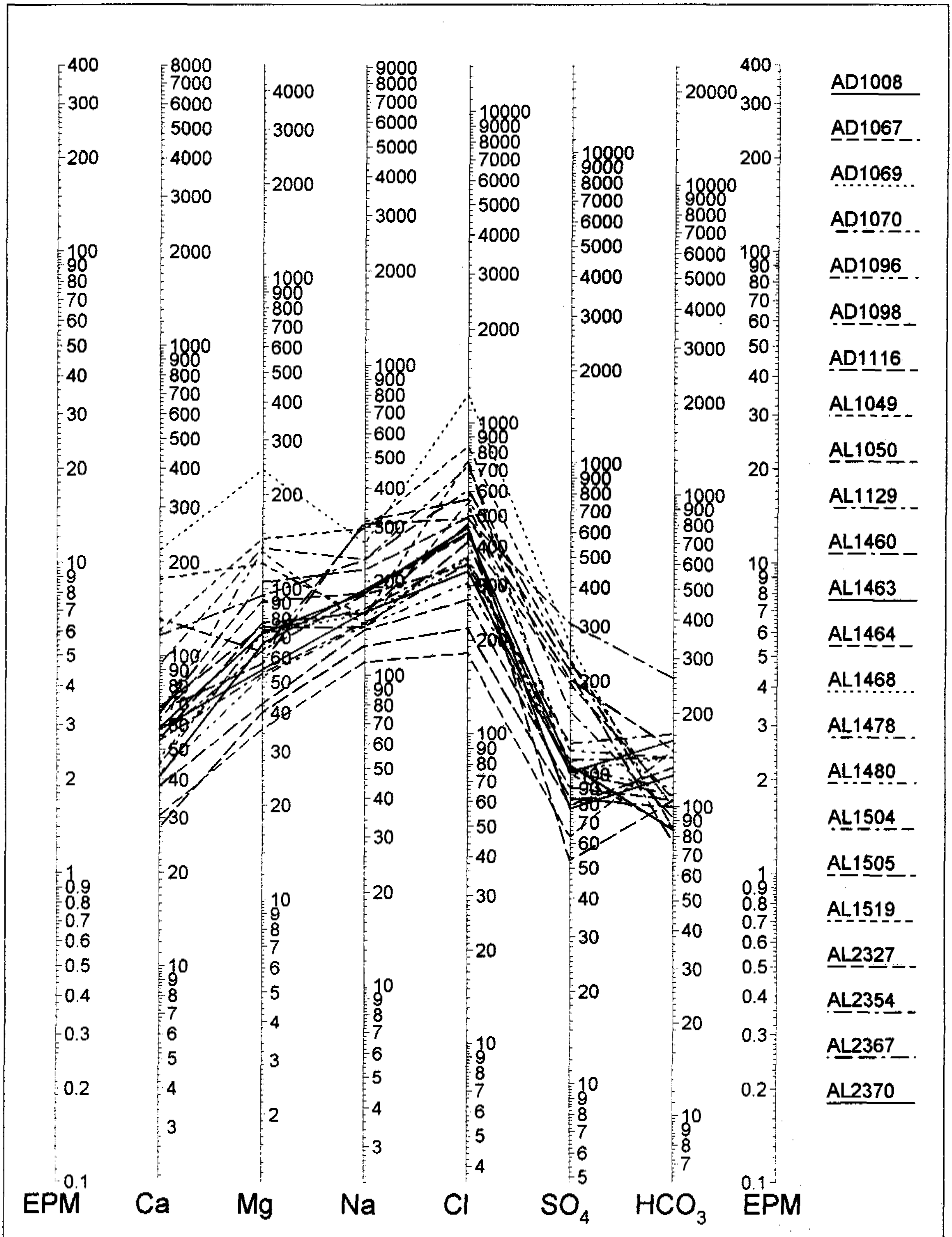


Fig. 15g: NO3 / Cl plot
Groundwater samples, Mafraq area

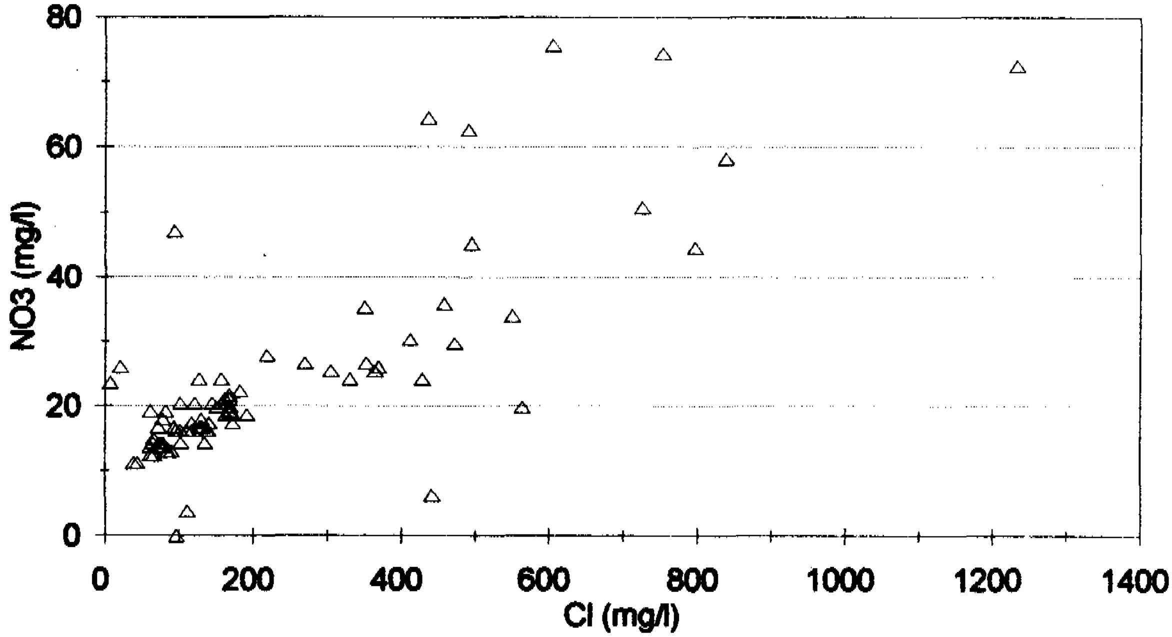


Figure 16: Dhuleil area

a) Location of sampling points
b) Distribution of electrical conducytivity
c) Piper diagram
d) Schoeller diagram
e) NO3 / Cl plot
f) Dhuleil well DP21, anion concentrations 1971-1989
g) Cl concentrations, Dhuleil, 1970-1989
h) SO4 concentrations, Dhuleil, 1970-1986

Fig. 16a: Location of sampling points, Dhuleil area

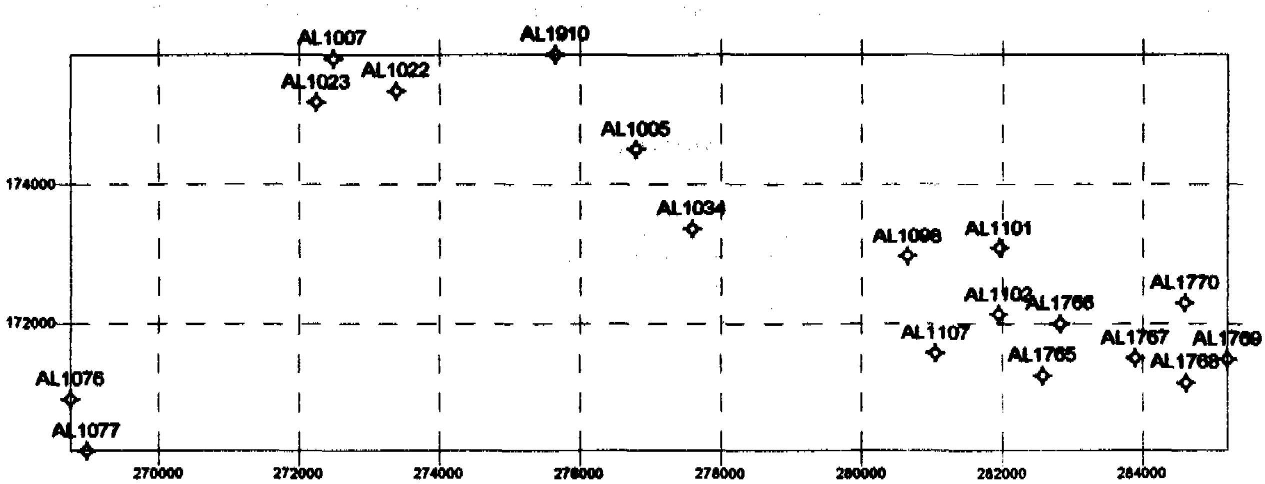
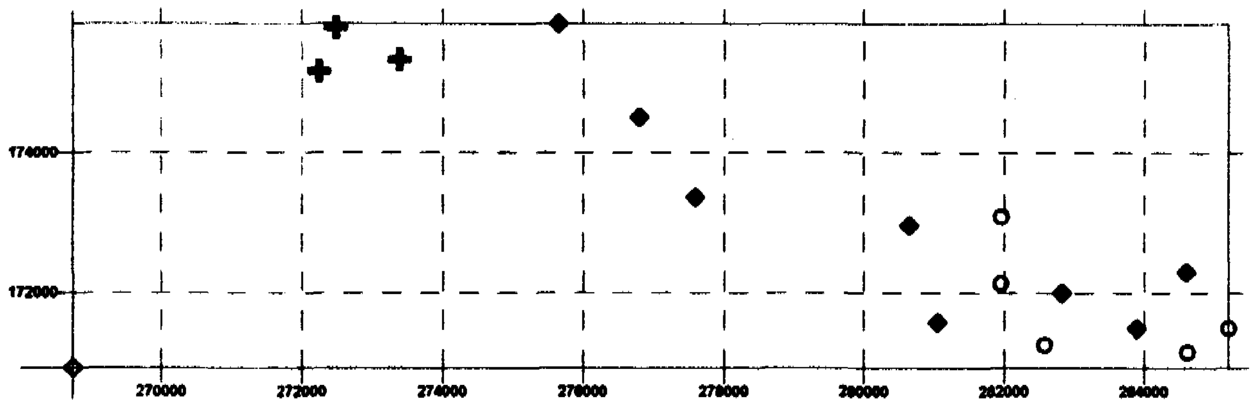


Fig. 16b: Dhuleil area
Electrical conductivity of groundwater samples



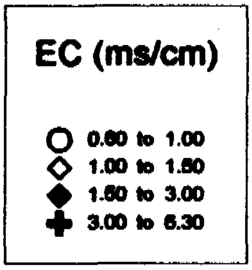


Fig. 16c: Piper Diagram .. Dhuleil area

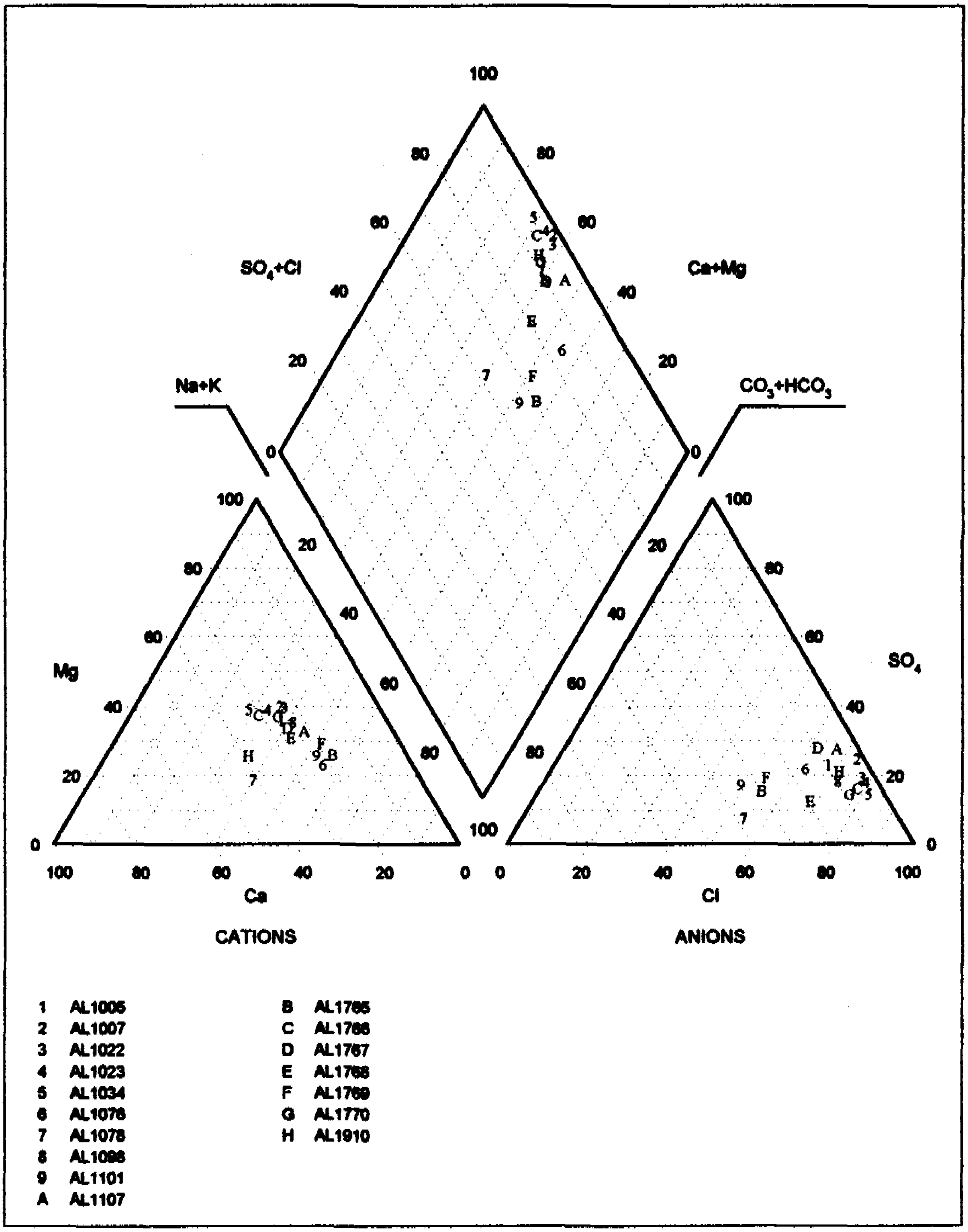


Fig. 16d: Schoeller Diagram .. Dhuleil area

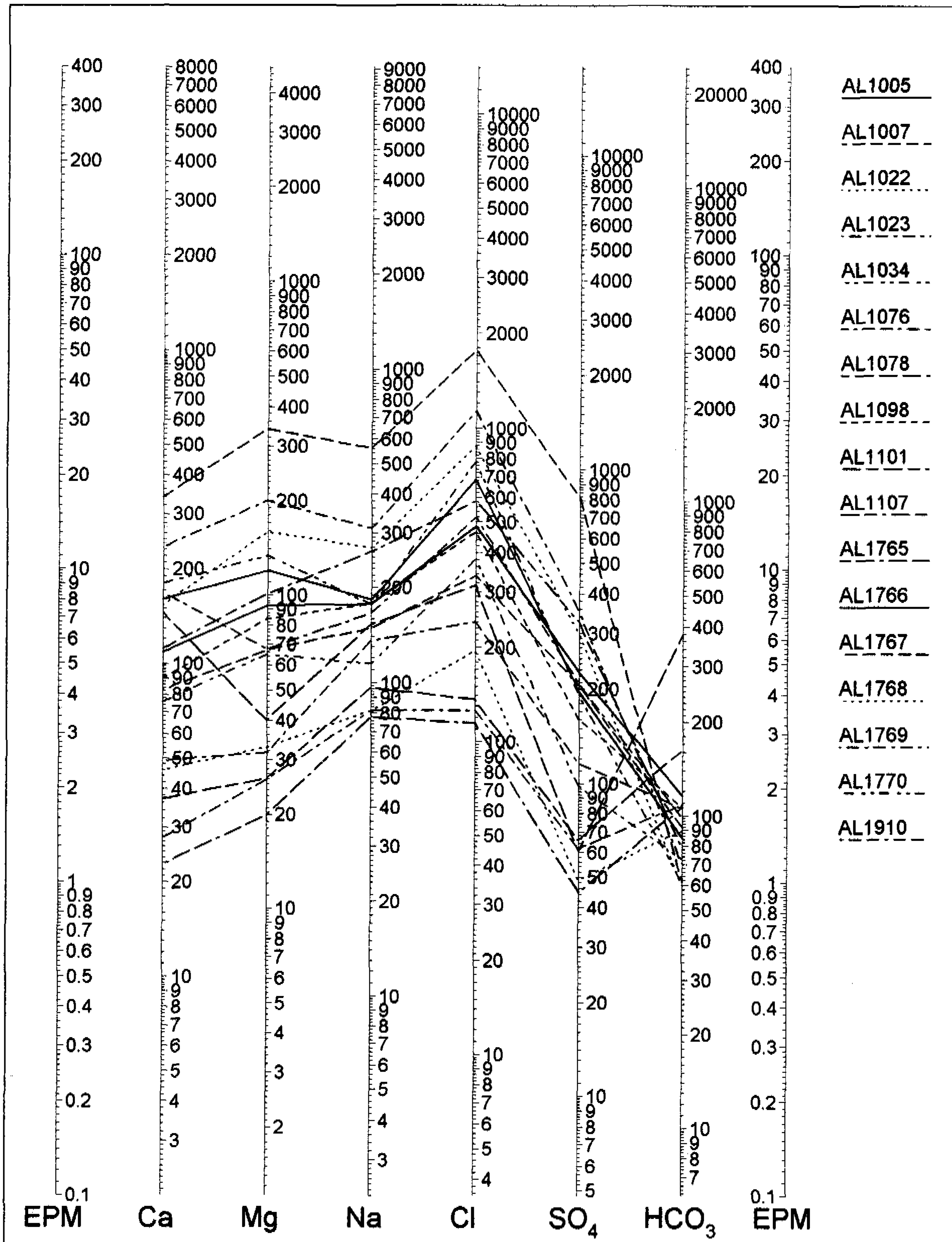


Fig. 16e: NO3 / Cl plot
Groundwater samples, Dhuleil area

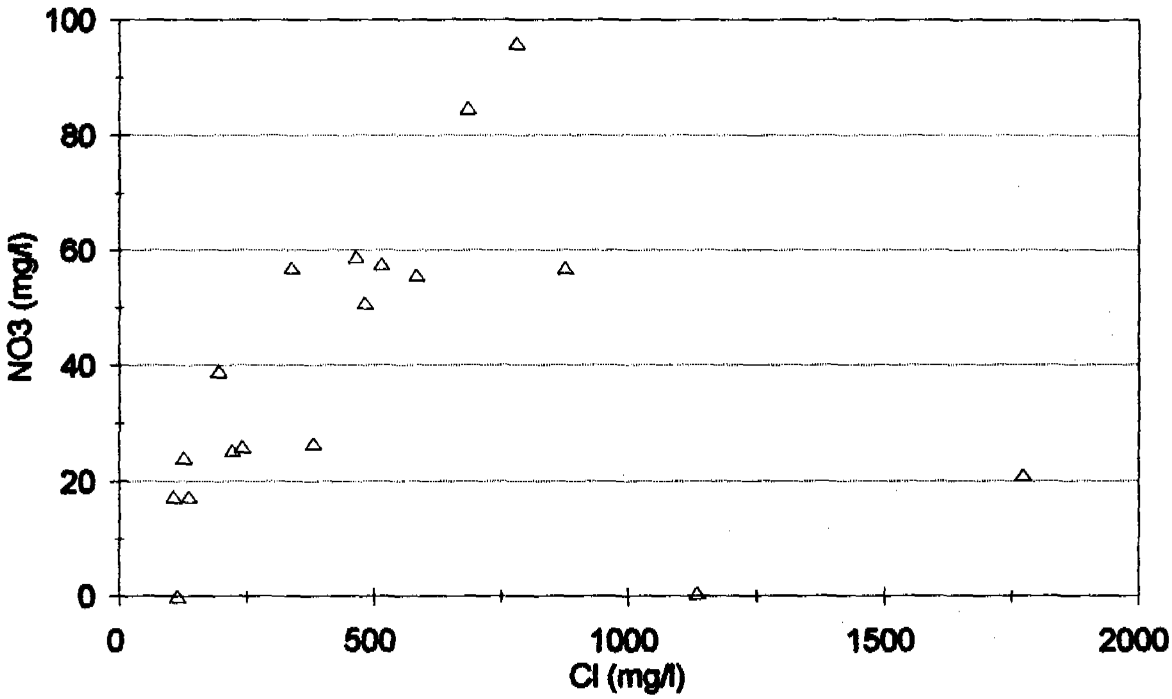


Fig. 16f : Dhuleil Well DP 21
Anion concentrations 1971 -1989

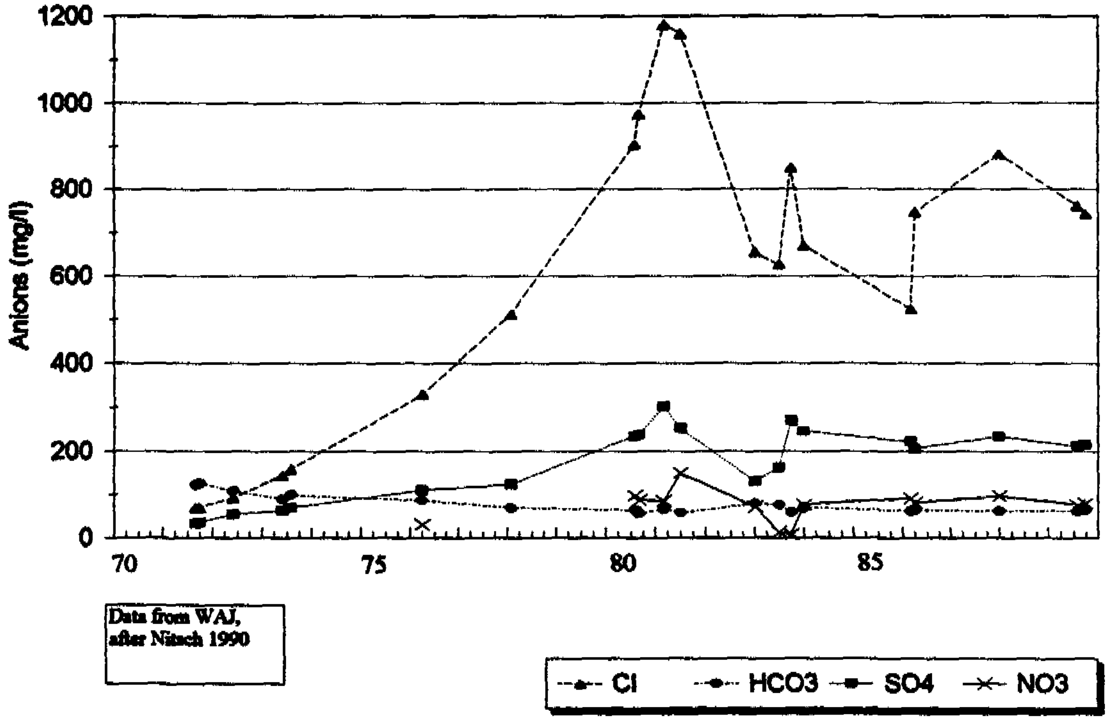
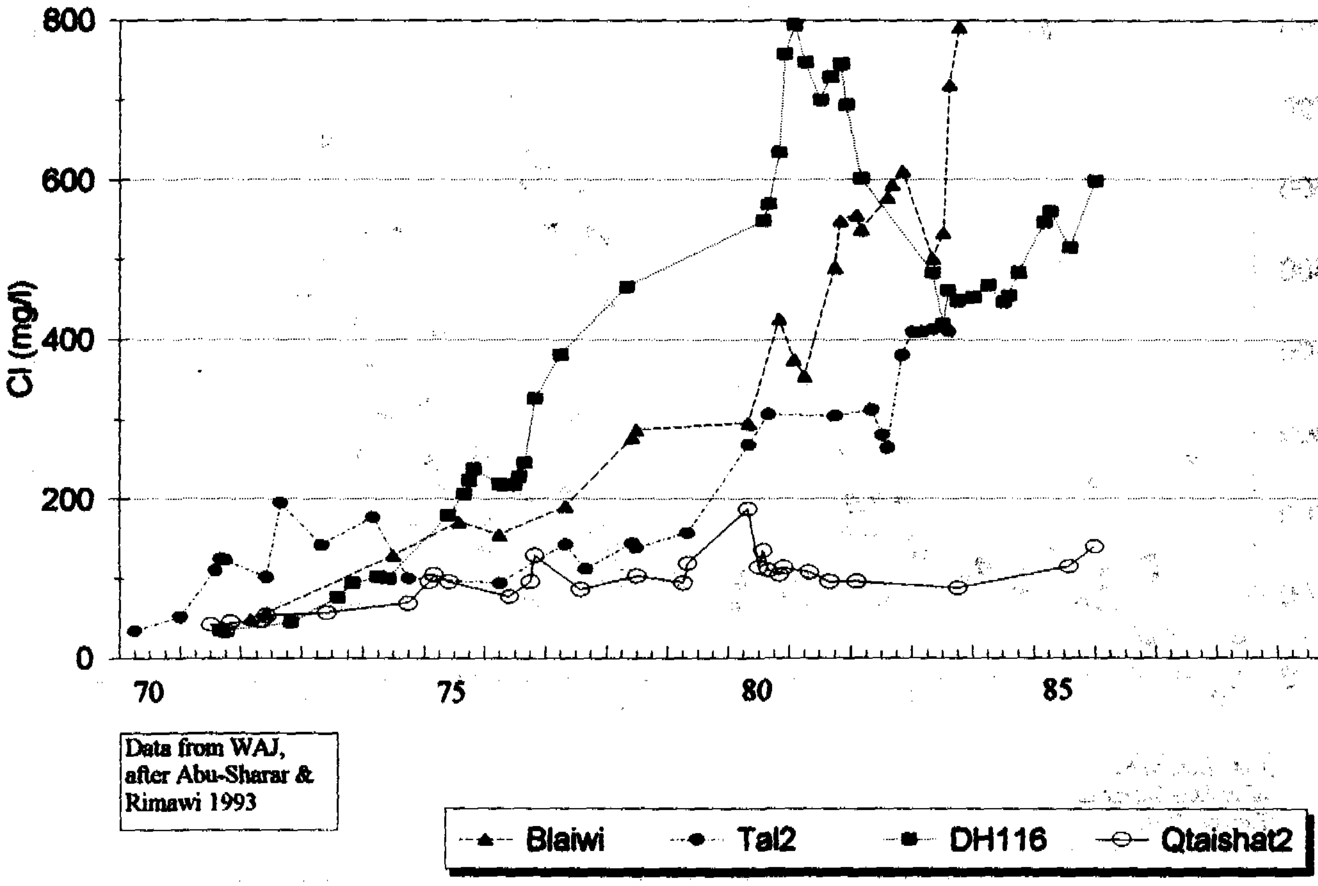
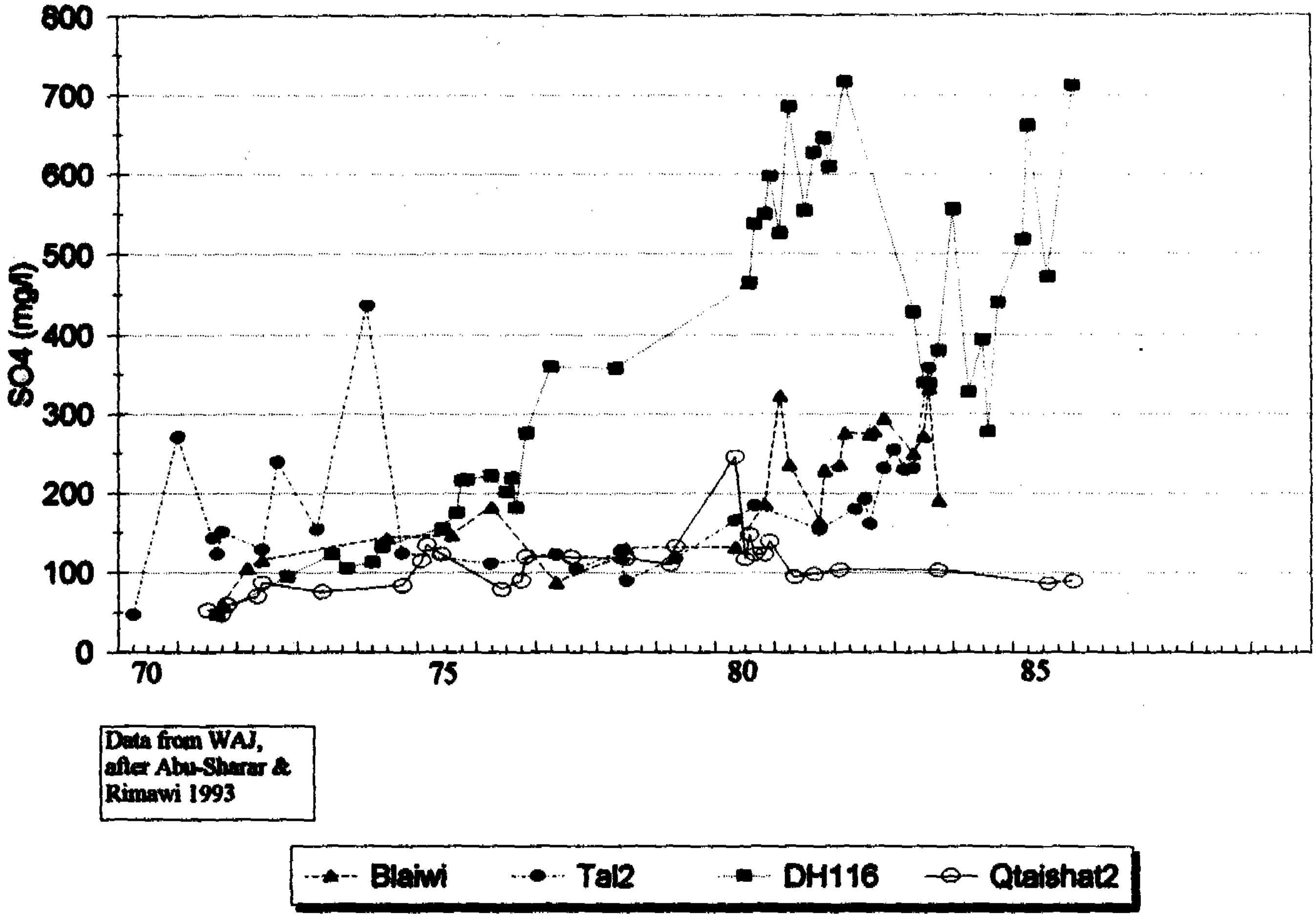


Fig. 16g: Cl concentrations, Dhuleil 1970 -1986



Data from WAJ, after Abu-Sharar & Rimawi 1993

Fig. 16h: SO4 concentrations, Dhuleil 1970 -1986



Data from WAJ, after Abu-Sharar & Rimawi 1993

Figure 17: Northeastern desert

a) Location of sampling points
b) Piper diagram
c) Schoeller diagram

Fig. 17a: Location of sampling points, northeastern desert of Jordan

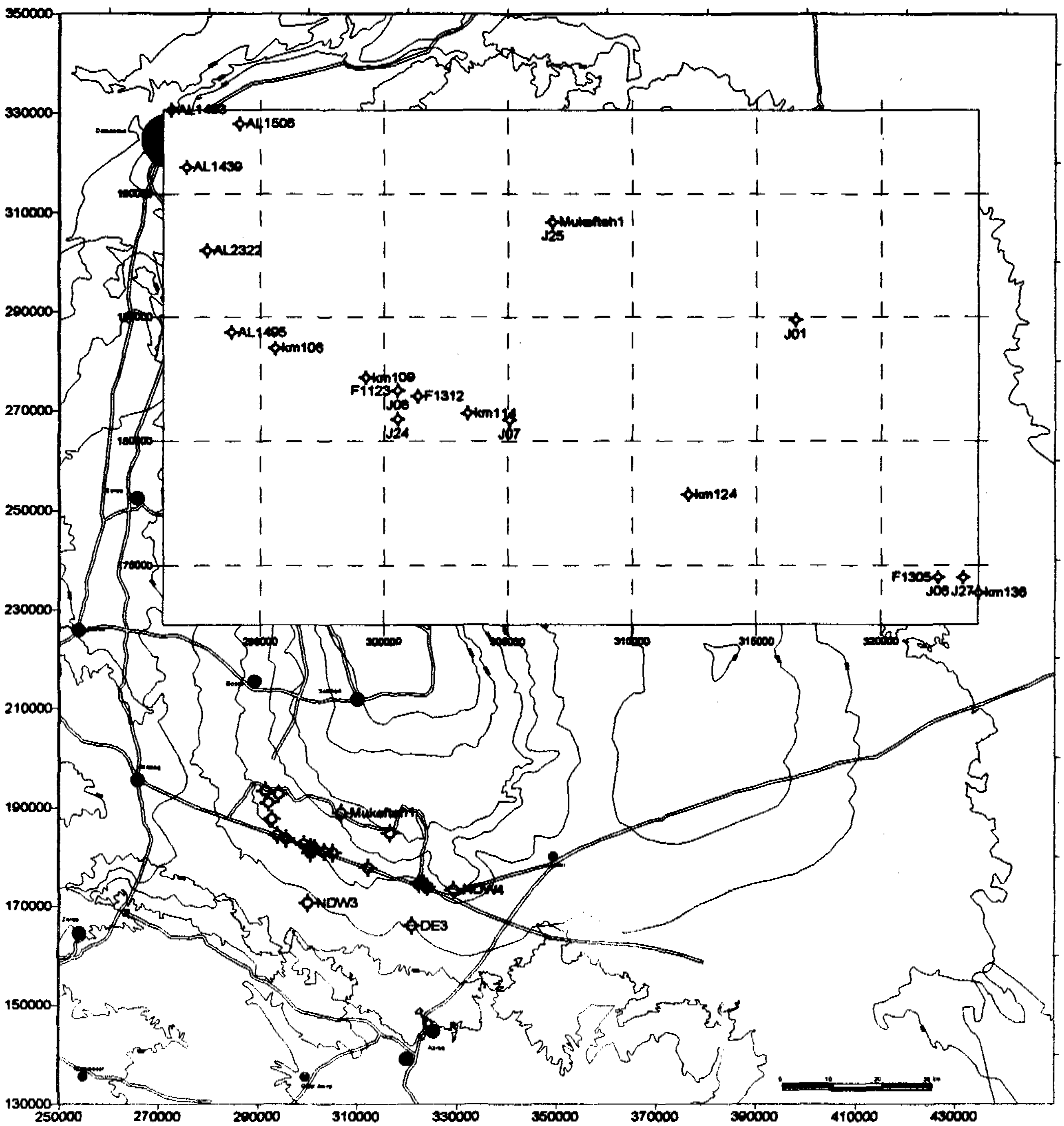


Fig. 17b: Piper Diagram .. Northeastern Desert

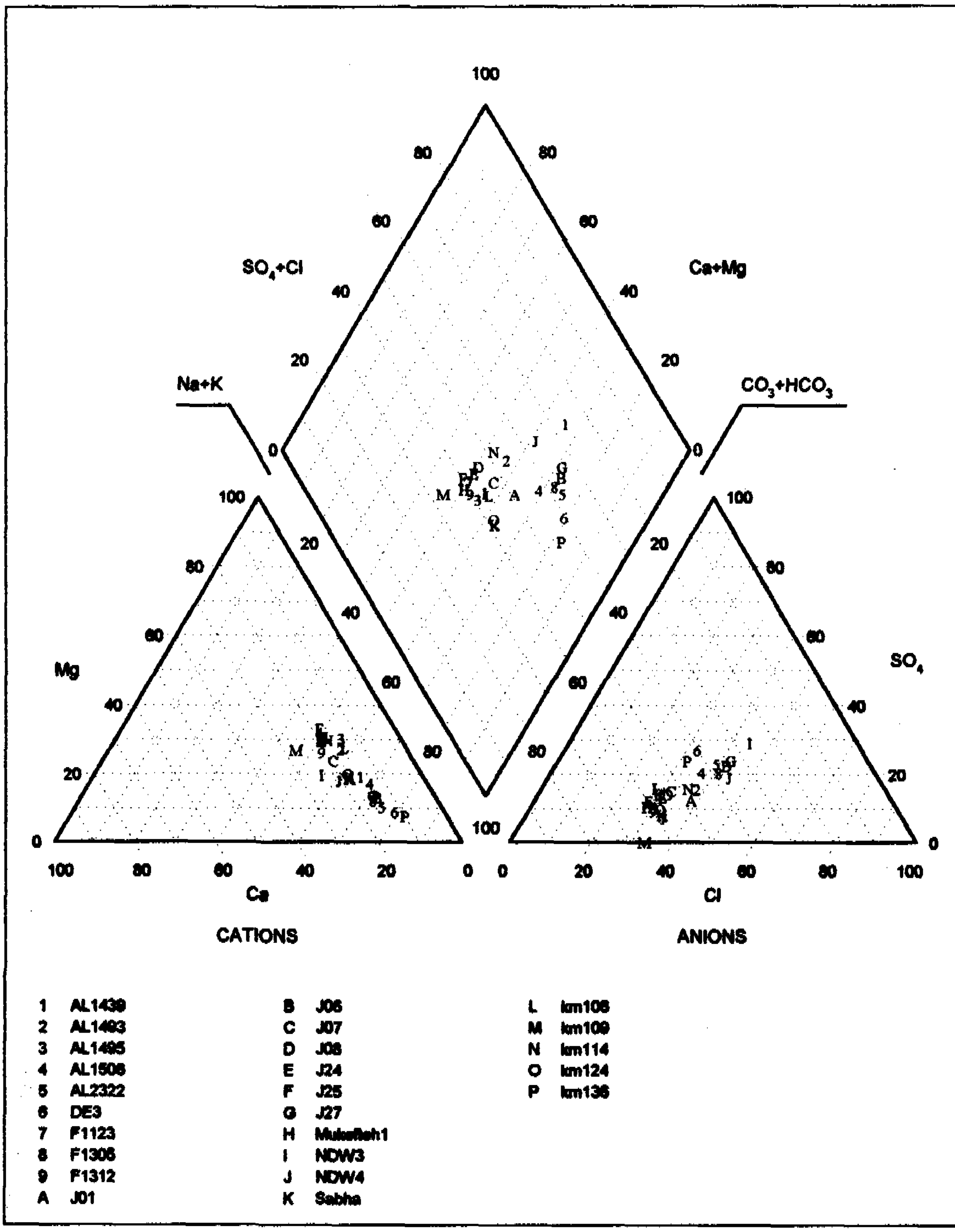


Fig. 17c: Schoeller Diagram .. Northeastern Desert

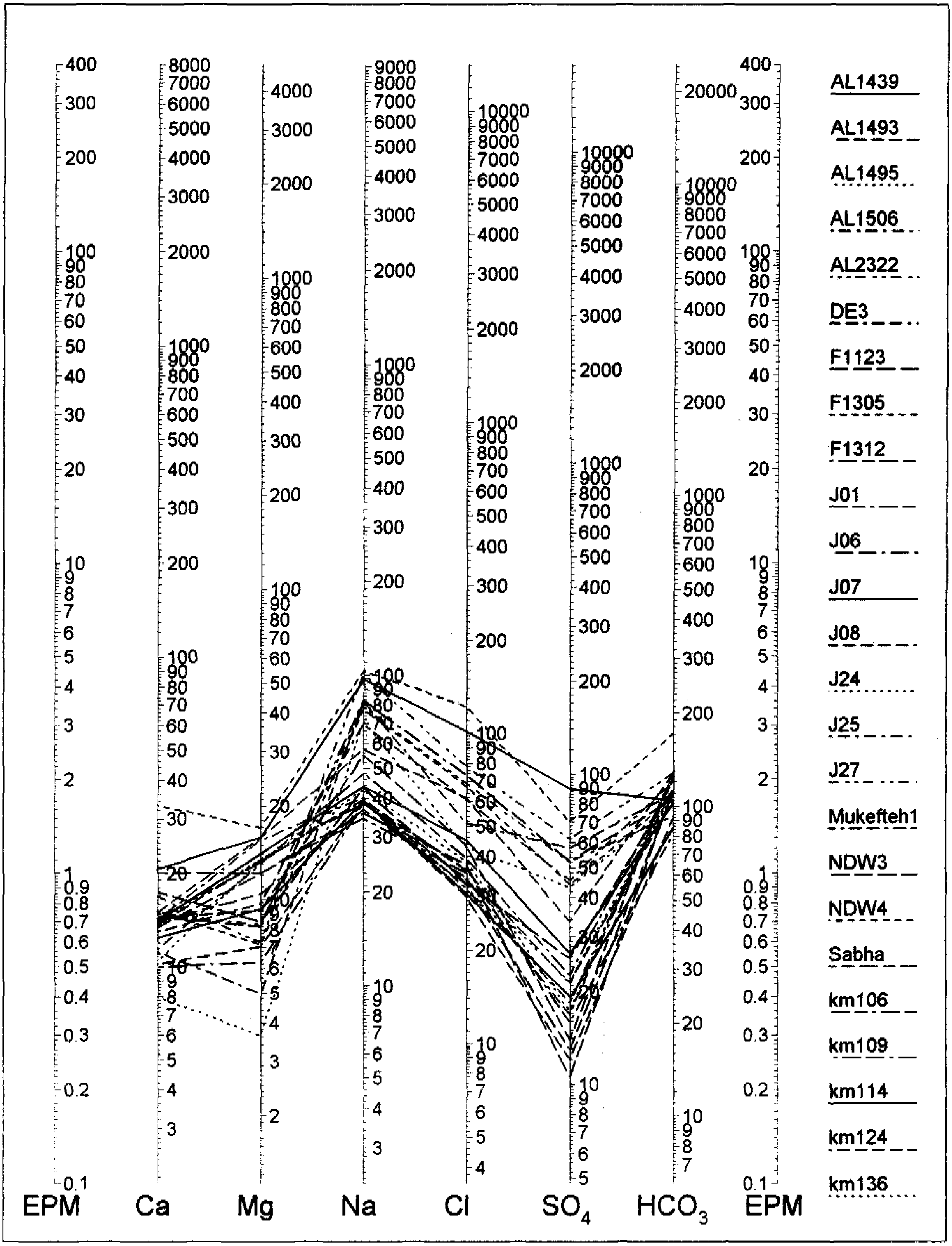


Figure 18: Azraq Basin

a) Location of sampling points
b) Piper diagram, AWSA well field
c) Schoeller diagram, AWSA well field
d) Piper diagram, basalt area near Azraq
e) Schoeller diagram, basalt area near Azraq
f) Piper diagram, Azraq springs
g) Schoeller diagram, Azraq springs

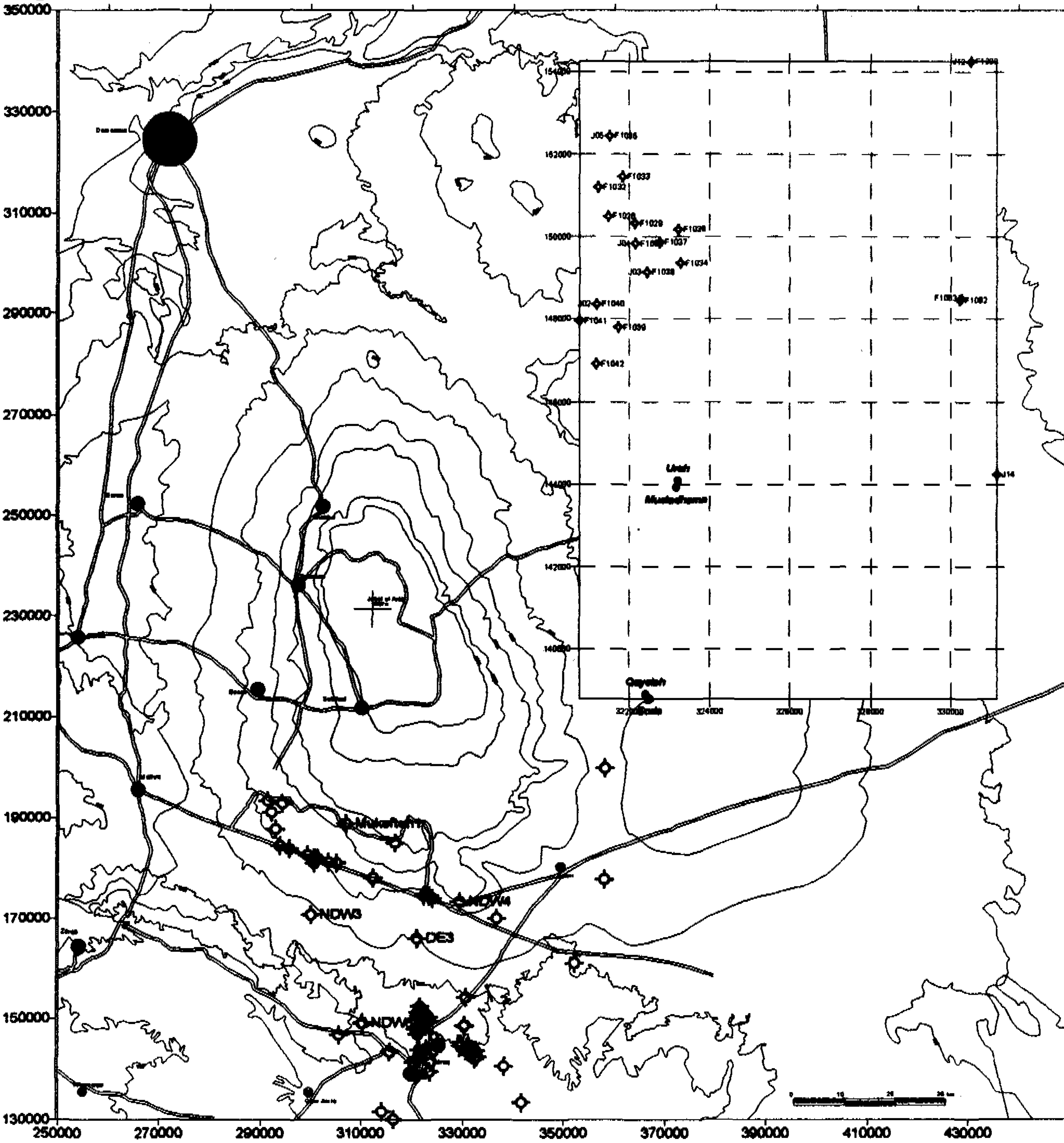
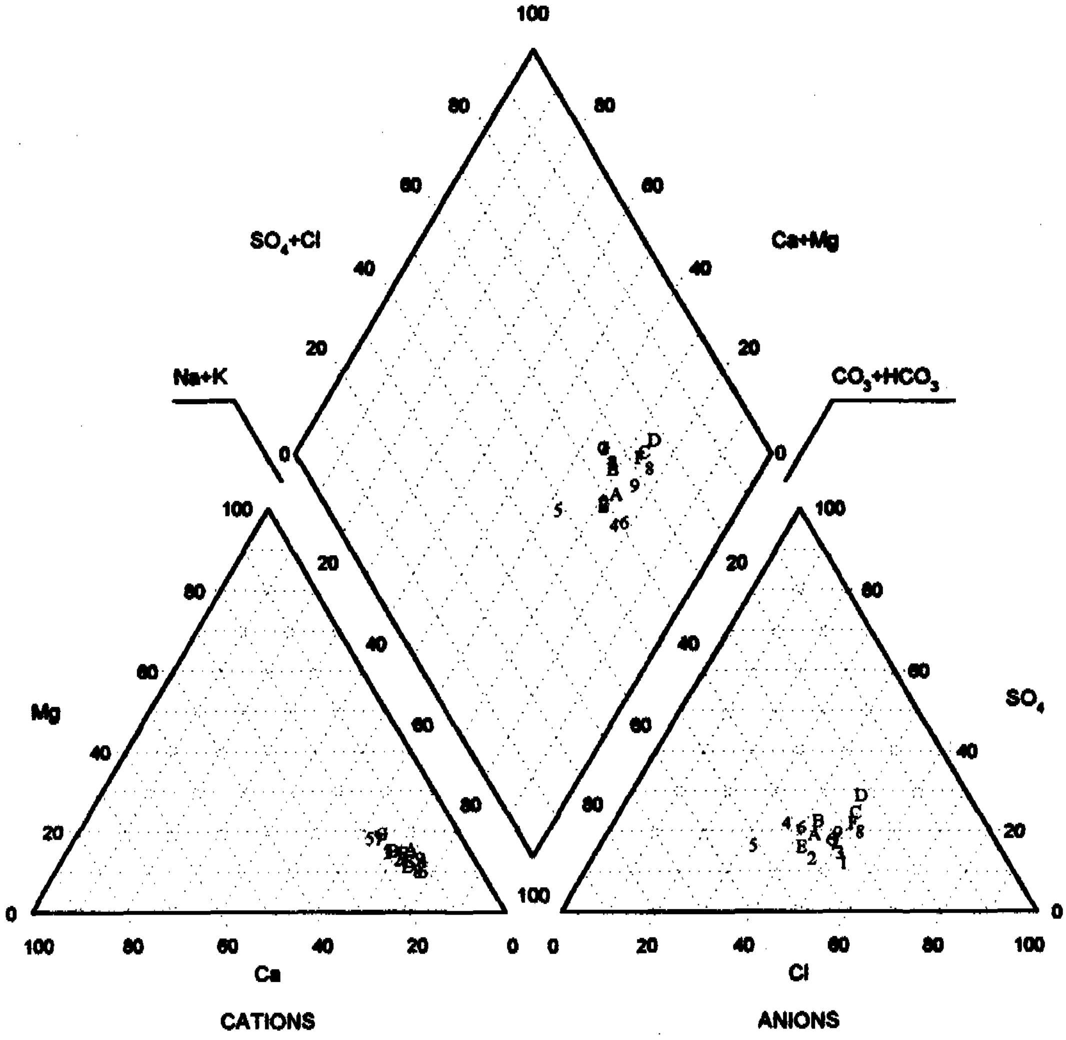


Fig. 18a: Location of sampling points, Azraq Basin

Fig. 18b: Piper Diagram .. AWSA well field



1	F1028	B	F1039
2	F1029	C	F1040
3	F1030	D	F1041
4	F1032	E	F1042
5	F1033	F	J02
6	F1034	G	J05
7	F1035		
8	F1036		
9	F1037		
A	F1038		

Fig. 18c: Schoeller Diagram .. AWSA well field

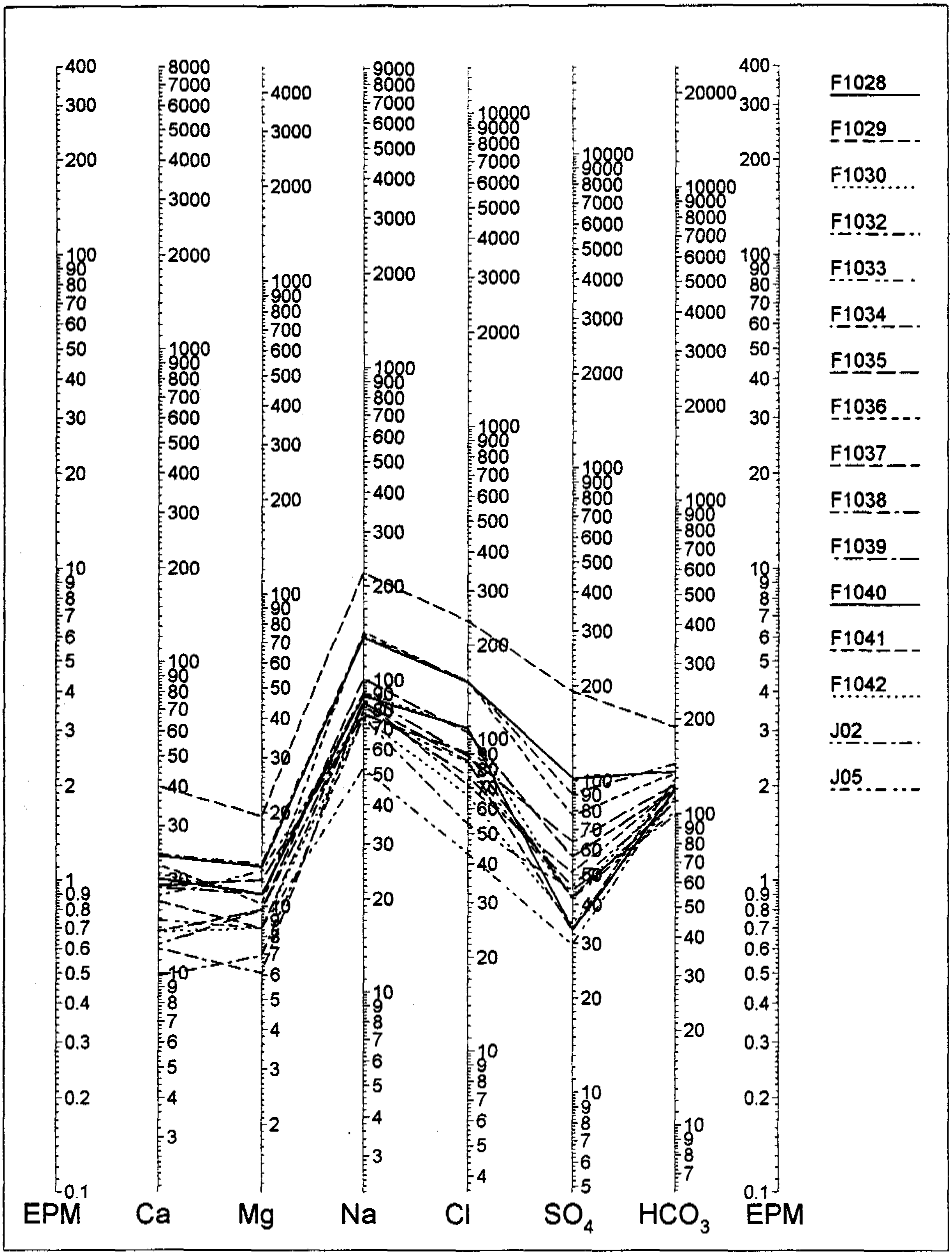


Fig. 18d: Piper Diagram .. Basalt area near Azraq

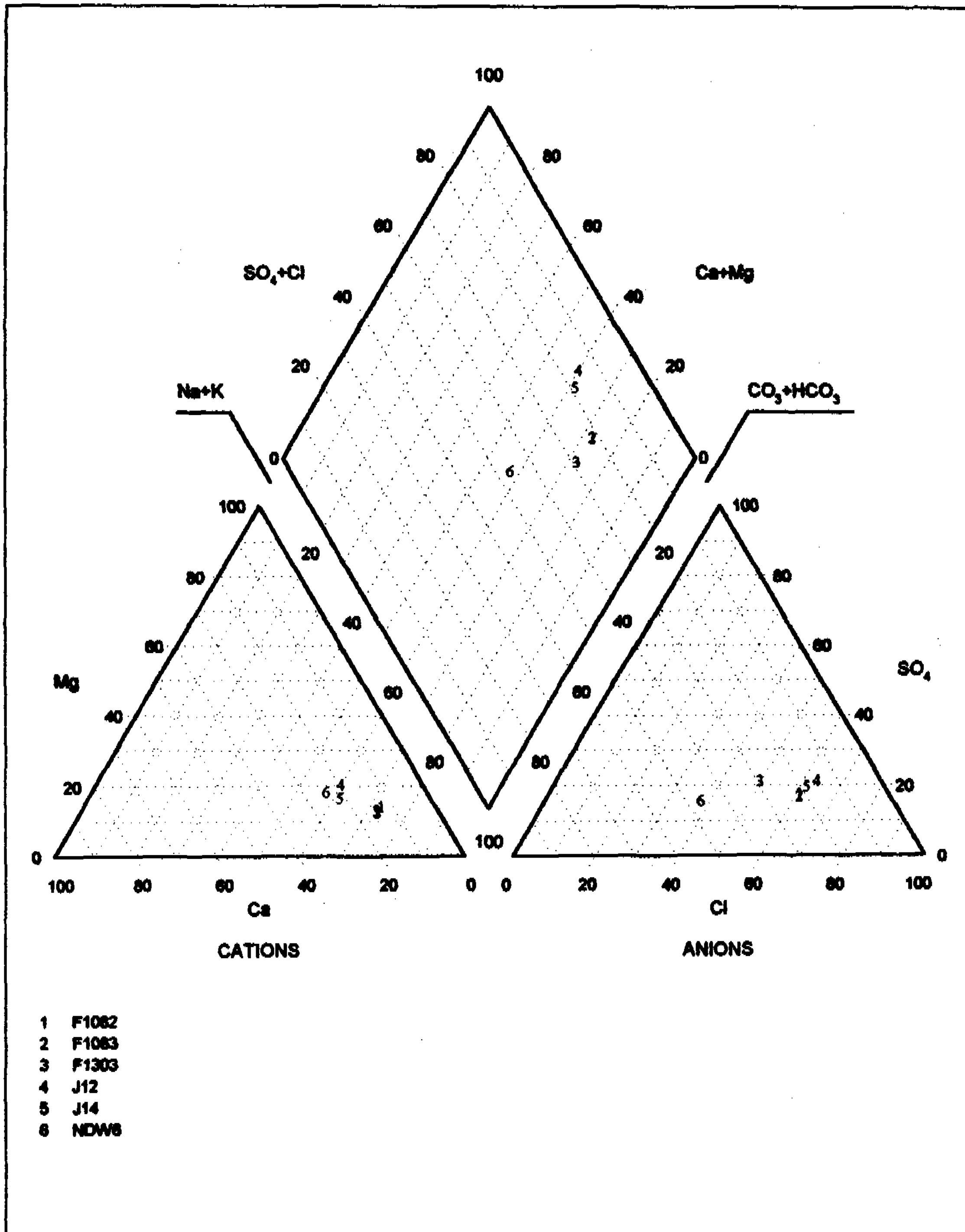


Fig. 18e: Schoeller Diagram .. Basalt area near Azraq

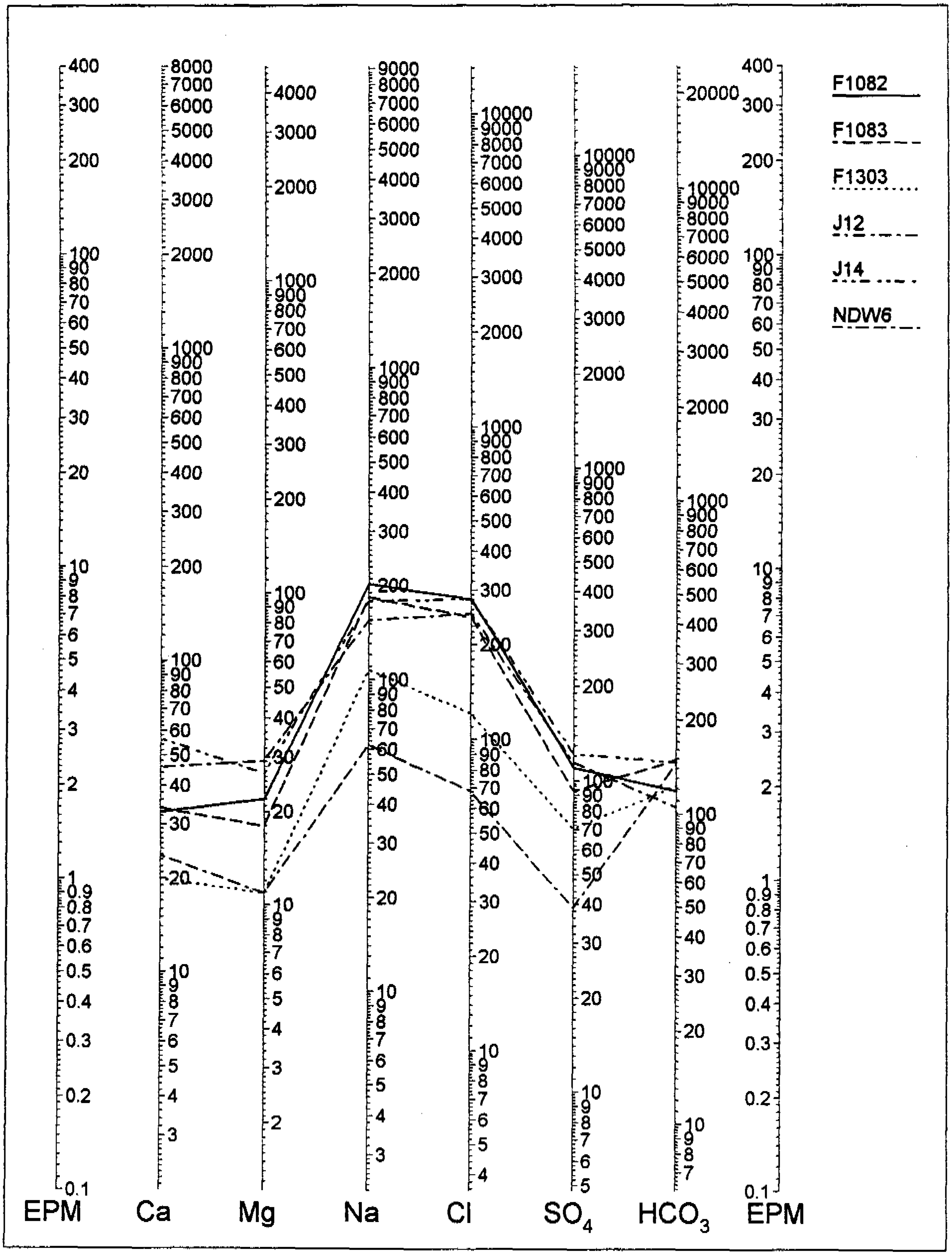


Fig. 18f : Piper Diagram .. Azraq springs

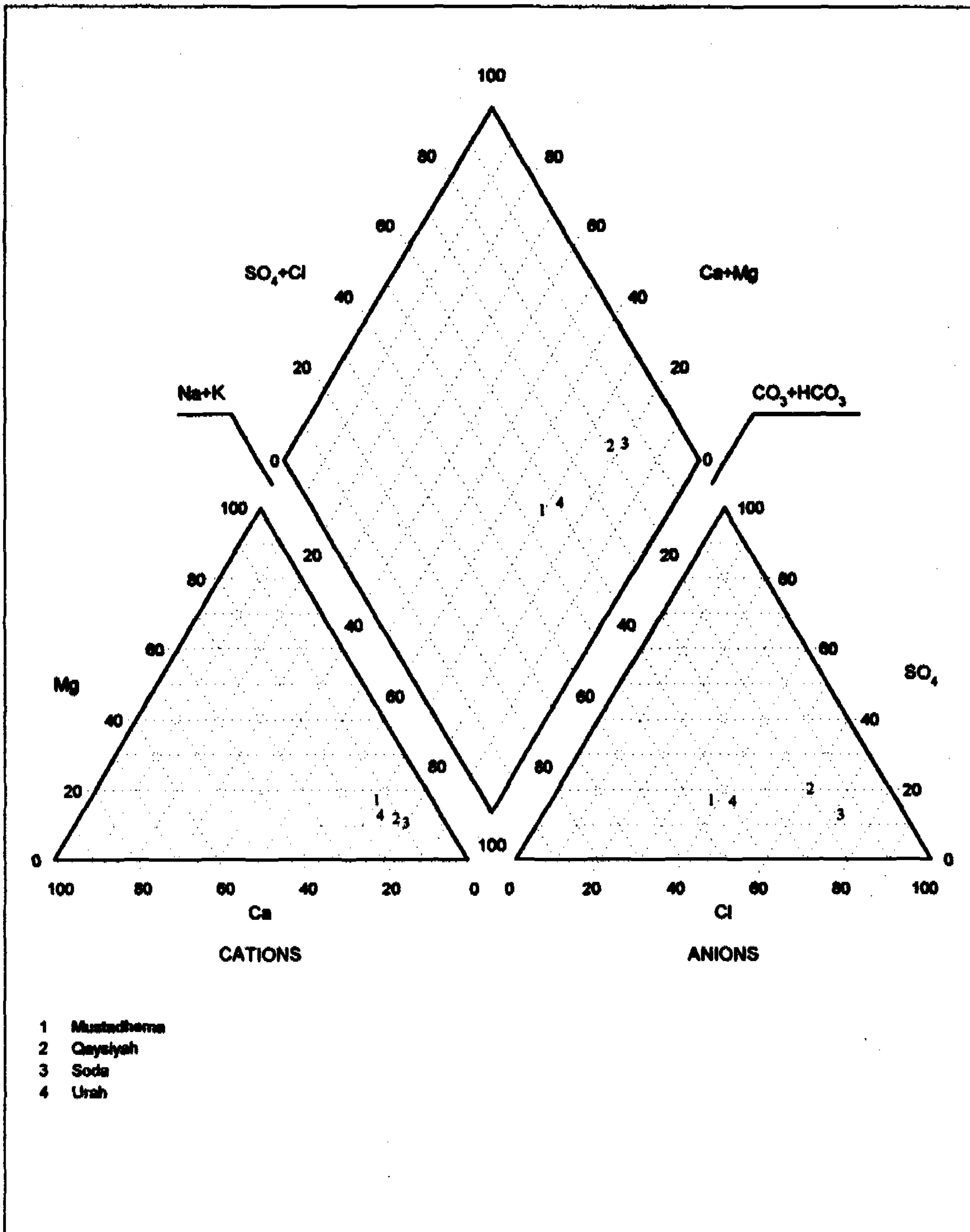


Fig.18g: Schoeller Diagram .. Azraq springs

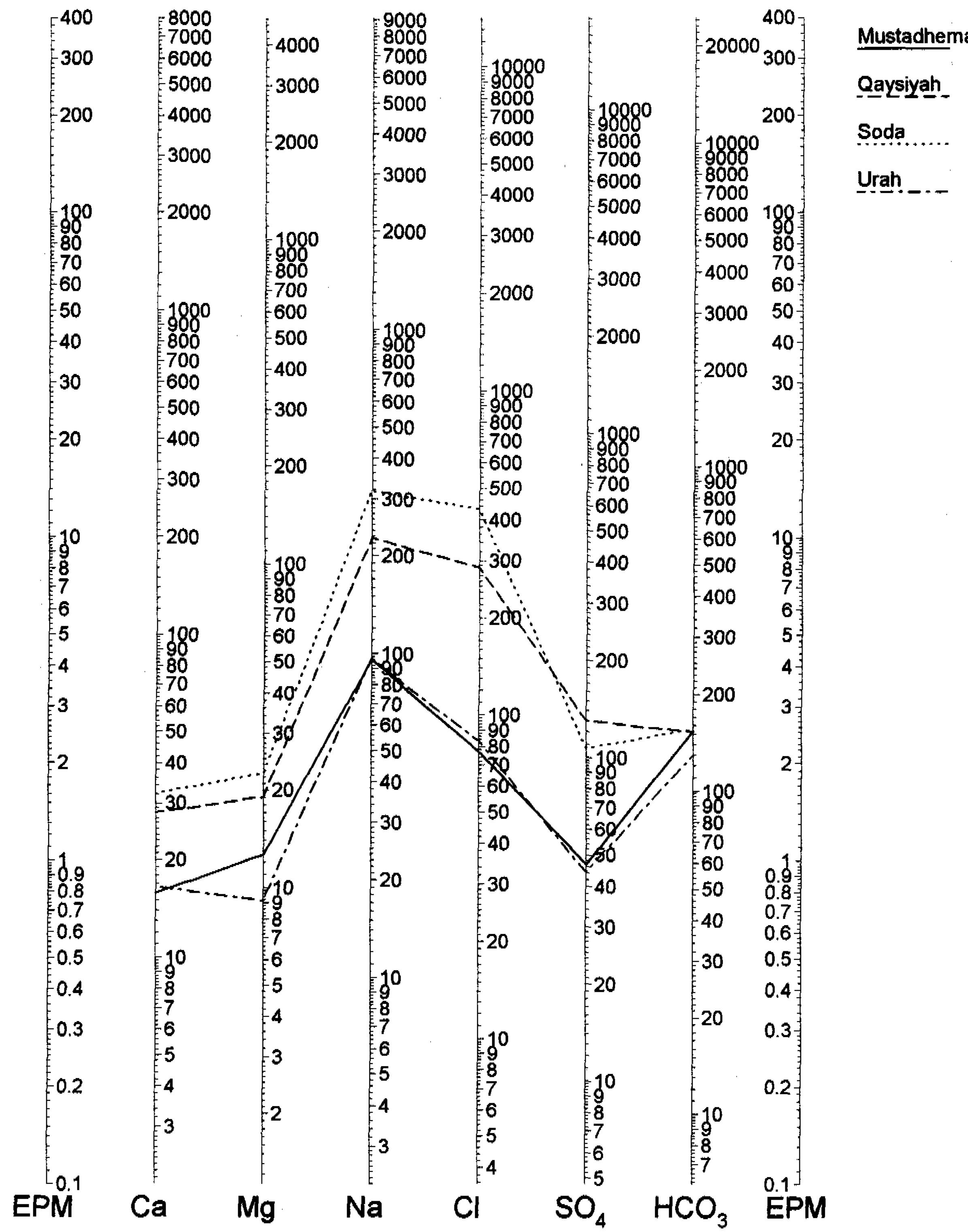


Figure 19: Hamad area

a) Locxation of sampling points
b) Piper diagram
c) Schoeller diagram, Muqat - Qasr Burqu
d) Schoeller diagram, Hamad area

Fig. 19a: Location of sampling points, Azraq Basin

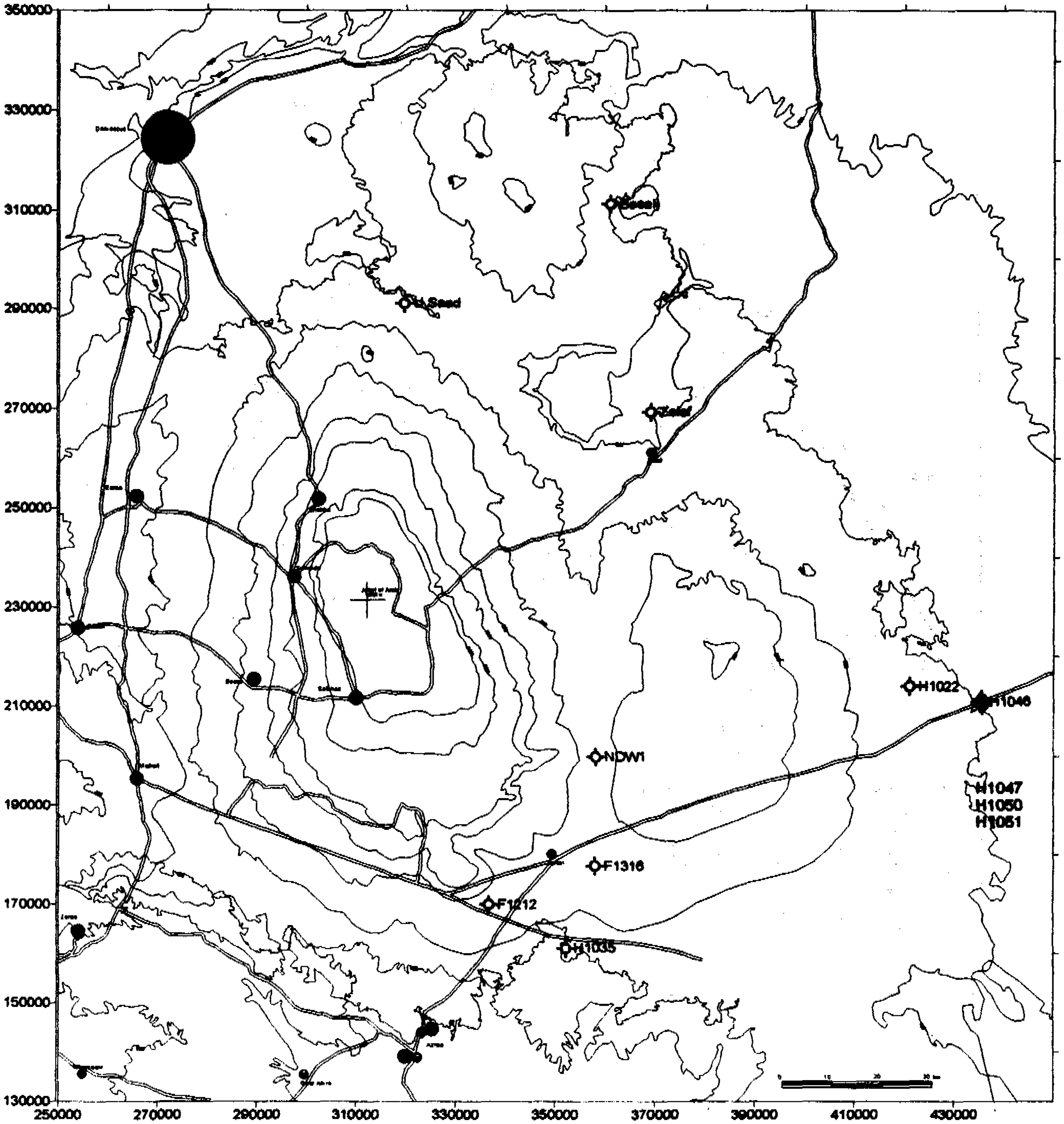


Fig. 19b: Piper Diagram .. Hamad area

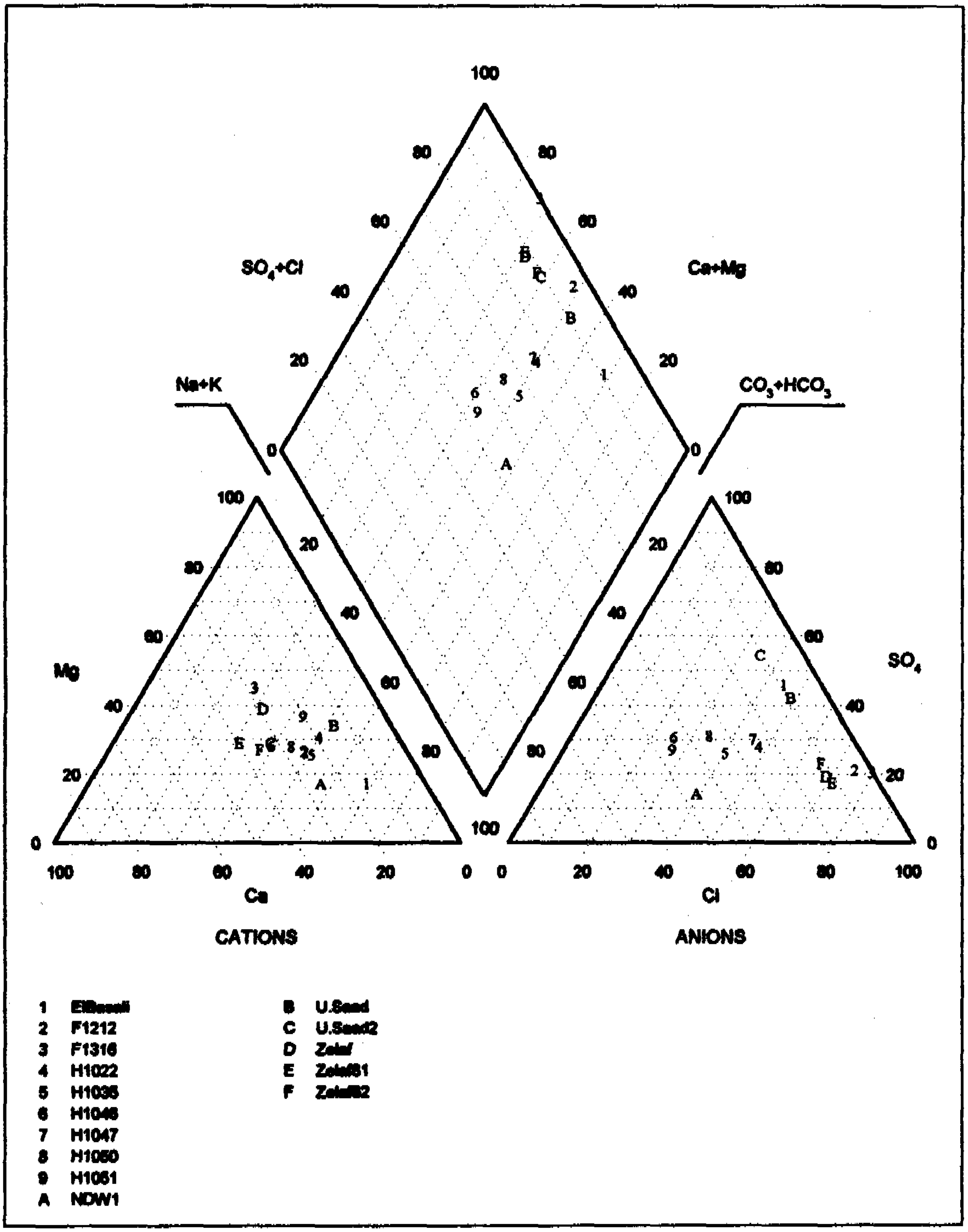


Fig. 19c: Schoeller Diagram .. Hamad area, Muqat - Qasr Burqu

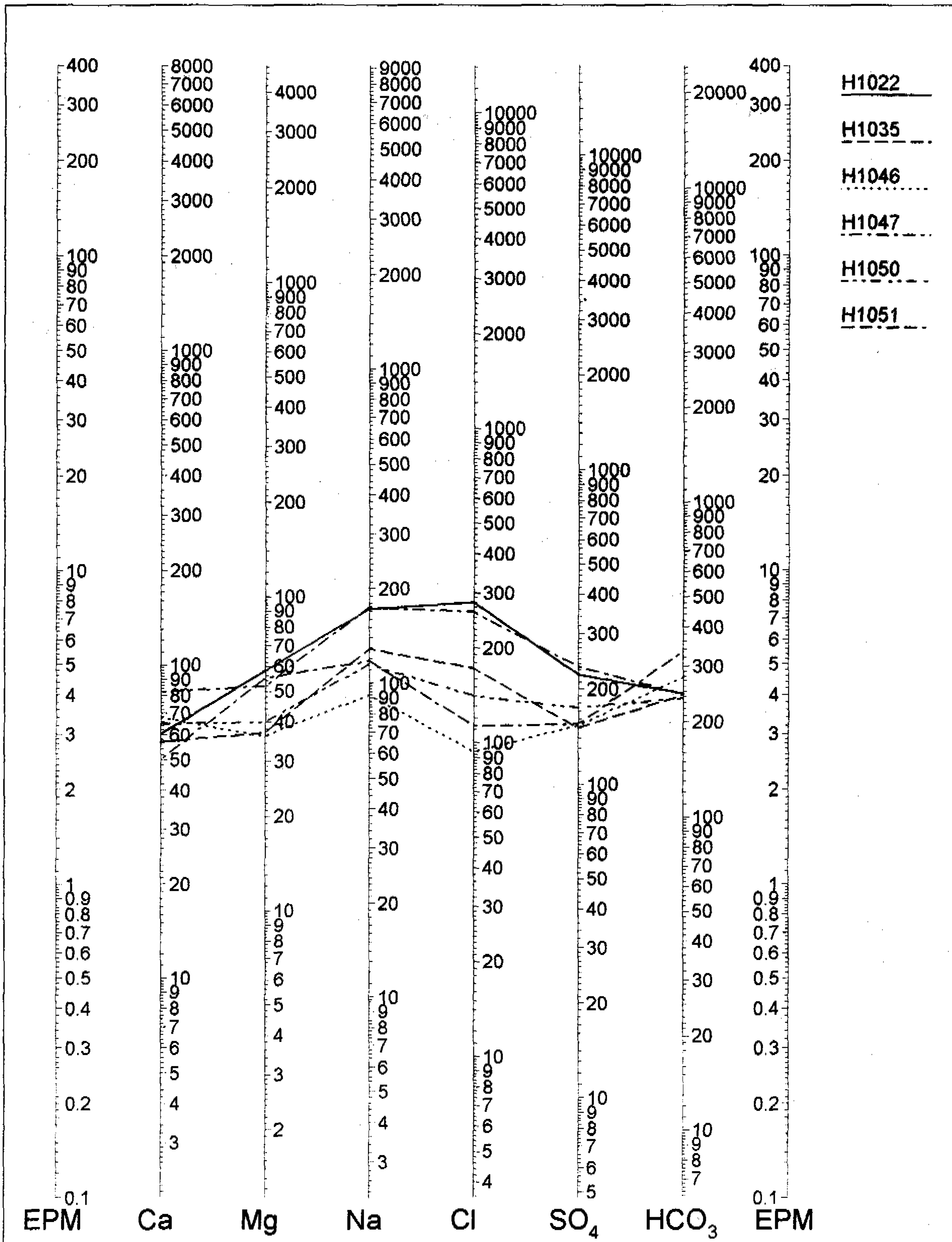


Fig. 19d: Schoeller Diagram .. Hamad area

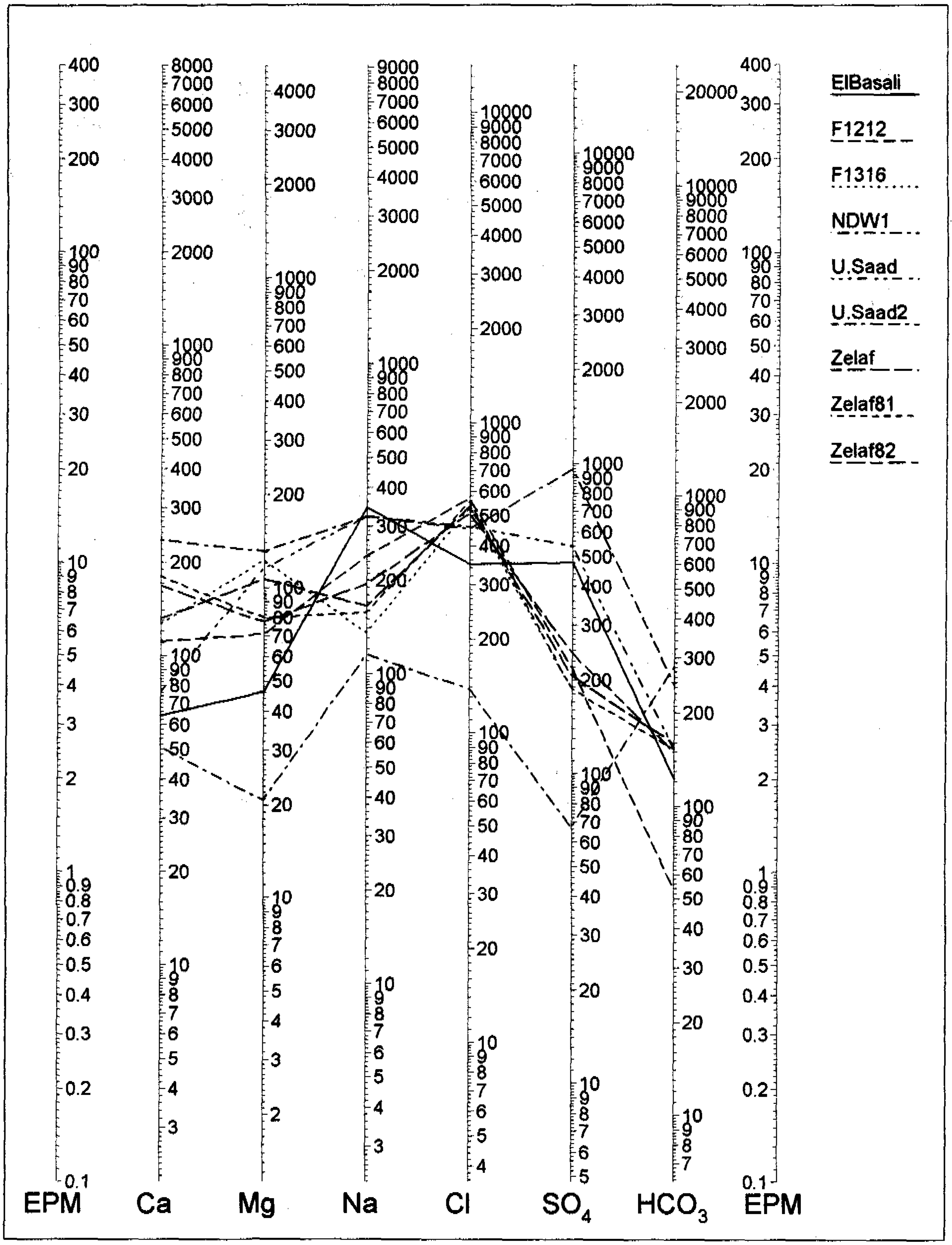


Figure 20: Statistical comparison of water analyses from different areas of the basalt aquifer system,
Box- and- whisker plots
a) Electrical conductivity, b) Ca, c) Mg, d) Na, e) HCO_3, f) SO_4, g) Cl, h) NO_3

Fig.20a: Box-and-Whisker Plot, Electrical conductivity

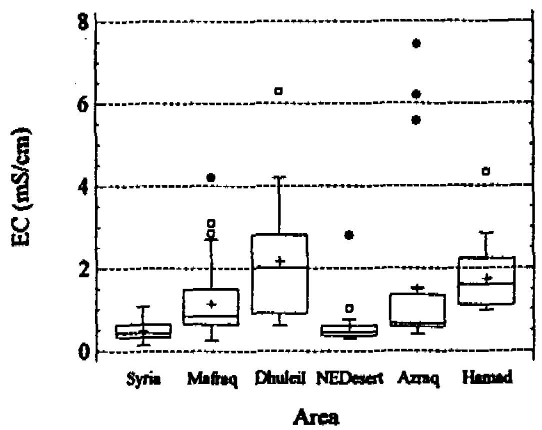


Fig.20b: Box-and-Whisker Plot, Ca concentration

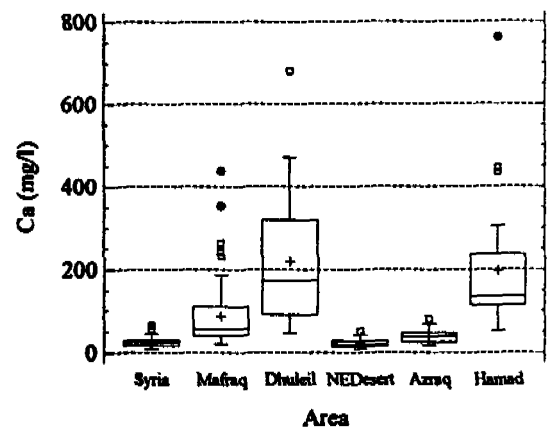


Fig.20c: Box-and-Whisker Plot, Mg concentration

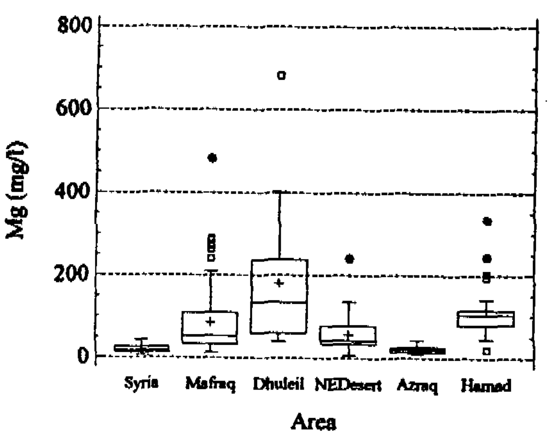
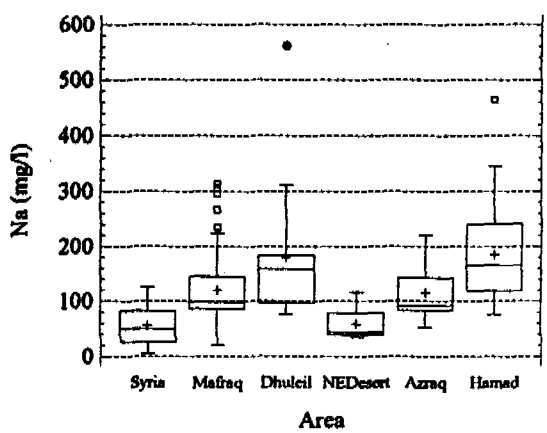


Fig.20d: Box-and-Whisker Plot, Na concentration



Statistical comparison of water analyses from different areas of the basalt aquifer system,
Box- and- whisker plots

Fig.20e: Box-and-Whisker Plot, HCO3 concentration

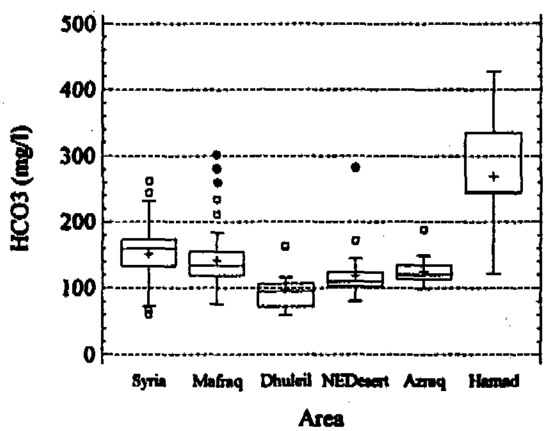


Fig.20f: Box-and-Whisker Plot, SO4 concentration

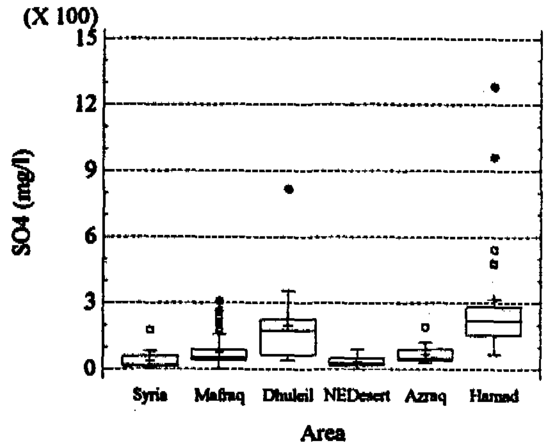


Fig.20g: Box-and-Whisker Plot, Cl concentration

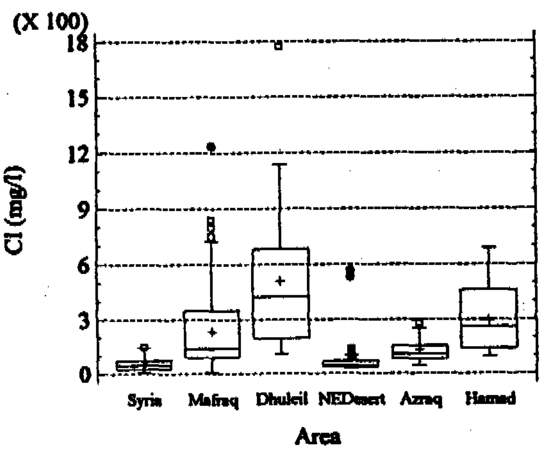


Fig.20h: Box-and-Whisker Plot, NO3 concentration

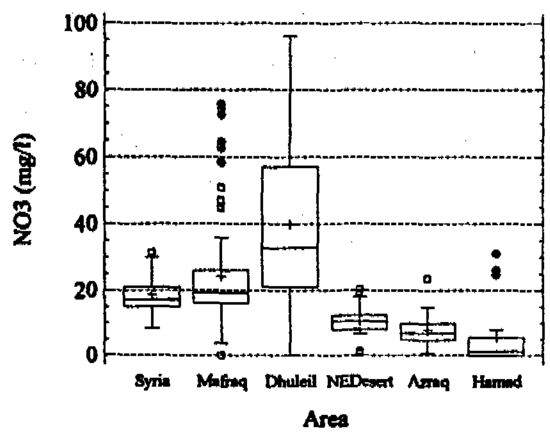


Fig.21: Piper Diagram .. Different areas of the basalt aquifer system

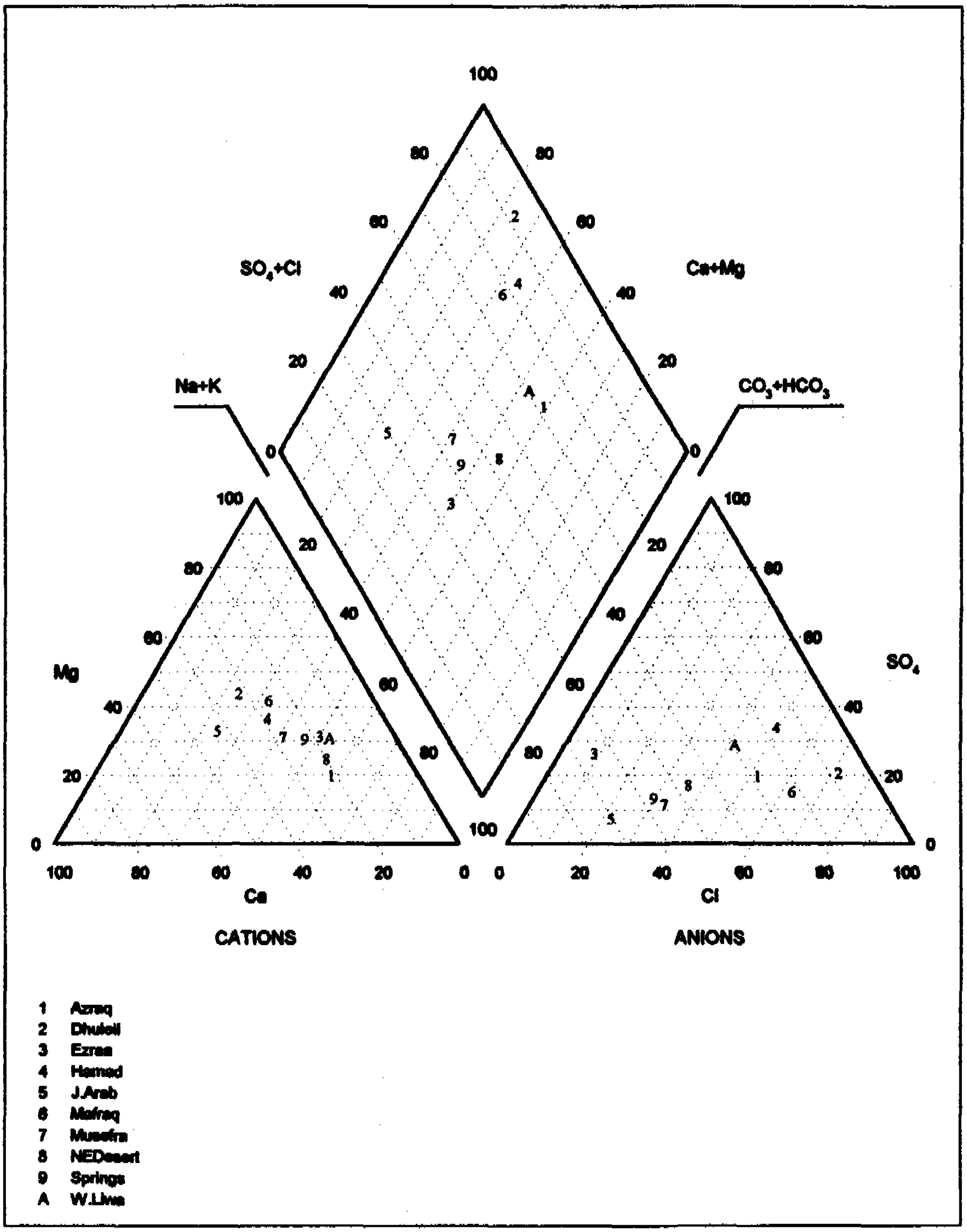
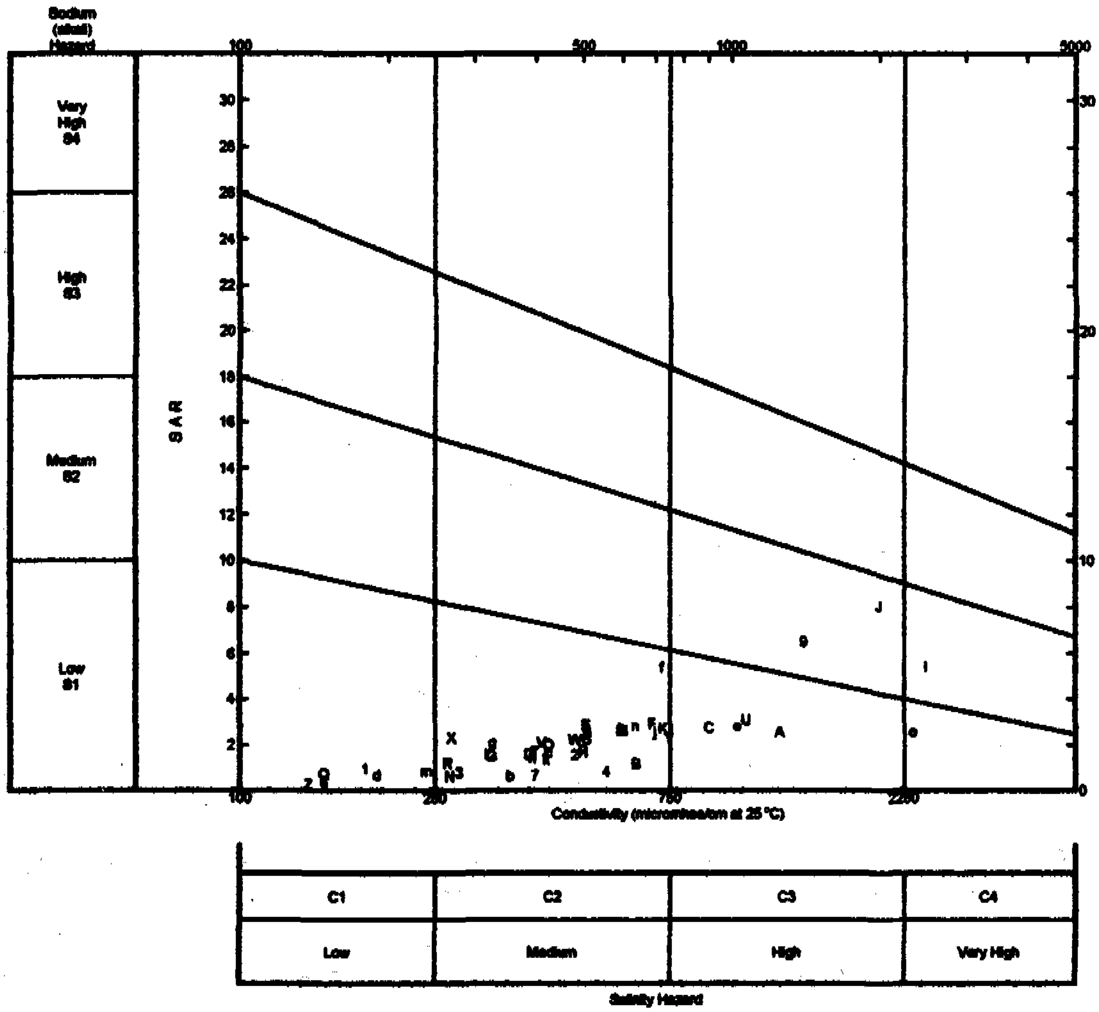
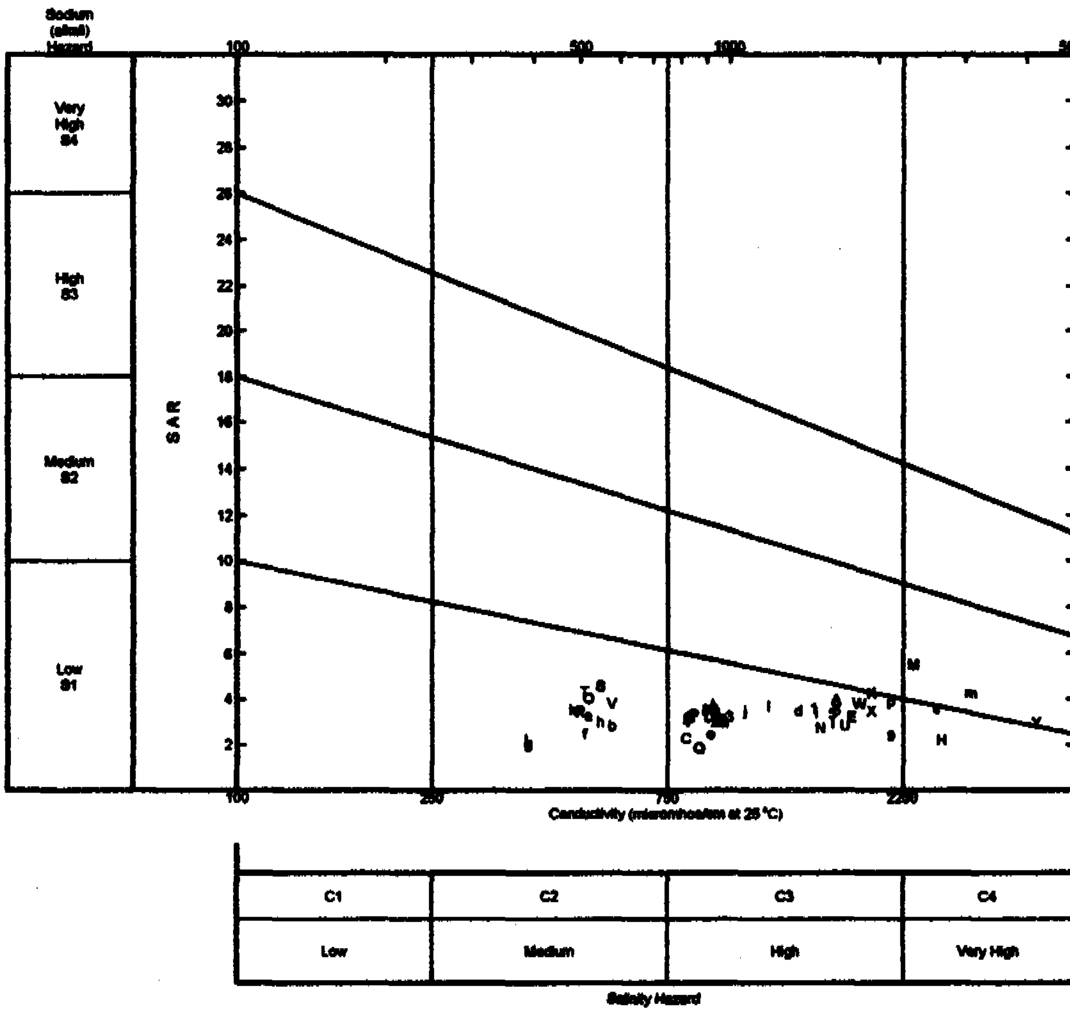


Fig.22a: Wilcox Diagram .. Basalt aquifer area in Syria



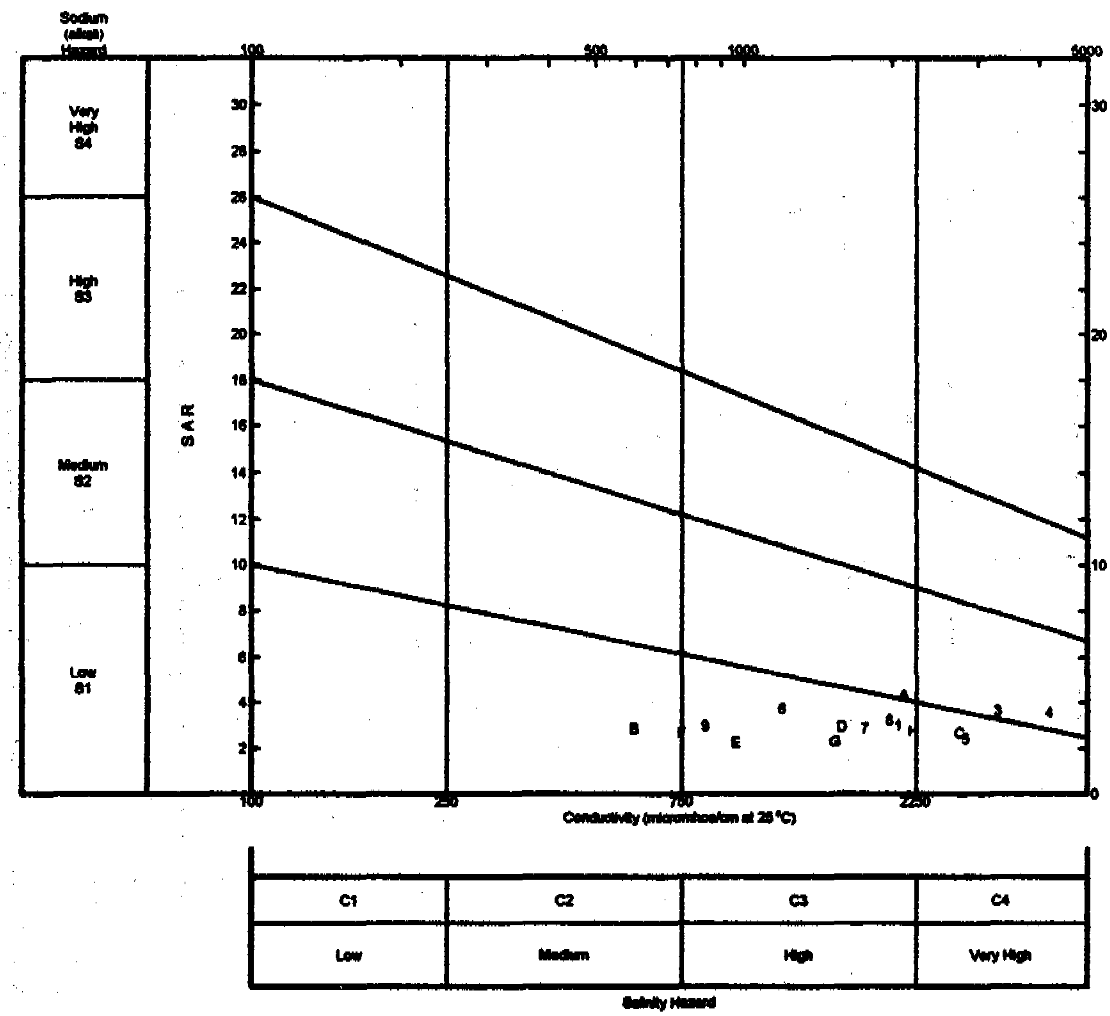
1	[illegible]	E	[illegible]	R	Majadal	e	[illegible]
2	AlKahlye4	F	Dael	S	[illegible]	f	[illegible]
3	AlKoum	G	Dama	T	[illegible]	g	[illegible]
4	[illegible]	H	DeirAdass	U	[illegible]	h	[illegible]
5	[illegible]	I	DeirLabo	V	[illegible]	i	Tafasse
6	[illegible]	J	[illegible]	W	[illegible]	j	U.Abed
7	[illegible]	K	Ezraa	X	Nijran	k	[illegible]
8	[illegible]	L	G.Bustan	Y	[illegible]	l	U.Saad
9	[illegible]	M	[illegible]	Z	Qinah	m	W.Aram
A	[illegible]	N	Inkh	a	Rain	n	Zelzoun
B	[illegible]	O	Khabab	b	[illegible]	o	Zelaf
C	Ch.Meskin	P	Koheel	c	Sahweh		
D	[illegible]	Q	Kraya	d	[illegible]		

Fig. 22b: Wilcox Diagram .. Mafraq area



1	AD1008	E	AD1116	R	AL1448	e	AL1486
2	AD1066	F	AD1177	S	AL1455	f	AL1483
3	AD1067	G	AD1183	T	AL1456	g	AL1495
4	AD1068	H	AL1049	U	AL1460	h	AL1503
5	AD1069	I	AL1050	V	AL1462	i	AL1504
6	AD1070	J	AL1051	W	AL1463	j	AL1505
7	AD1071	K	AL1062	X	AL1464	k	AL1506
8	AD1077	L	AL1097	Y	AL1468	l	AL1514
9	AD1086	M	AL1129	Z	AL1474	m	AL1519
A	AD1088	N	AL1236	a	AL1476	n	AL1522
B	AD1100	O	AL1436	b	AL1477	o	AL2323
C	AD1102	P	AL1441	c	AL1478	p	AL2327
D	AD1106	Q	AL1443	d	AL1480		

Fig. 22c: Wilcox Diagram .. Dhuleil area



1	AL1005
2	AL1007
3	AL1022
4	AL1023
5	AL1034
6	AL1076
7	AL1078
8	AL1088
9	AL1101
A	AL1107
B	AL1765
C	AL1766
D	AL1767
E	AL1768
F	AL1769
G	AL1770
H	AL1910

Fig. 22d: Wilcox Diagram .. Northeastern Desert

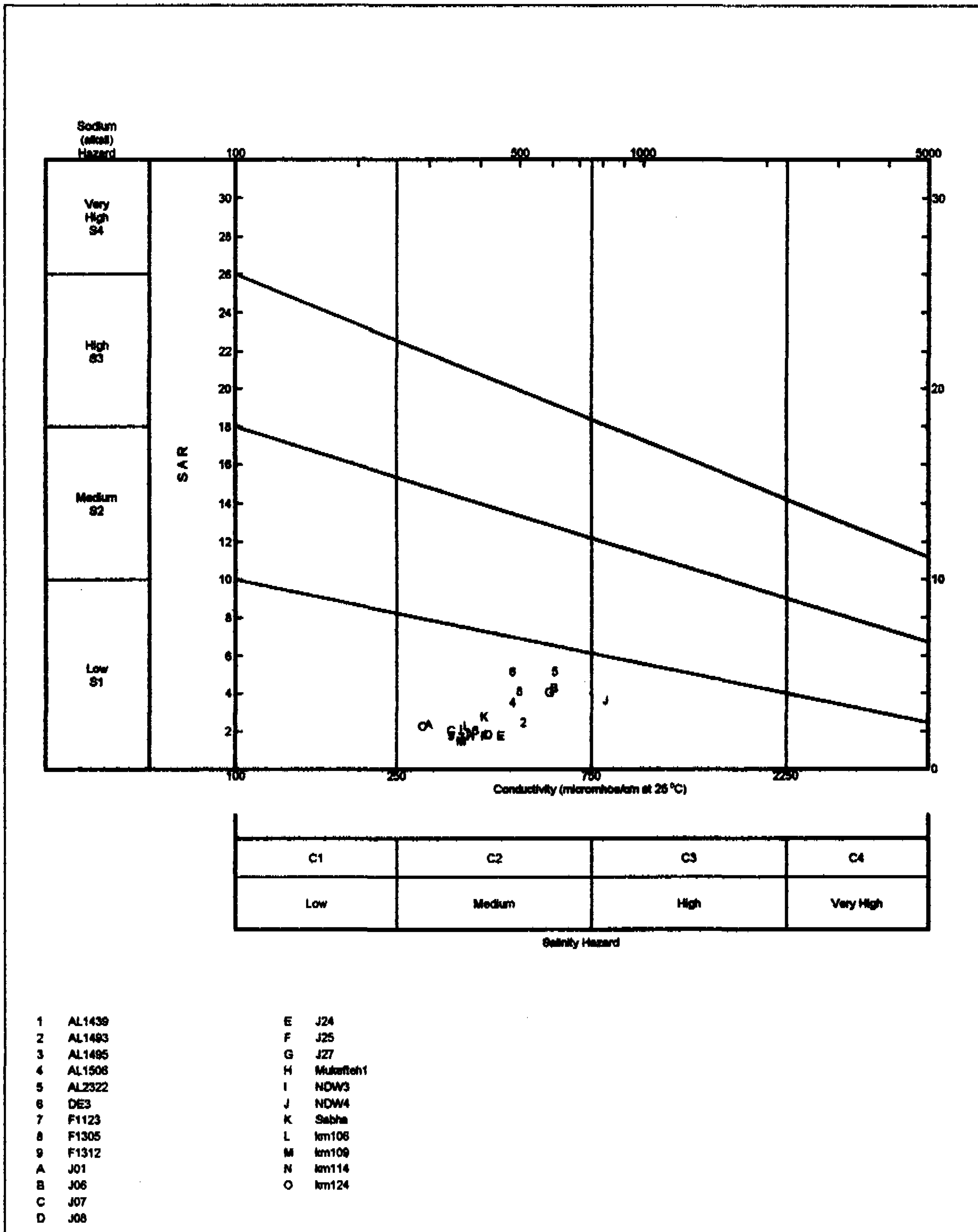
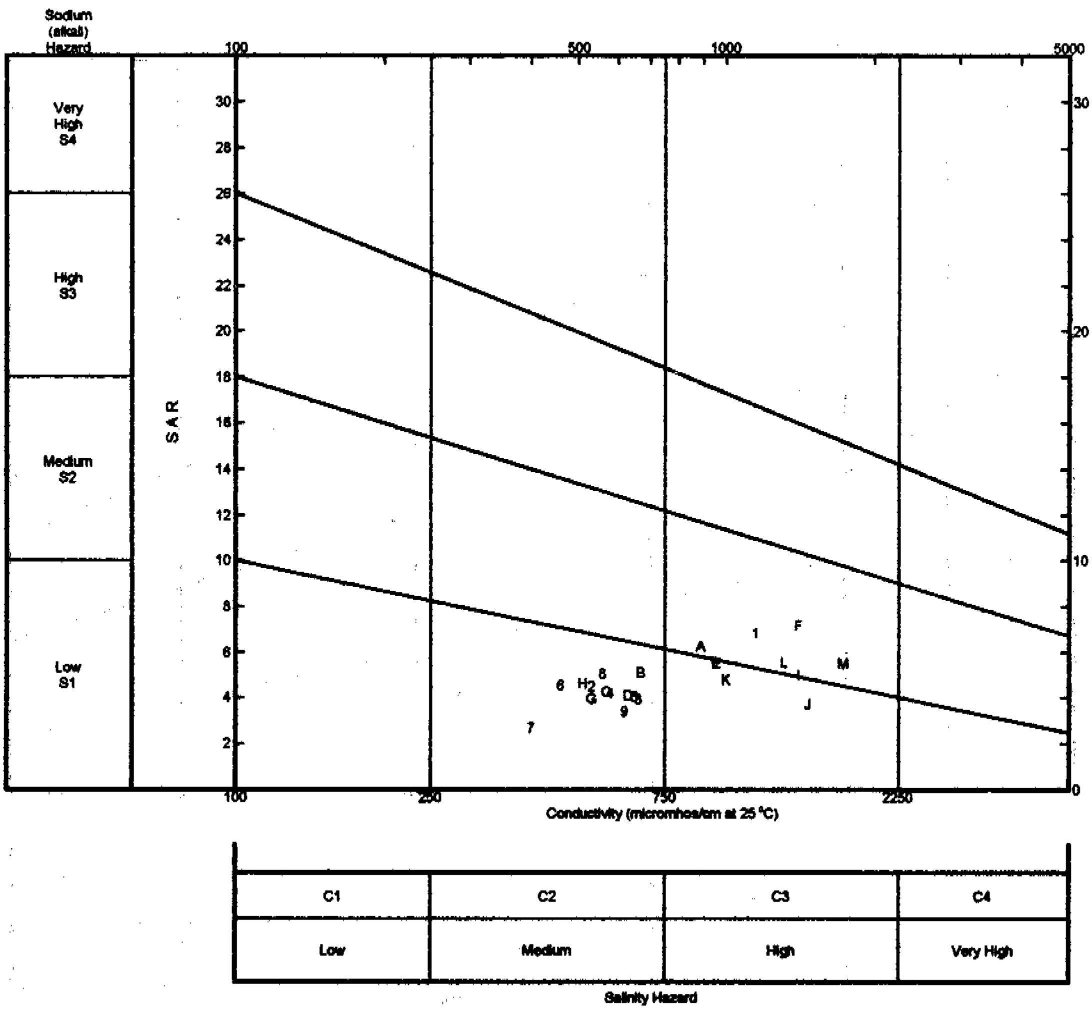


Fig. 22e: Wilcox Diagram .. Azraq area



1	F1021	E	F1040
2	F1022	F	F1041
3	F1028	G	F1042
4	F1029	H	F1043
5	F1030	I	F1050
6	F1032	J	F1053
7	F1033	K	F1059
8	F1034	L	F1244
9	F1035	M	F1272
A	F1036		
B	F1037		
C	F1038		
D	F1039		

Fig. 22f: Wilcox Diagram .. Hamad area

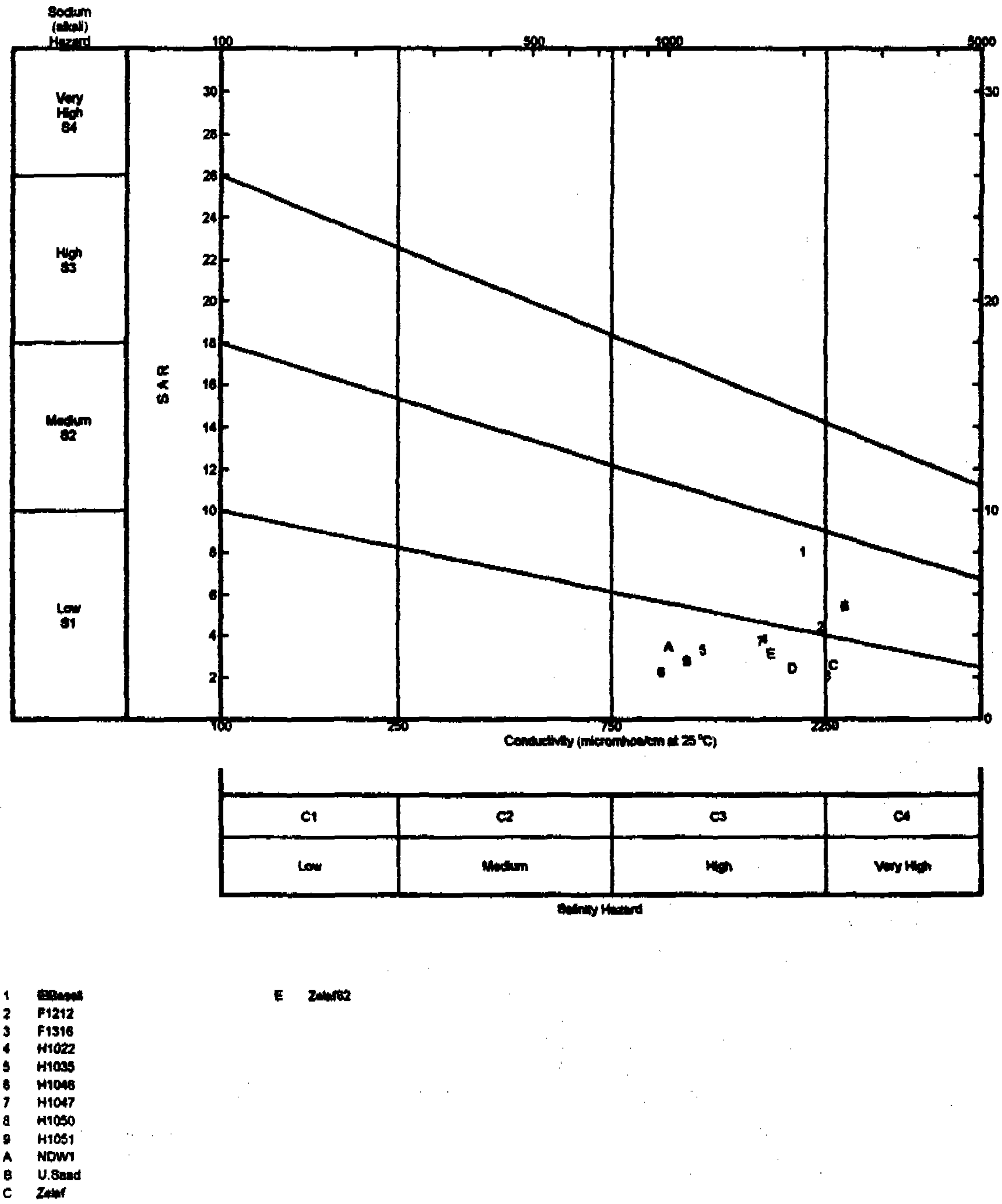


Fig. 23: Location of sampling points of chemical water anlyses

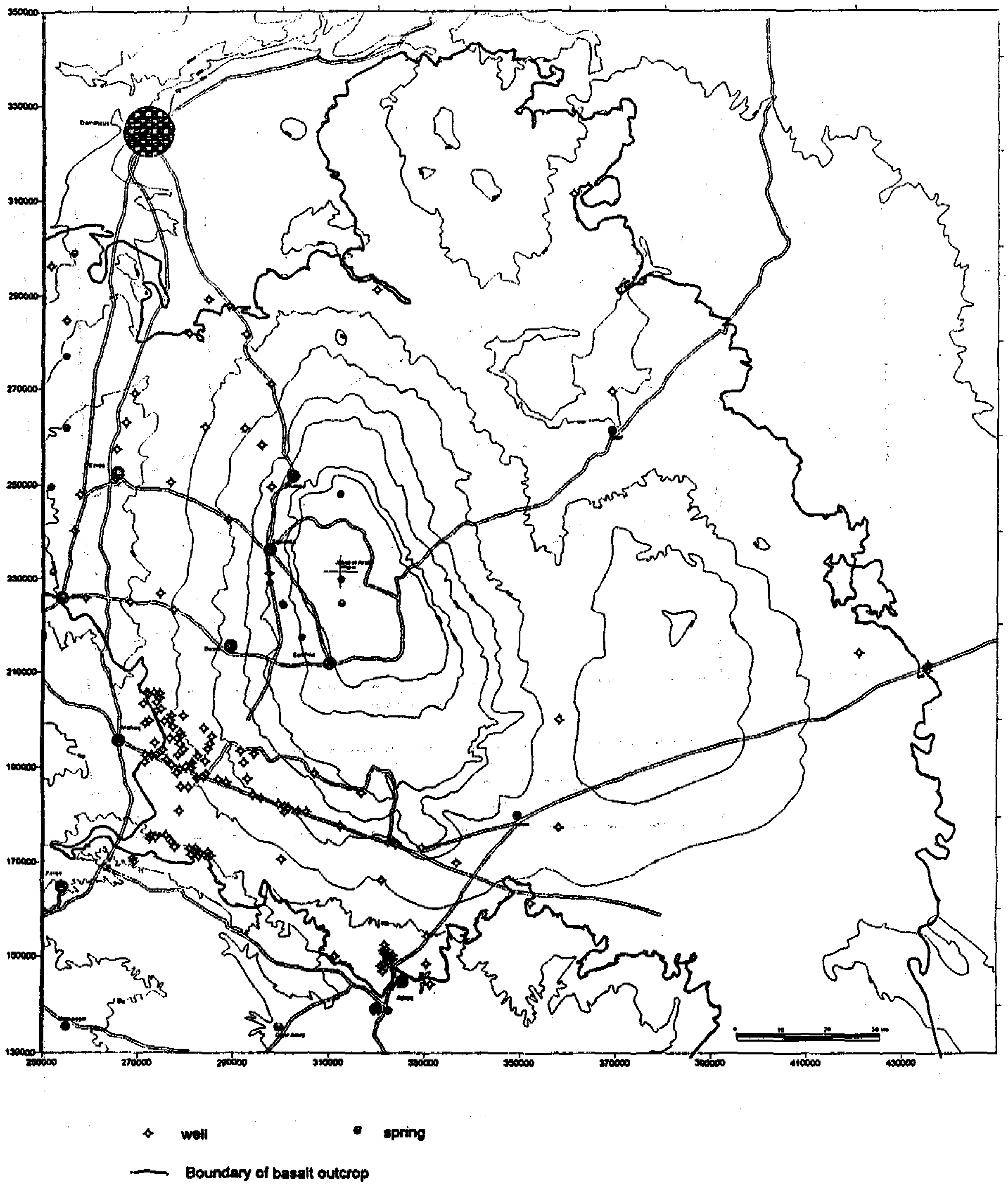


Fig. 24a: Ca concentration in groundwater samples

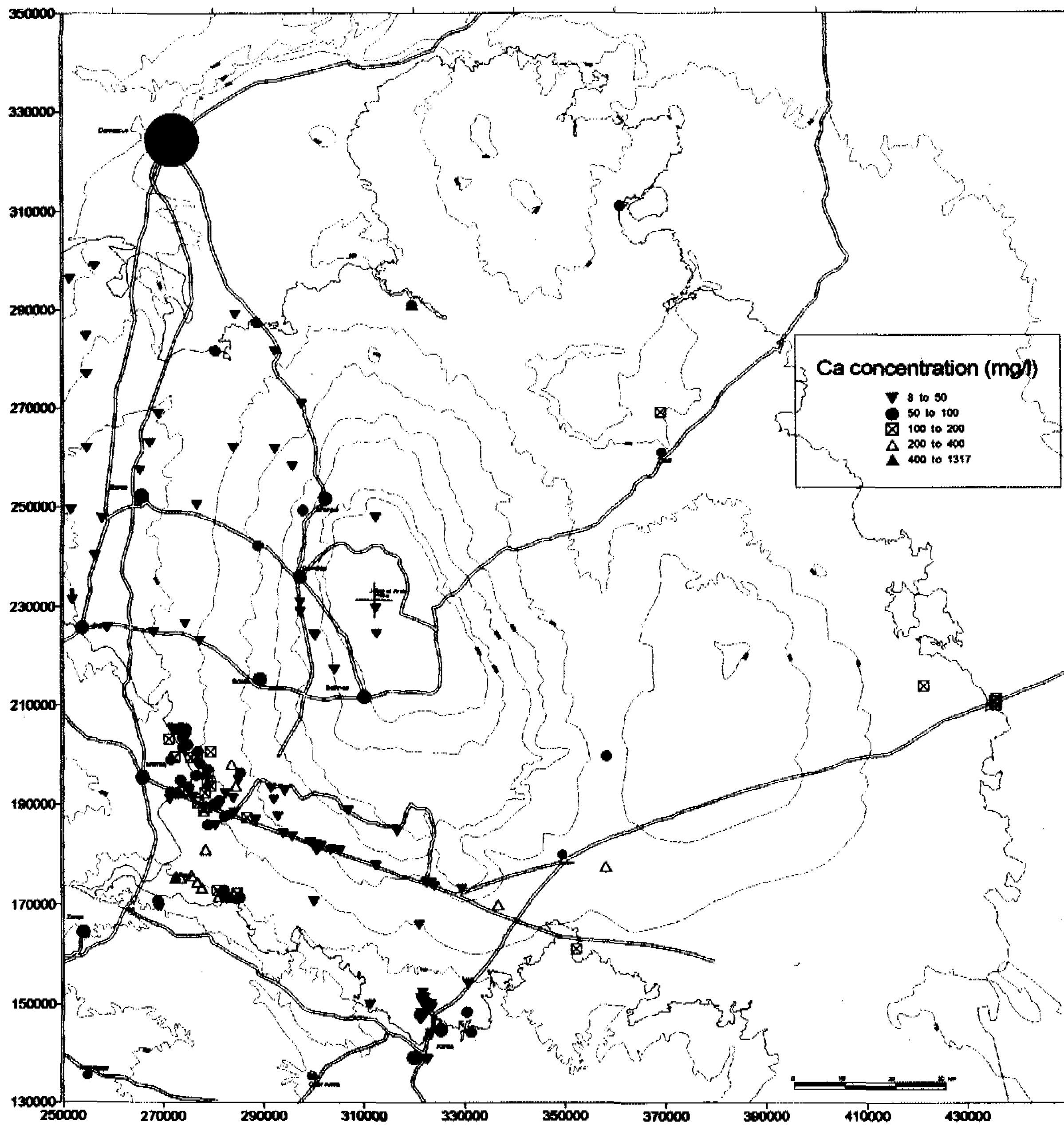


Fig. 24b: Mg concentration in groundwater samples

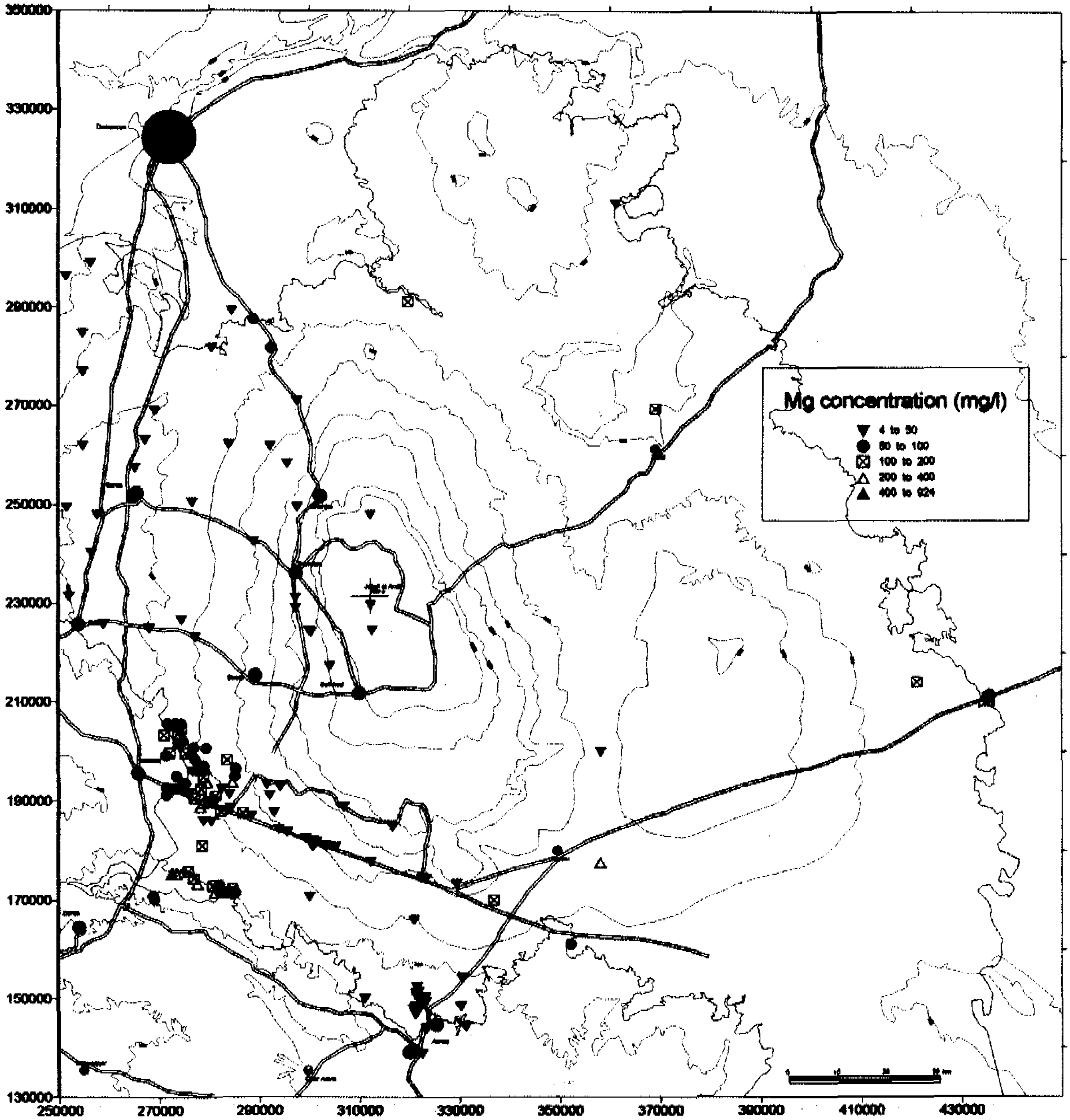


Fig. 24c: Na concentration in groundwater samples

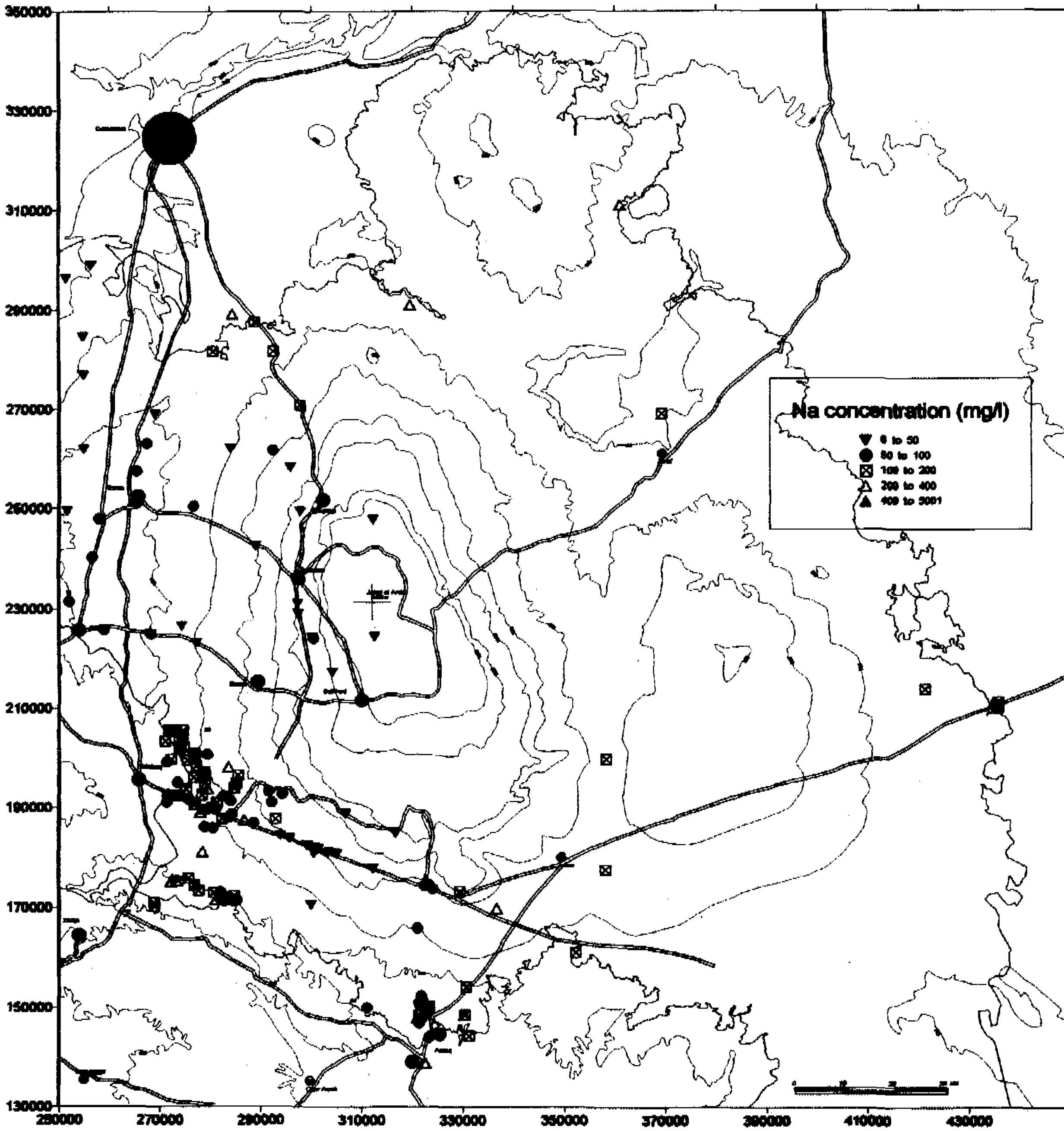


Fig. 24d: HCO3 concentration in groundwater samples

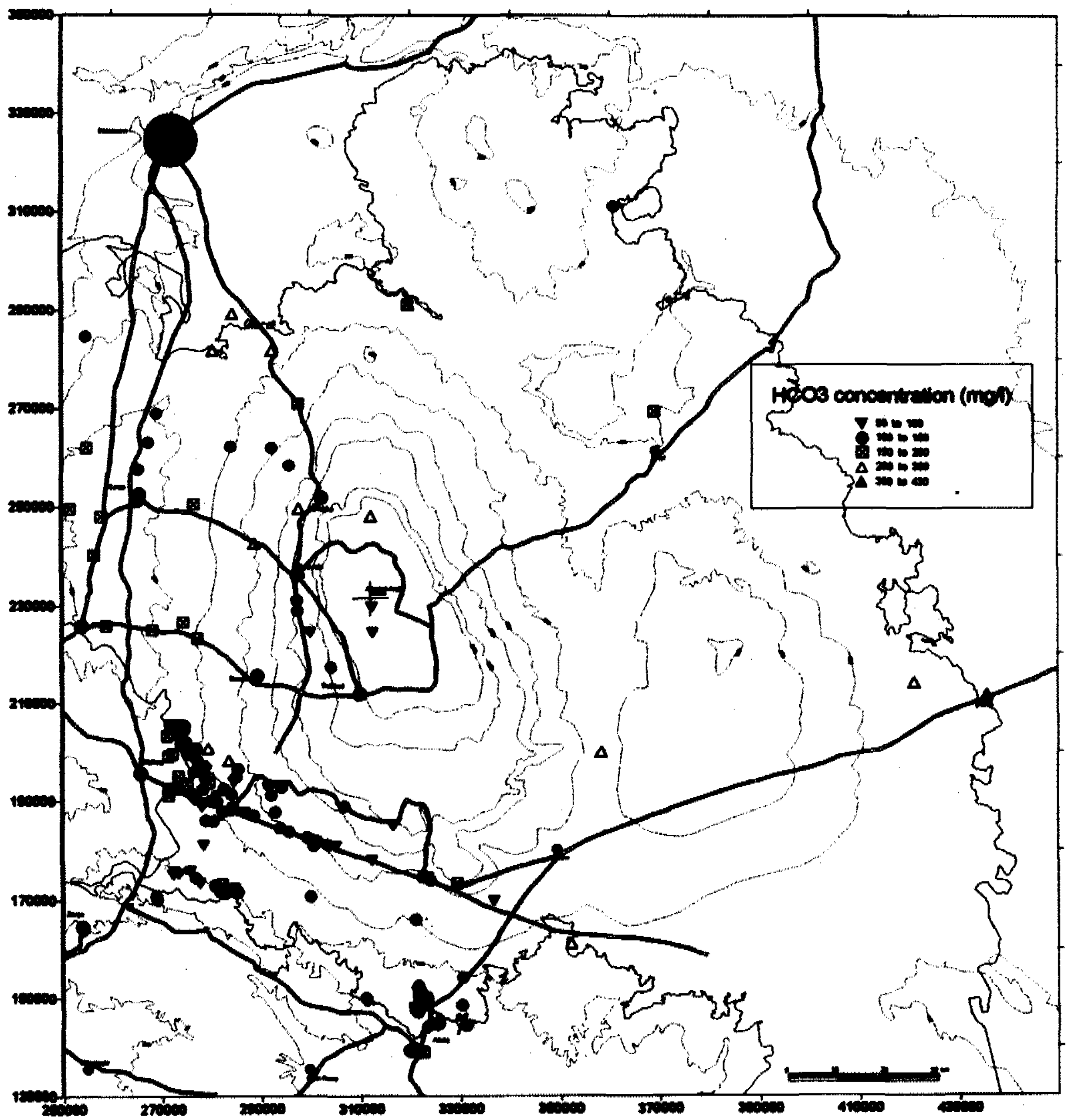


Fig. 24e: SO4 concentration in groundwater samples

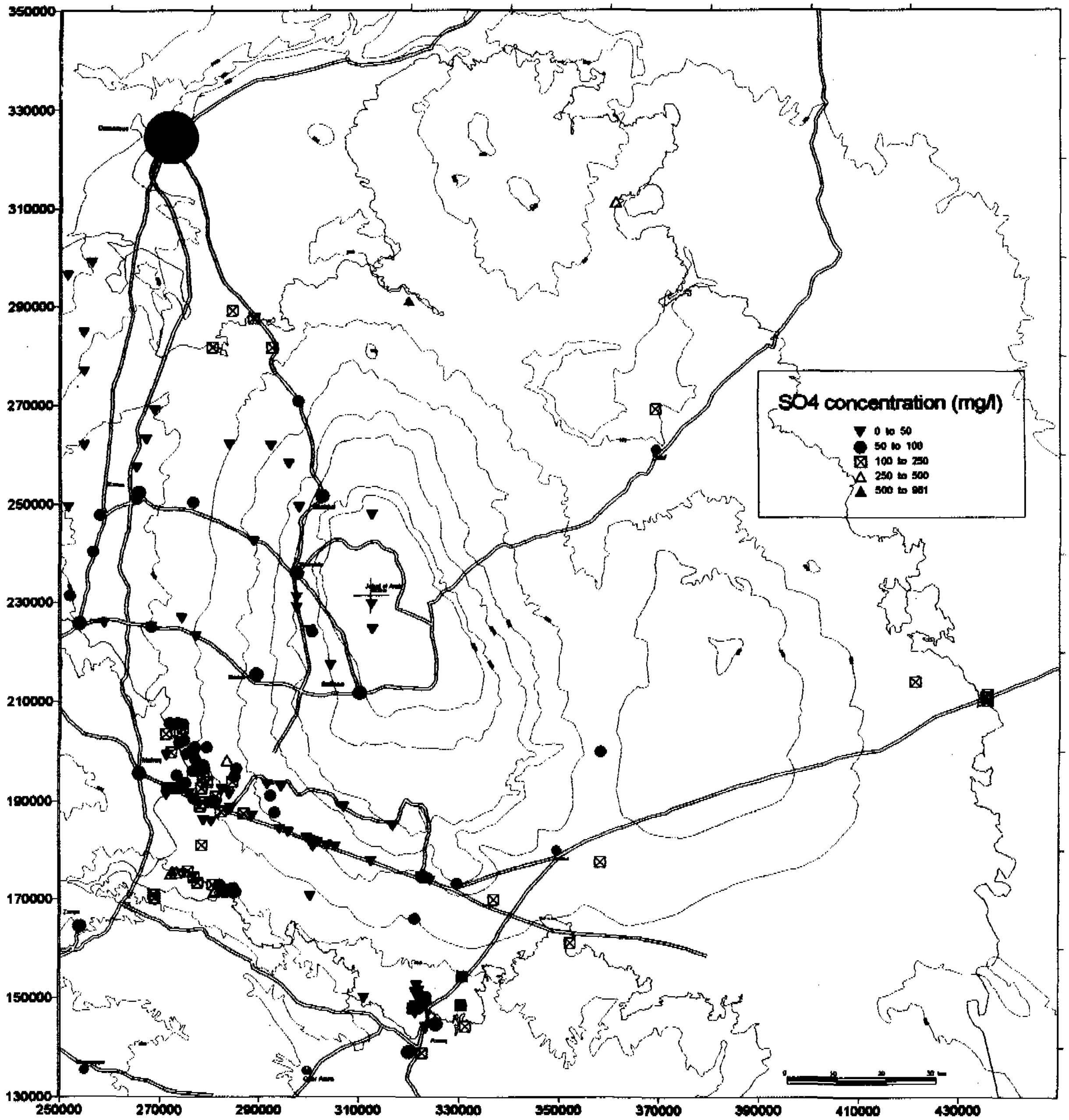


Fig. 24f: Cl concentration in groundwater samples

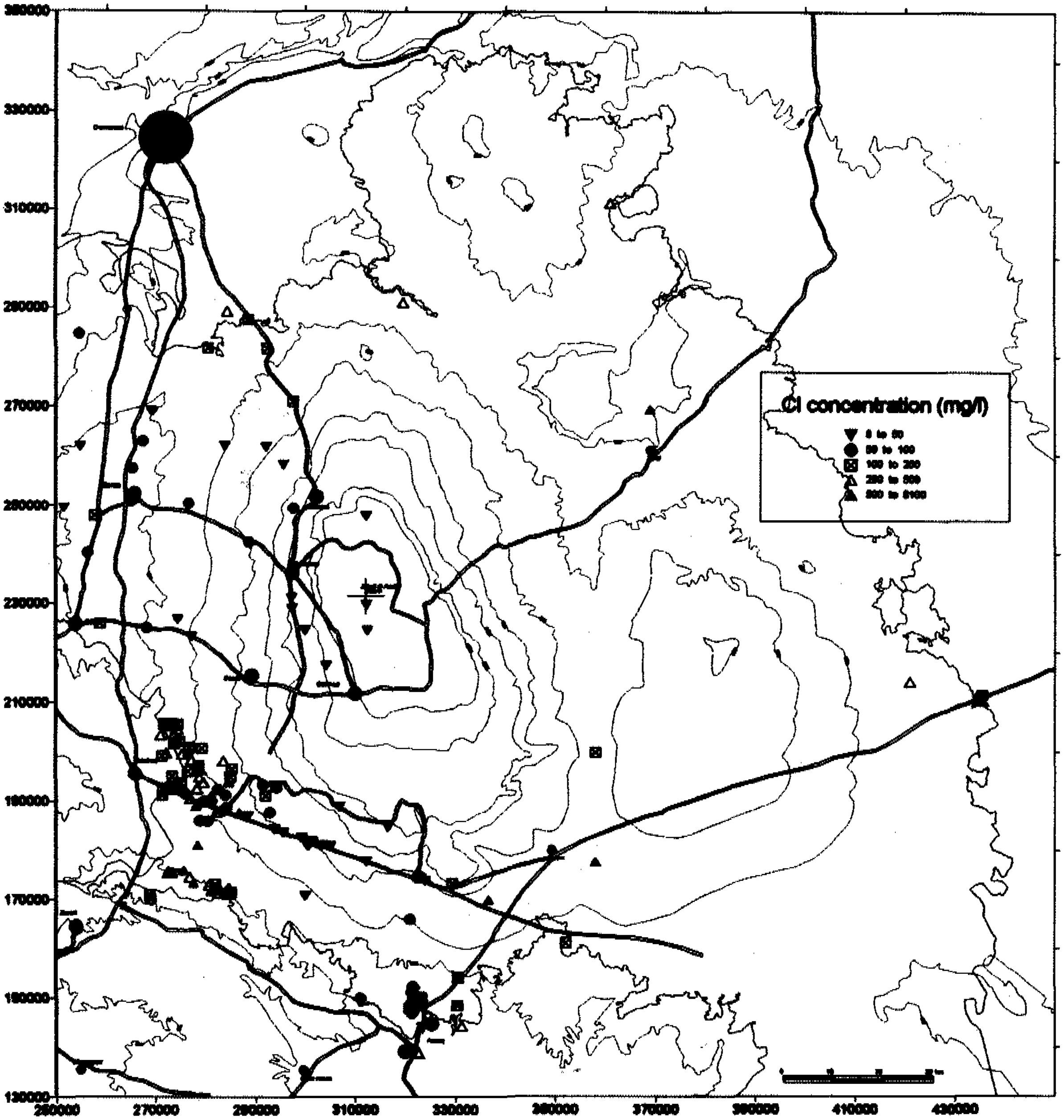


Fig. 24g: NO3 concentration in groundwater samples

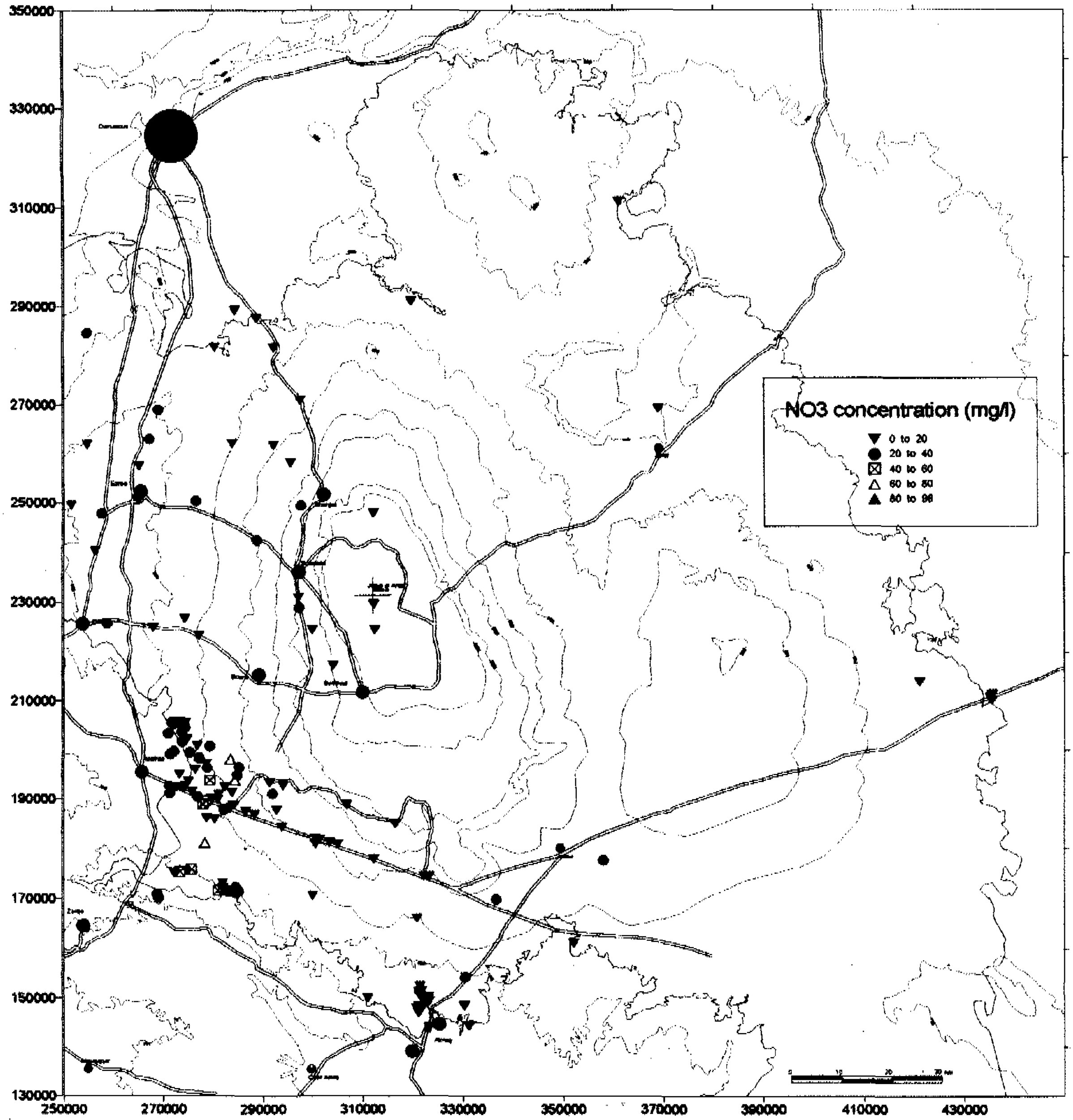
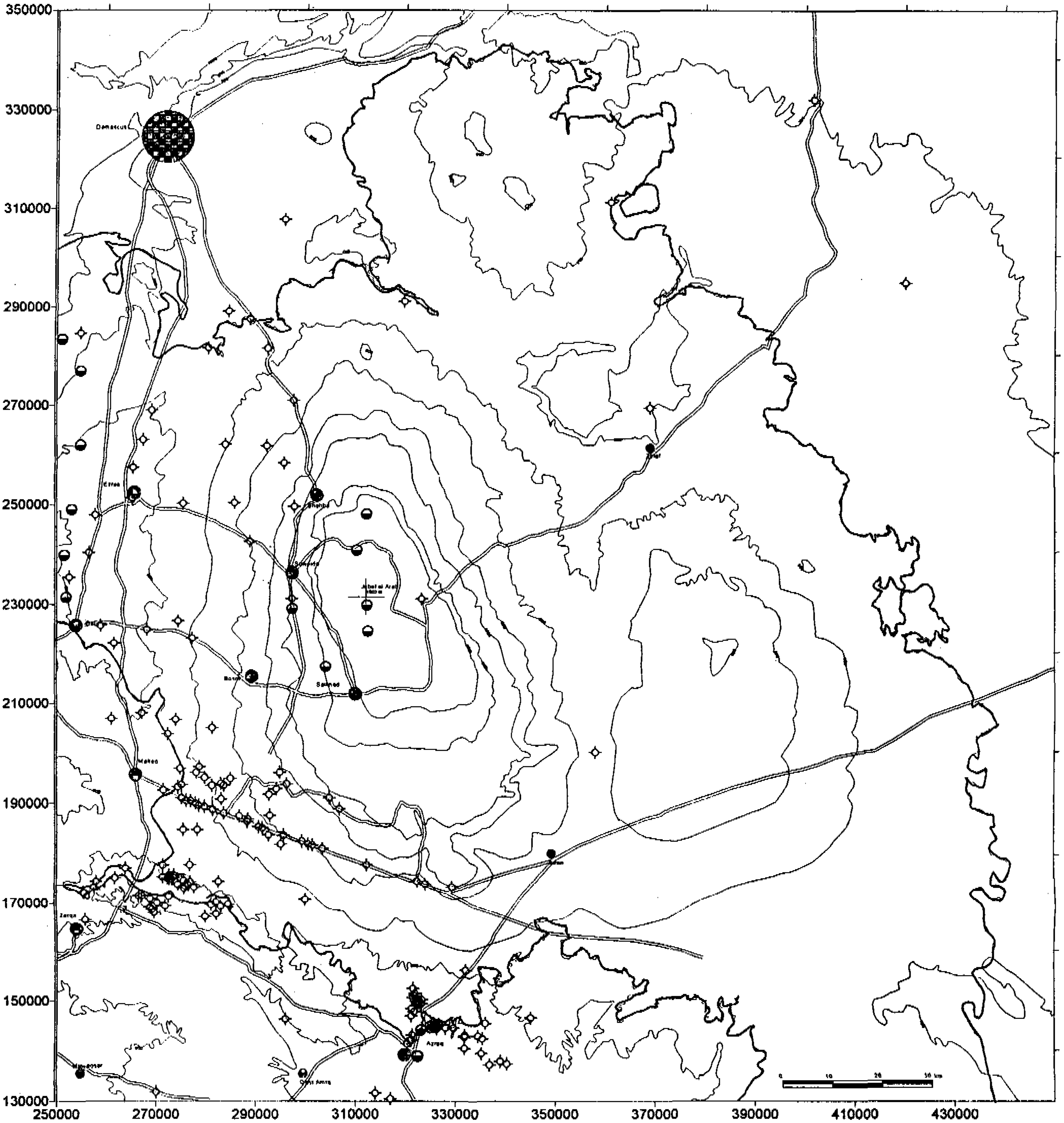


Fig. 25: Location of sampling points of isotope analyses of groundwater



well   spring   Boundary of the basalt aquifer

Springs Wadi Hreer - Wadi al Aram - Mzeirib see Fig. 12a

Fig. 26: Stable isotopes
2H / 18O plot

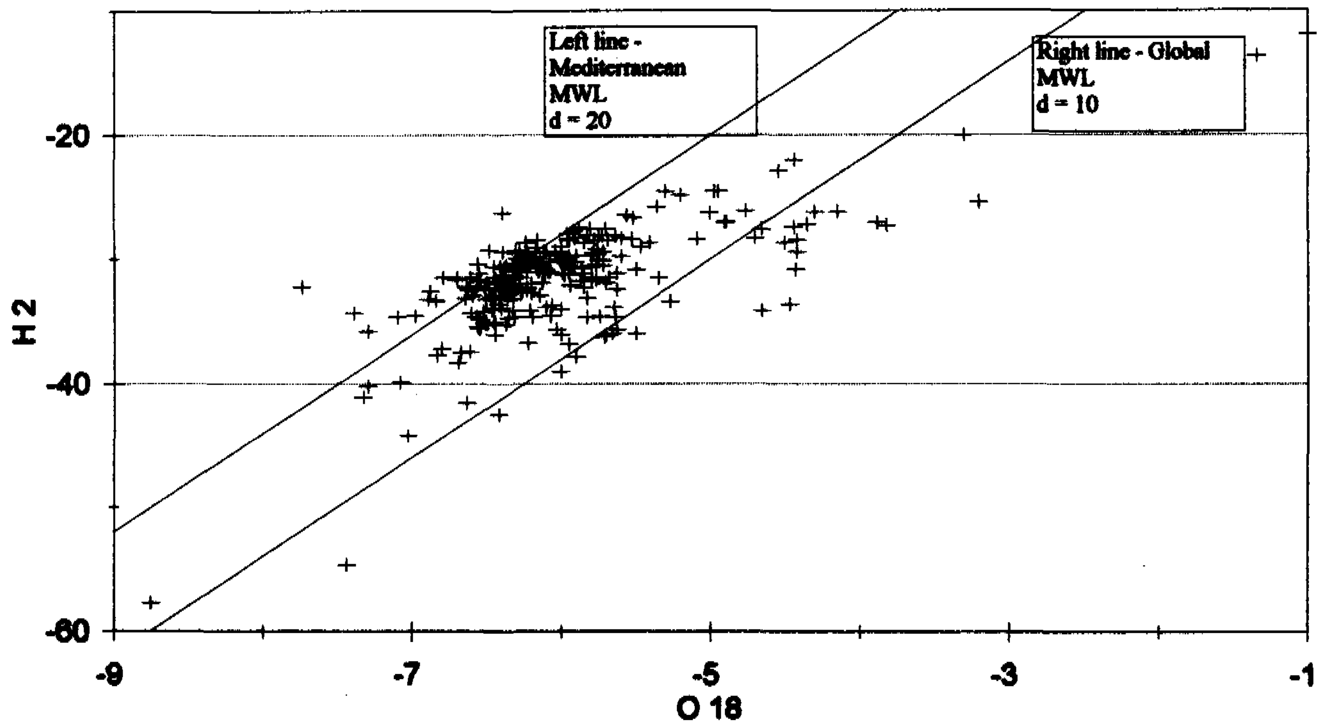


Fig. 27: Frequency distribution of deuterium excess values

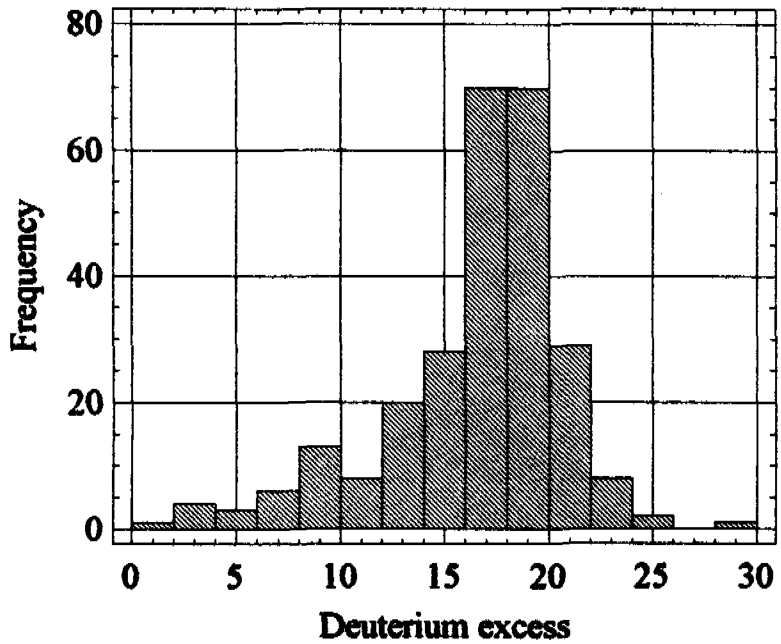


Fig. 28: O 18 values in groundwater samples

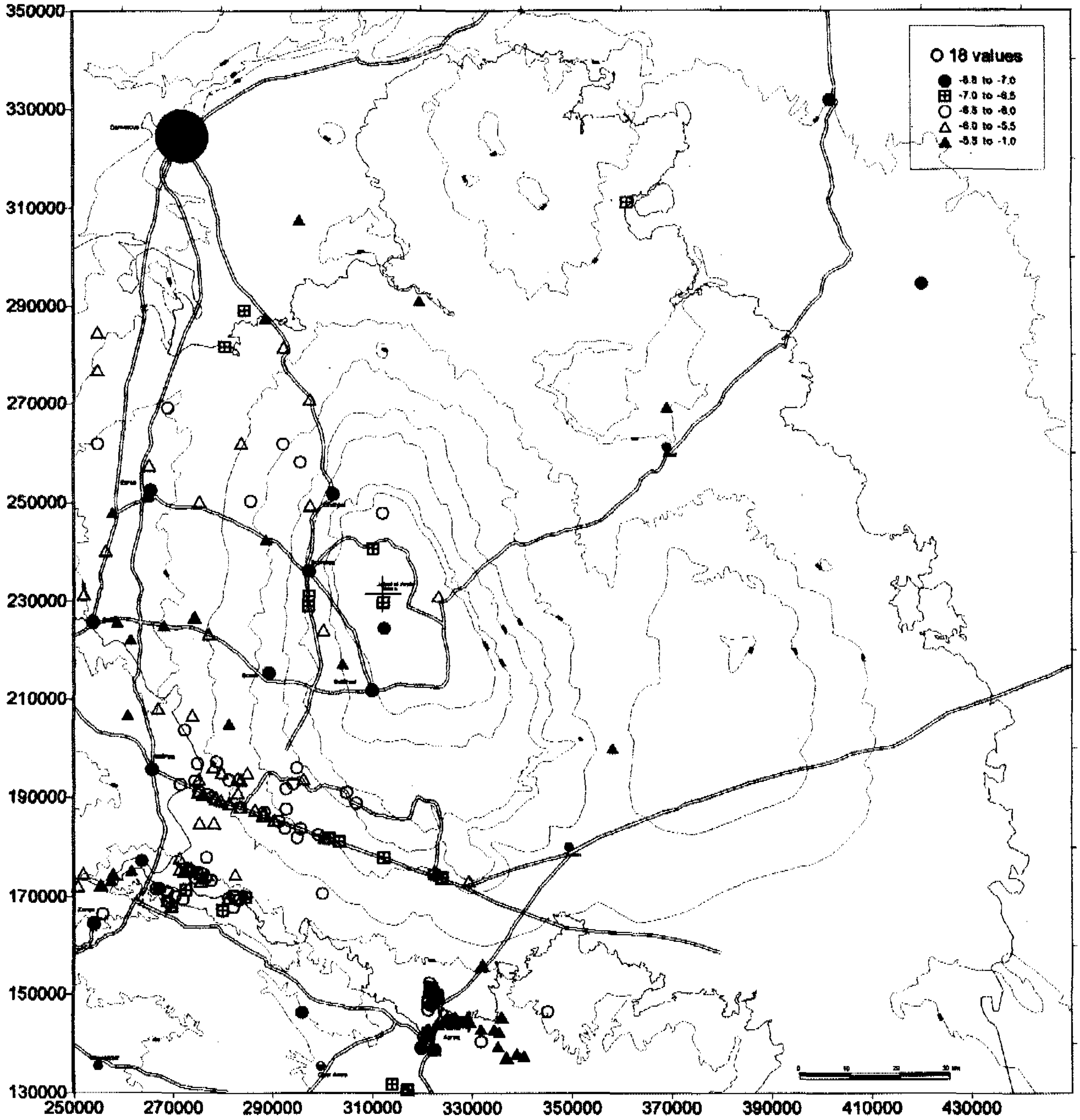


Fig. 29: Frequency distribution of 13 C values

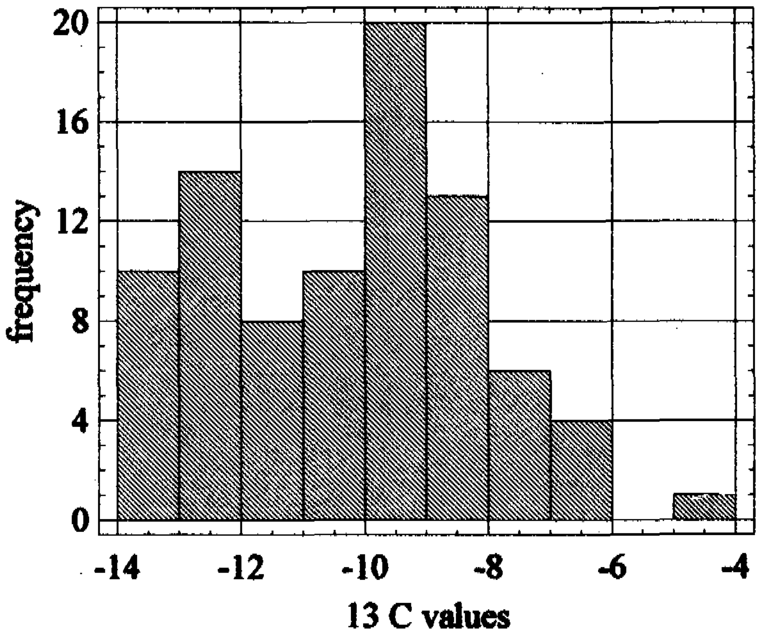
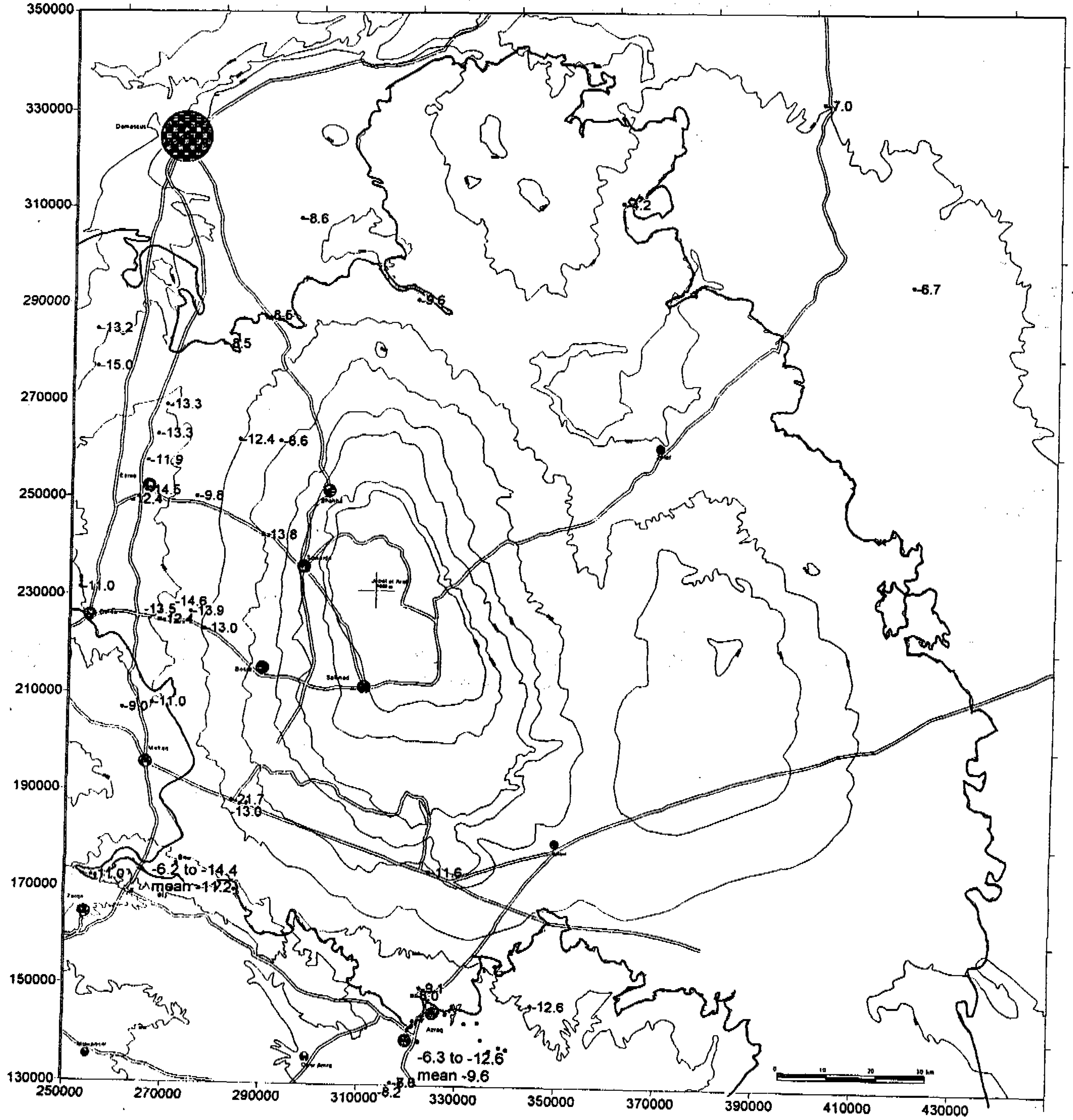


Fig. 30: 13C values of groundwater samples



— Boundary of the basalt aquifer

Fig.31: Diagram of conventional 14C water ages against adjusted age

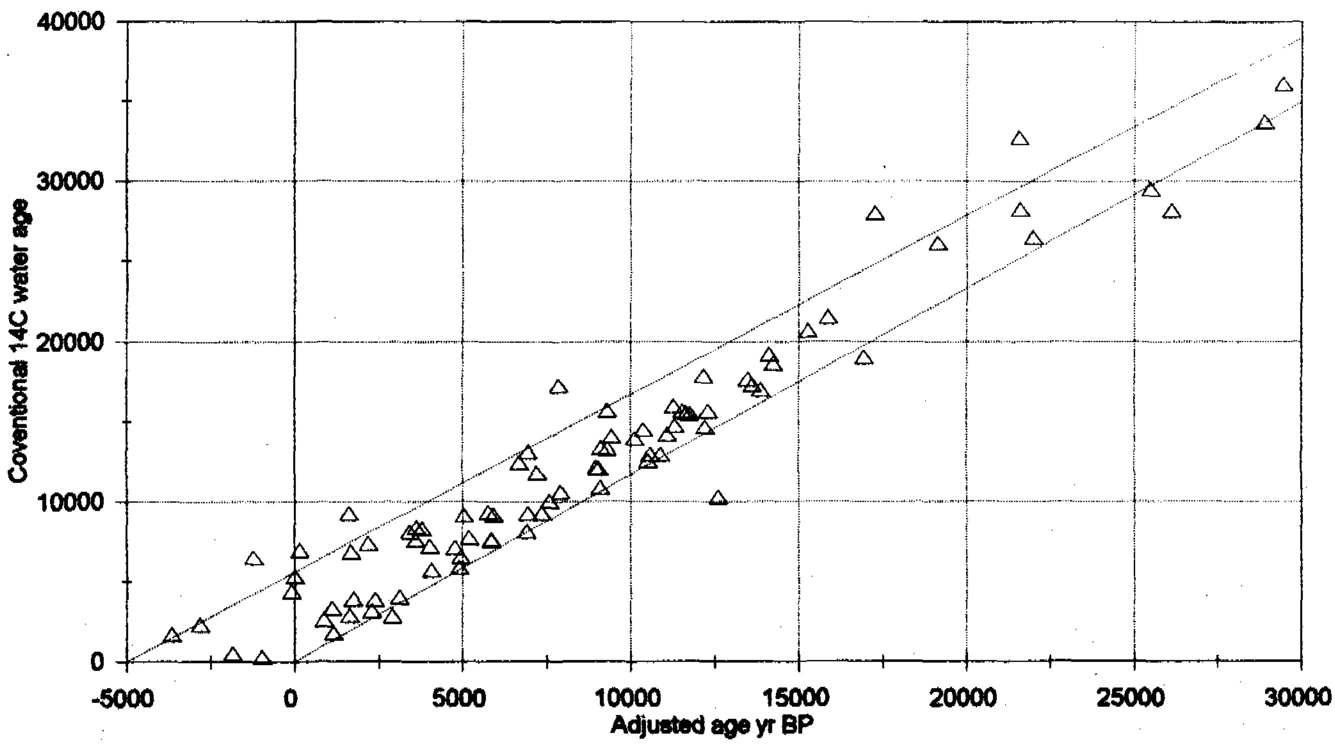
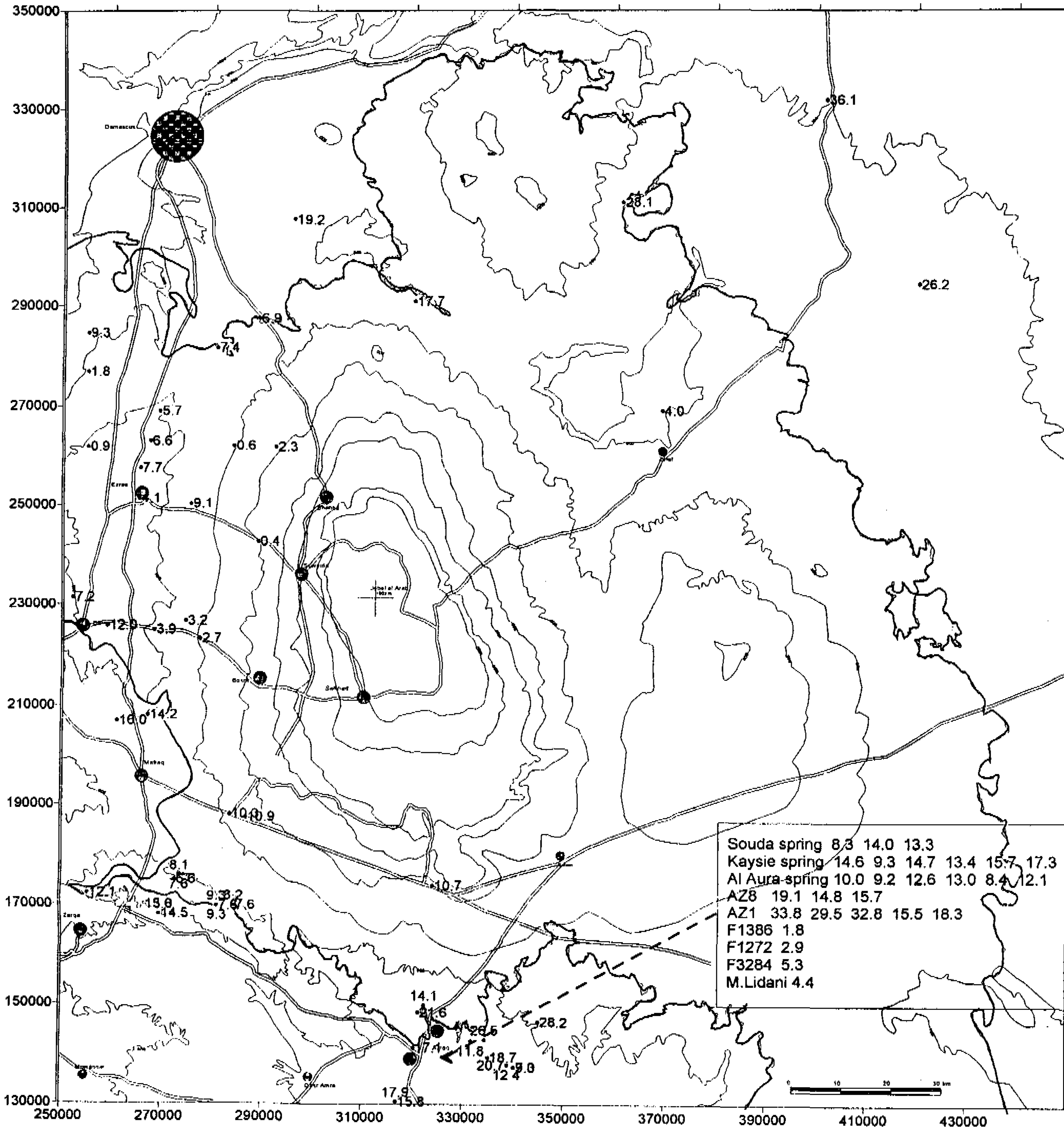


Fig.32: Conventional 14C water age



Conventional water ages in thousand years

Boundary of the basalt aquifer

Fig. 33: Deuterium excess values in groundwater samples

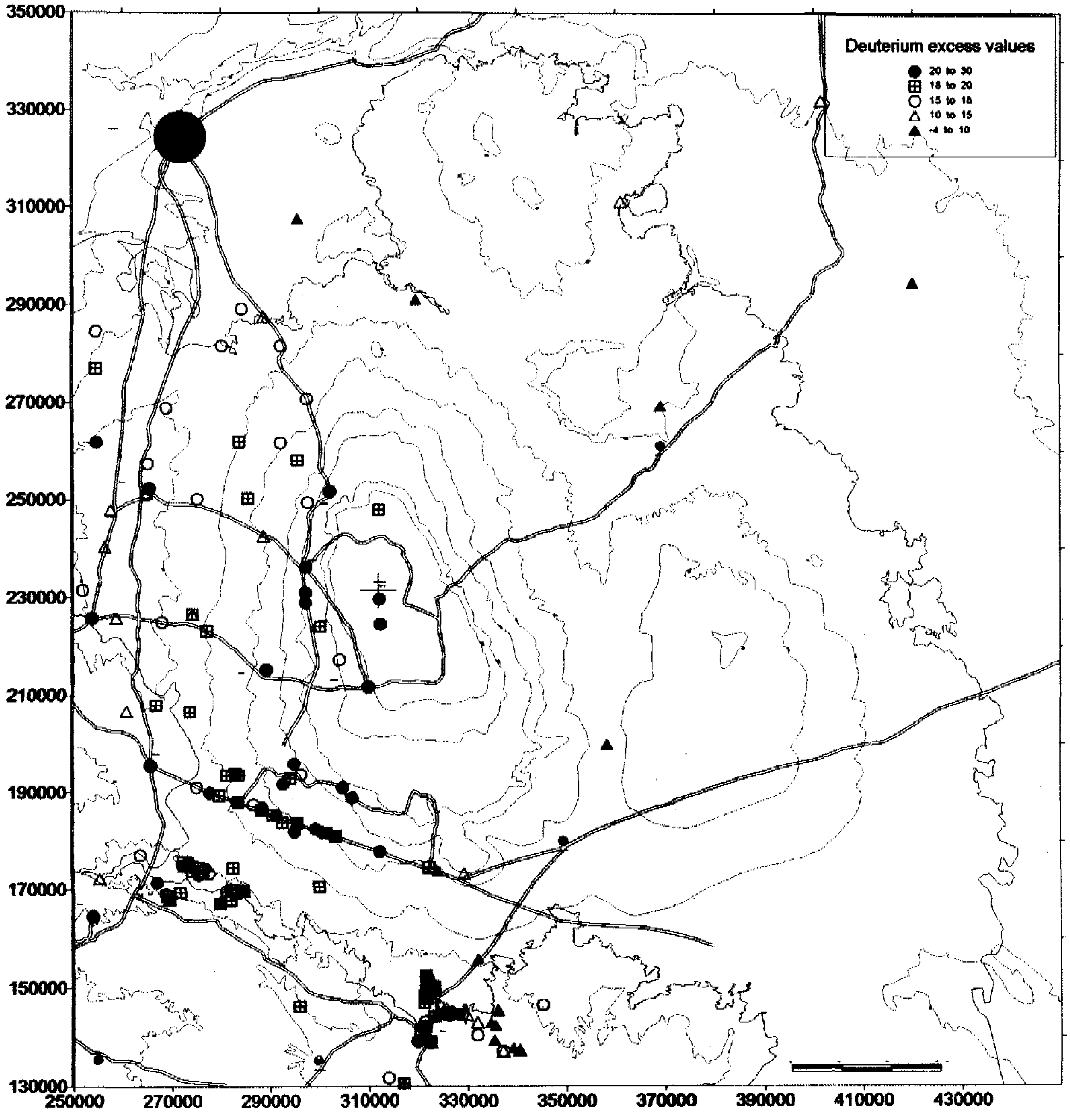


Fig. 34: Adjusted O 18 values in groundwater samples

Correction for evaporation effect

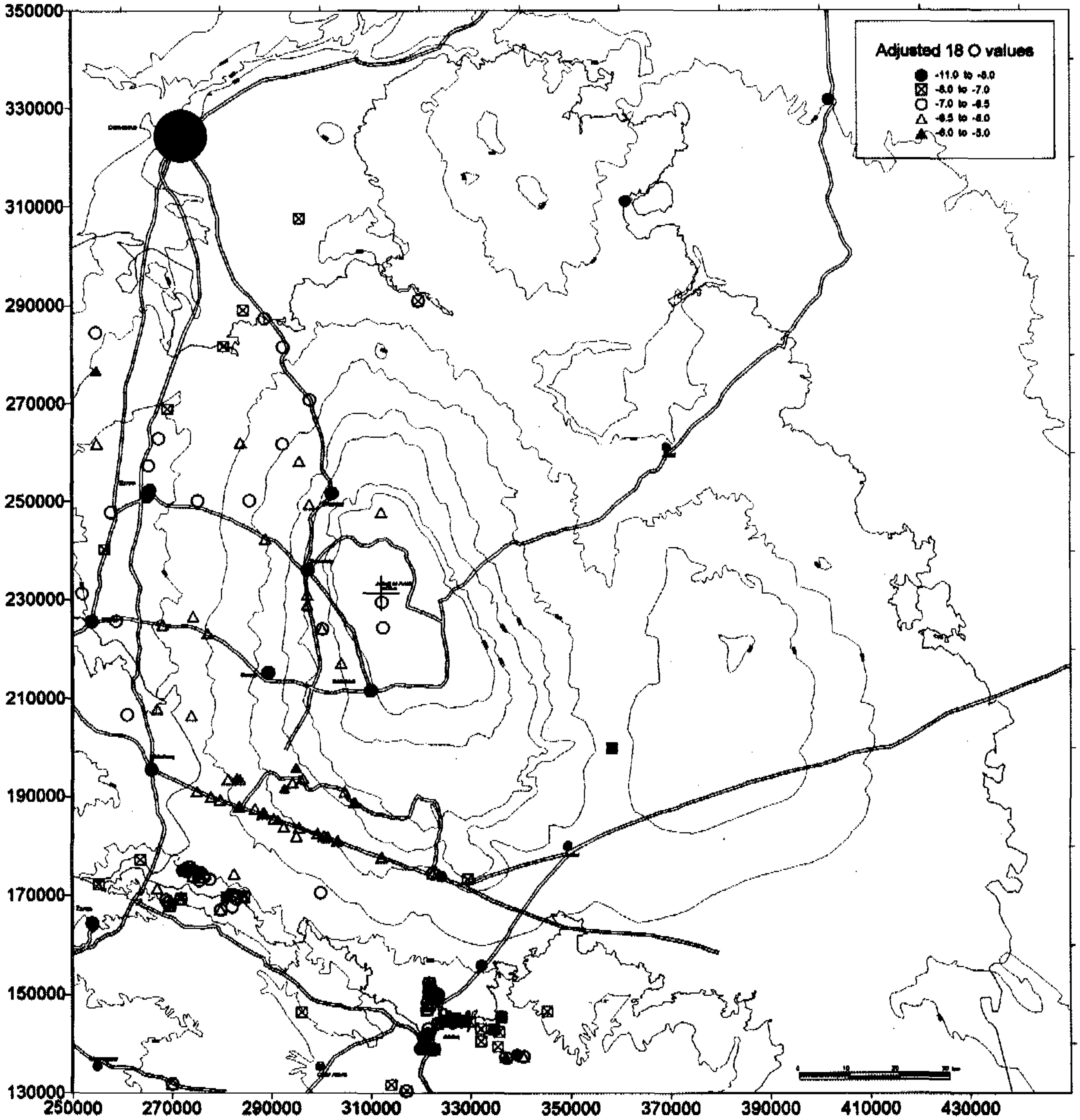


Fig.35: Deuterium excess / 18O plot

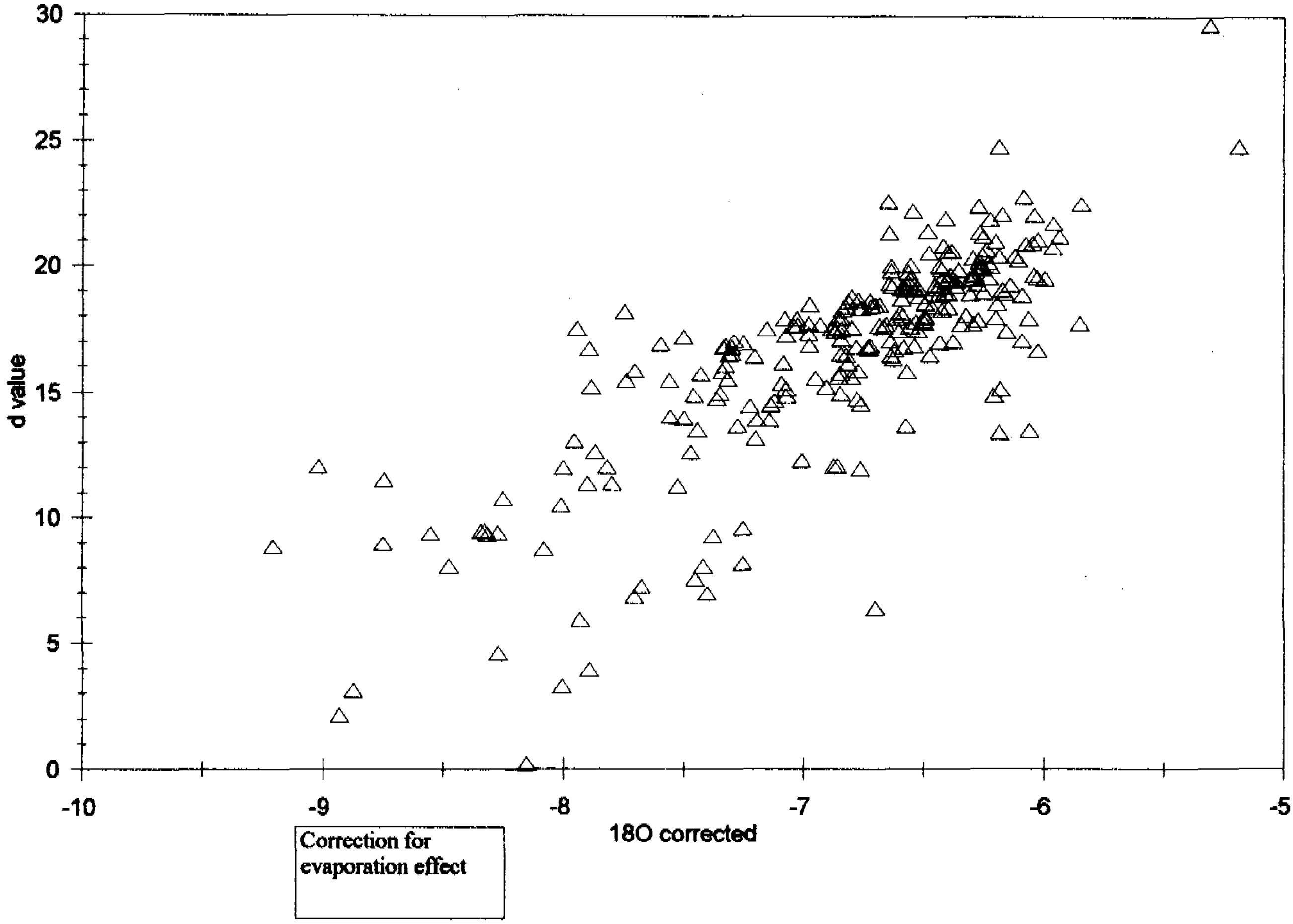


Fig.36: Diagram 13C values / 14C water ages

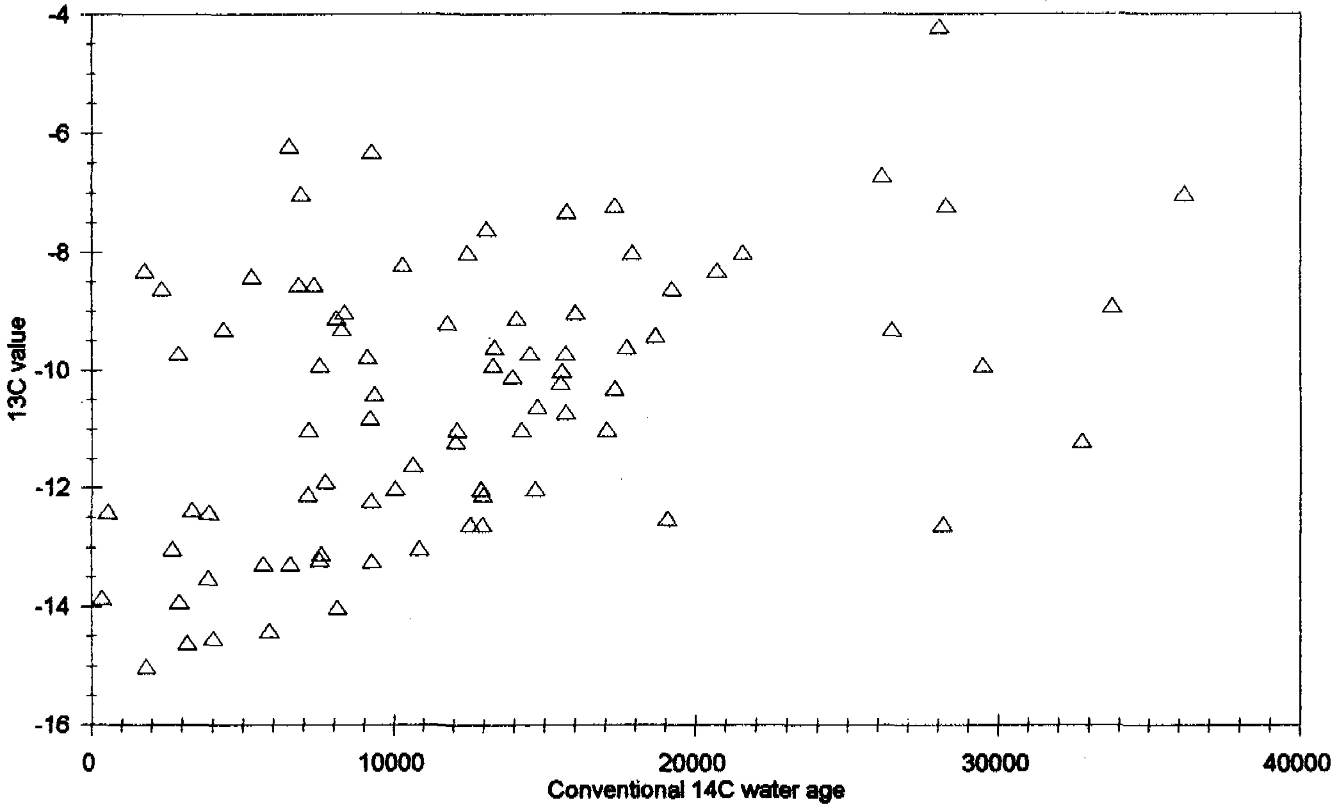
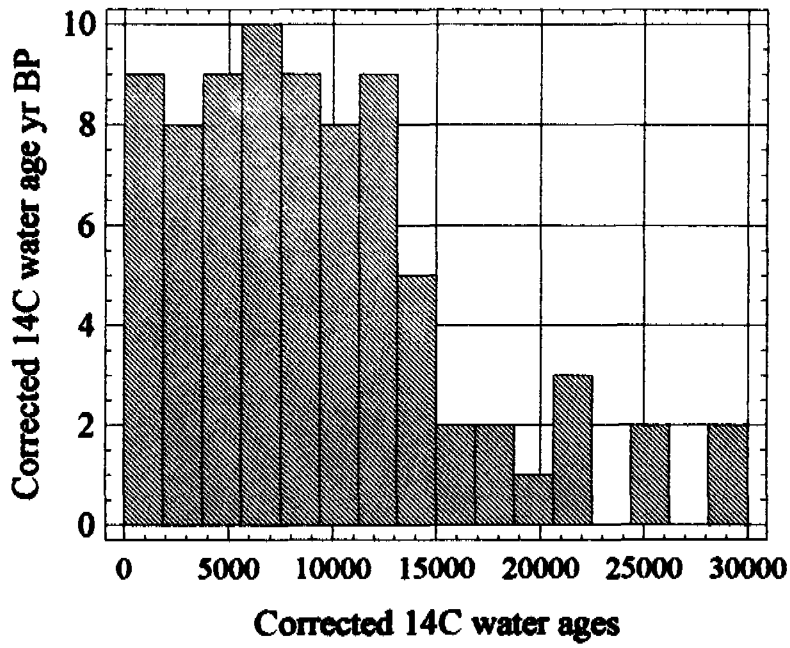
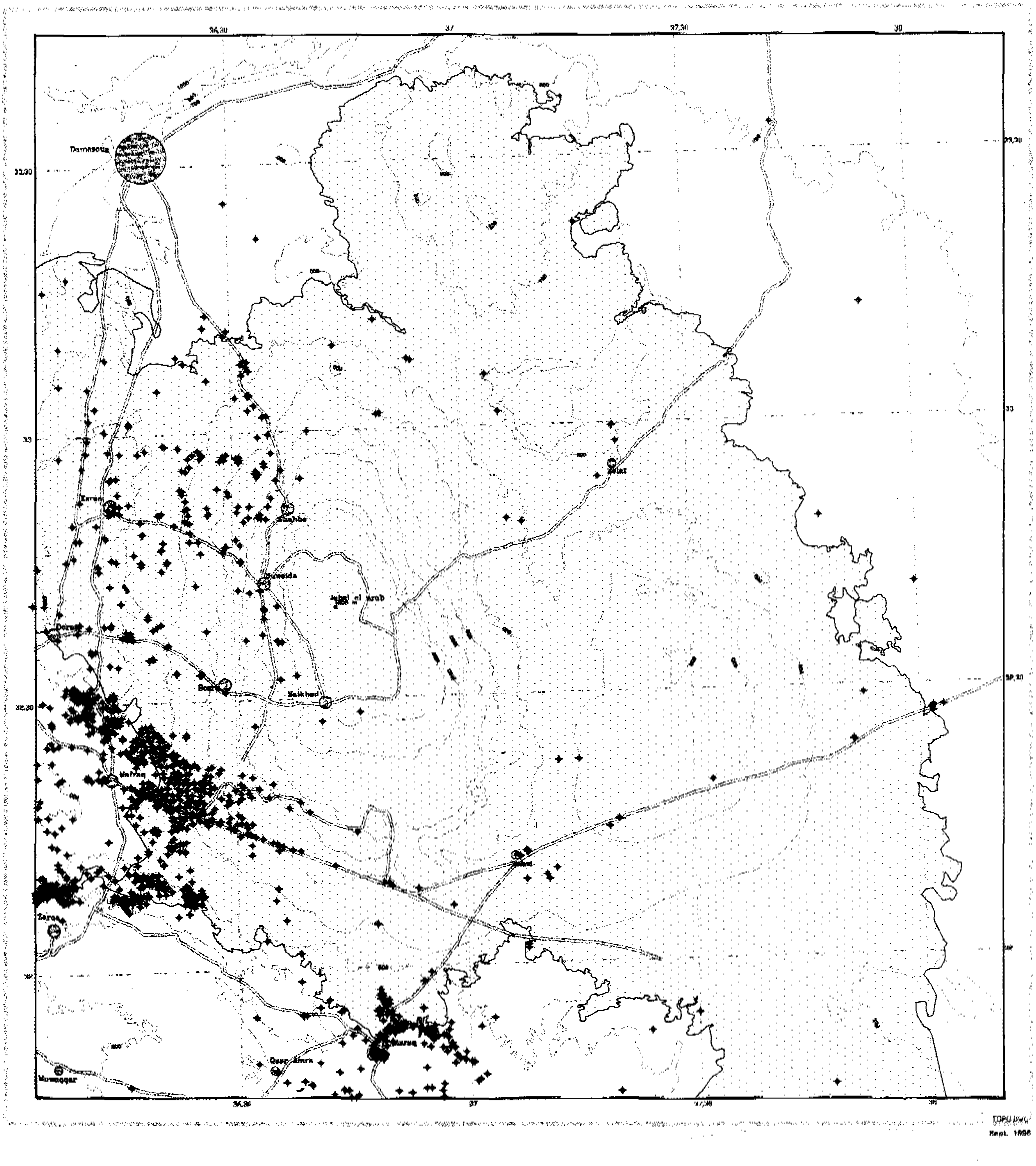


Fig. 37: Frequency distribution of 14C water ages



BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 1: Topographic Map of the Basalt Complex and its Surroundings



basalt outcrop

topographic contour

800

location of boreholes (n = 1276)

main road

ESCWA	United Nations Economic and Social Commission for Western Asia
WAJ	Water Authority of Jordan
Department for Irrigation and Water Resources, Syrian A.R.	
Advisory Services:	
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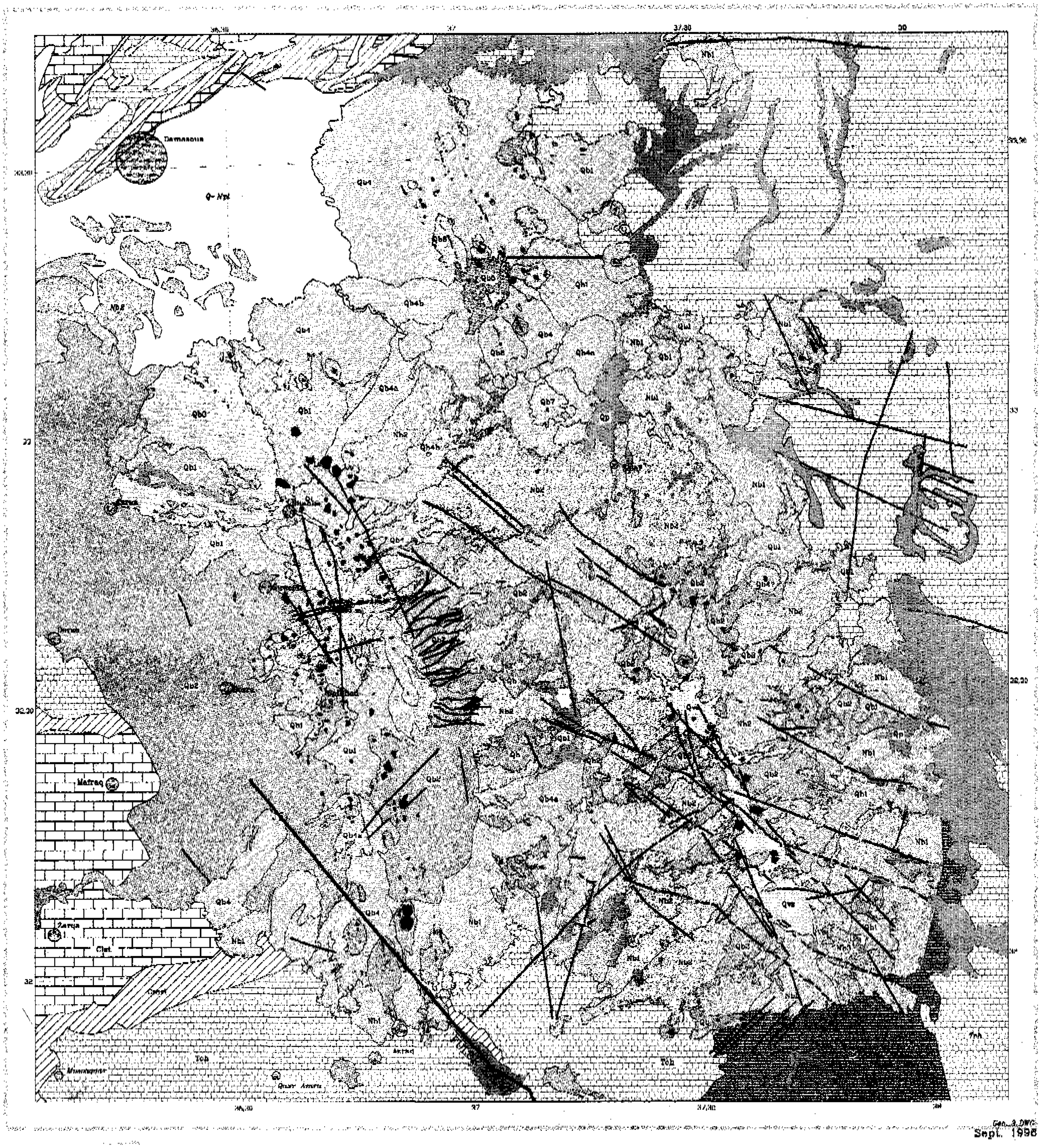
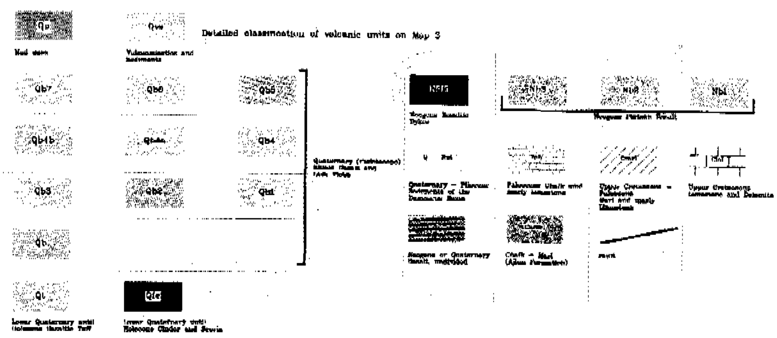
Topographic Map of the Basalt Complex and its Surroundings

Map 1	Scale: 1:500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 2a: Main Lithostratigraphic Units of the Basalt Complex and its Surroundings





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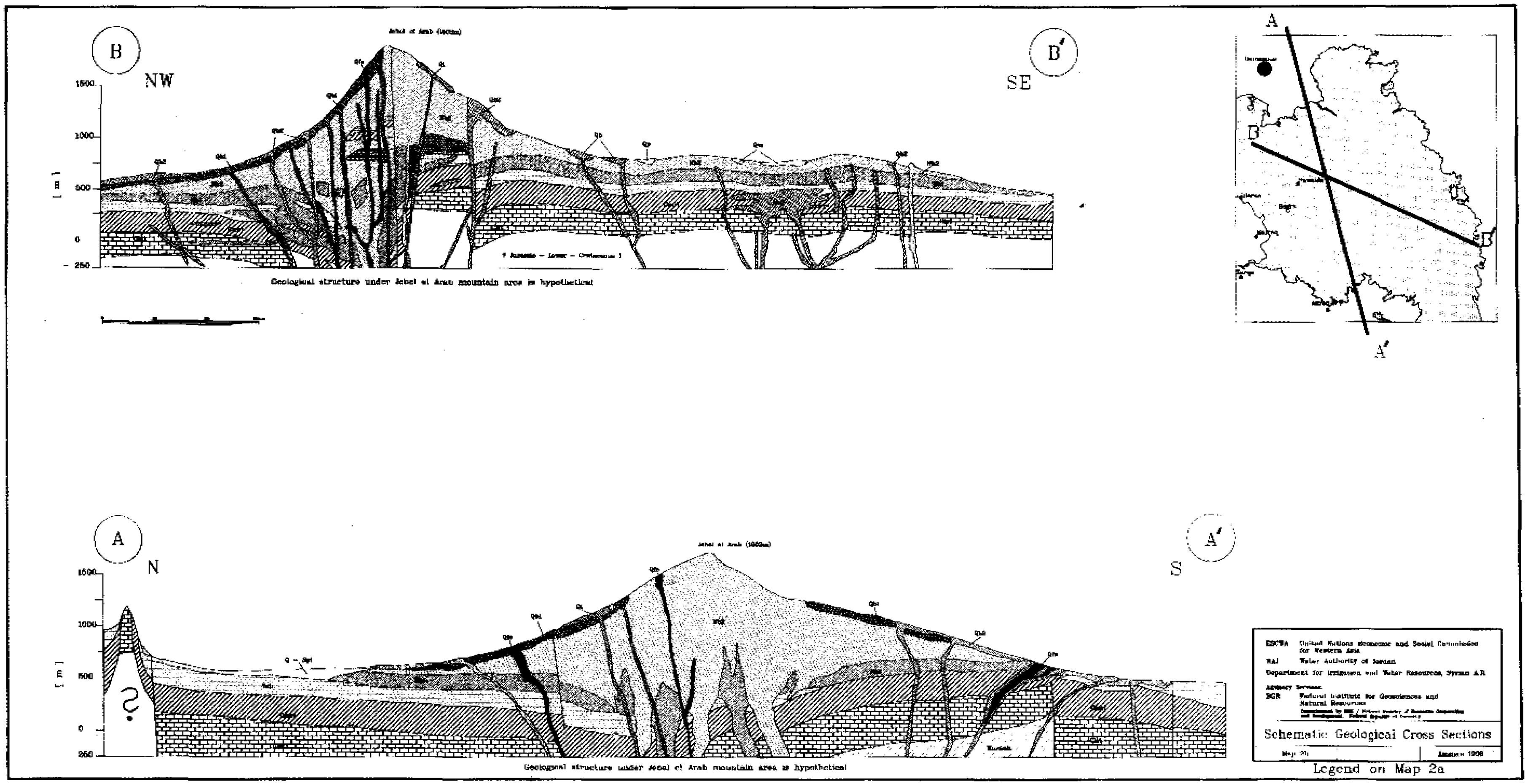
Main Lithostratigaphic Units of the Basalt Complex and its Surroundings

Map 2a	Scale: 1:500.000	Amman 1996

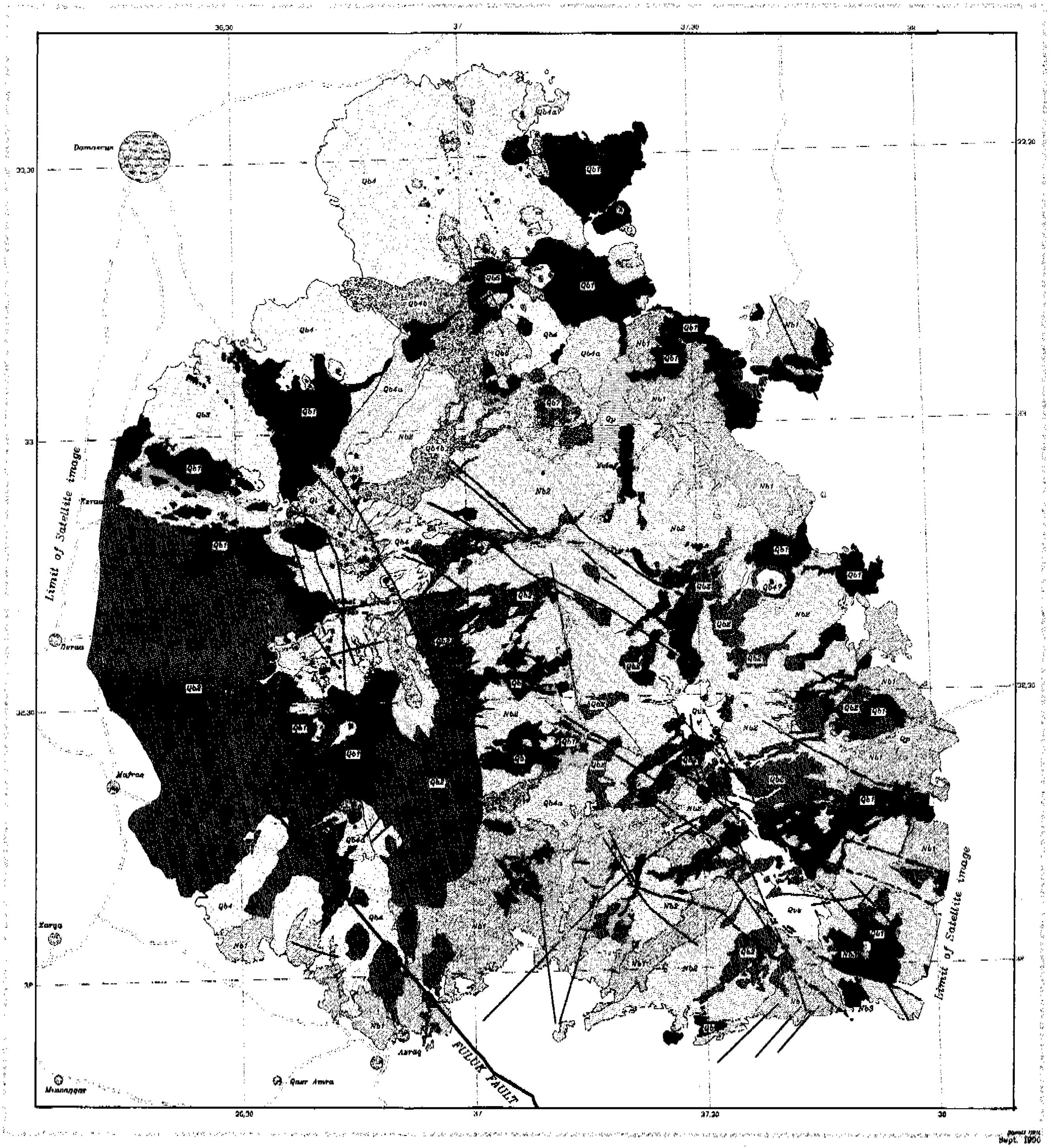
BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

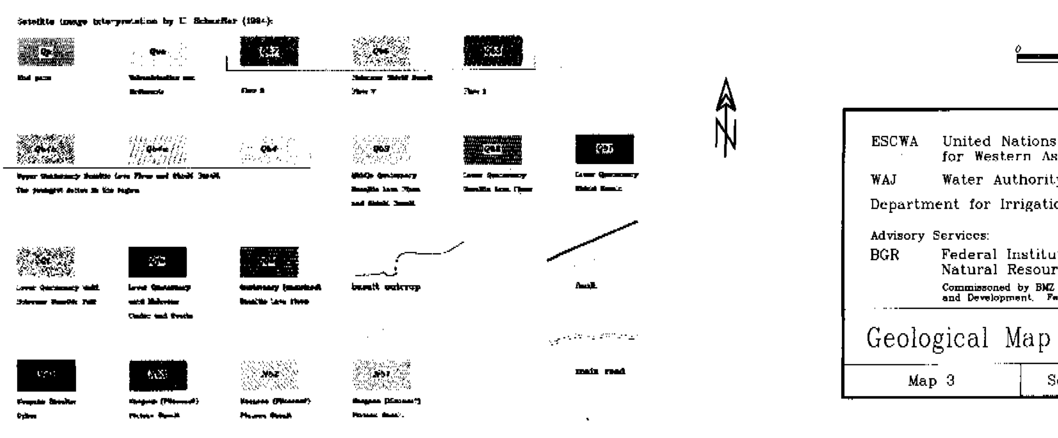
Map 2b: Schematic Geological Cross Sections



BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 3: Geological Map of the Basalt Complex





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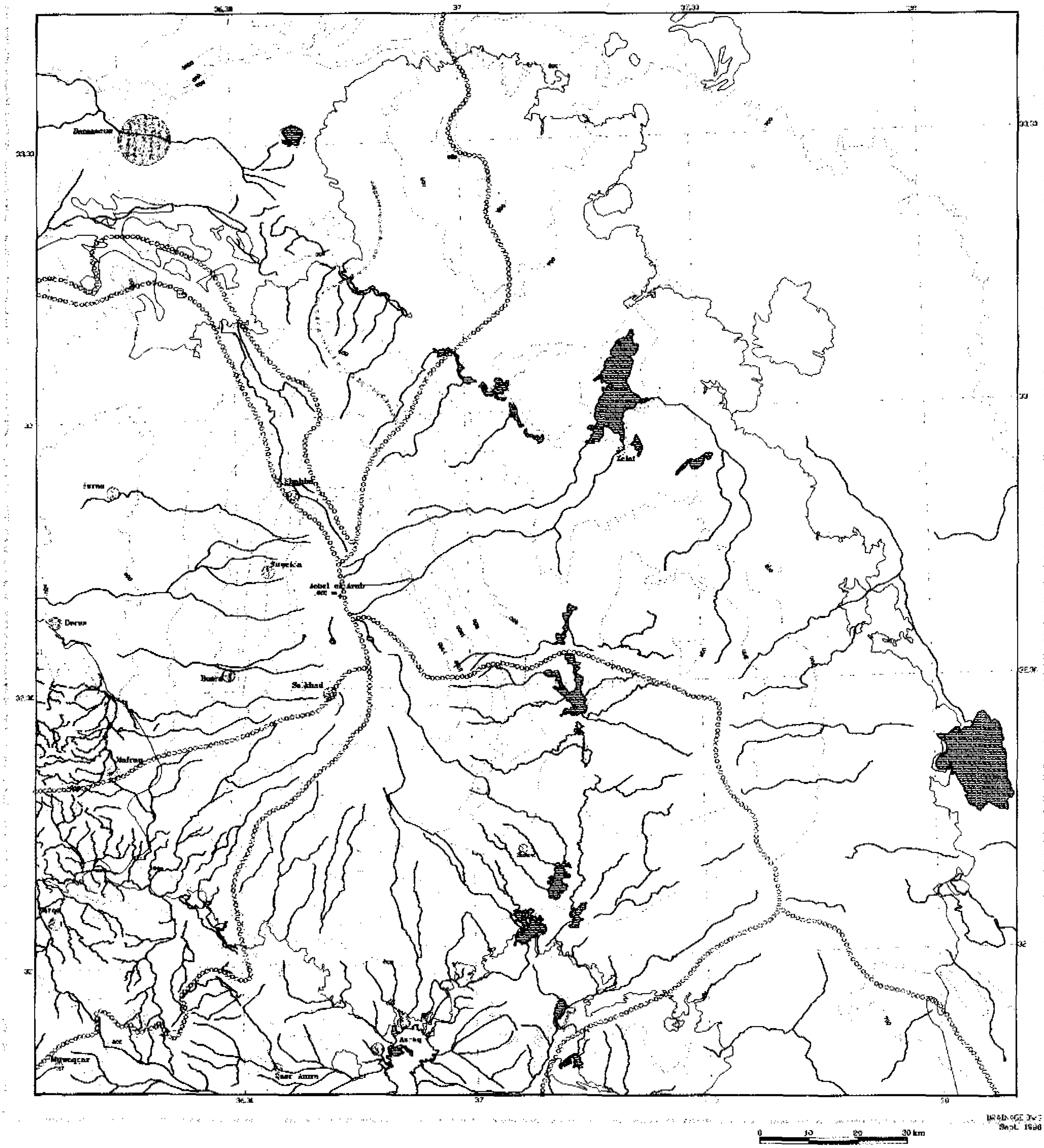
Geological Map of the Basalt Complex

Map 3	Scale: 1:500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 4: Drainage System



0 10 20 30 km

Surface water divide

Groundwater divide

Mud pan

Basalt outcrop

Topographic contour

Wadi

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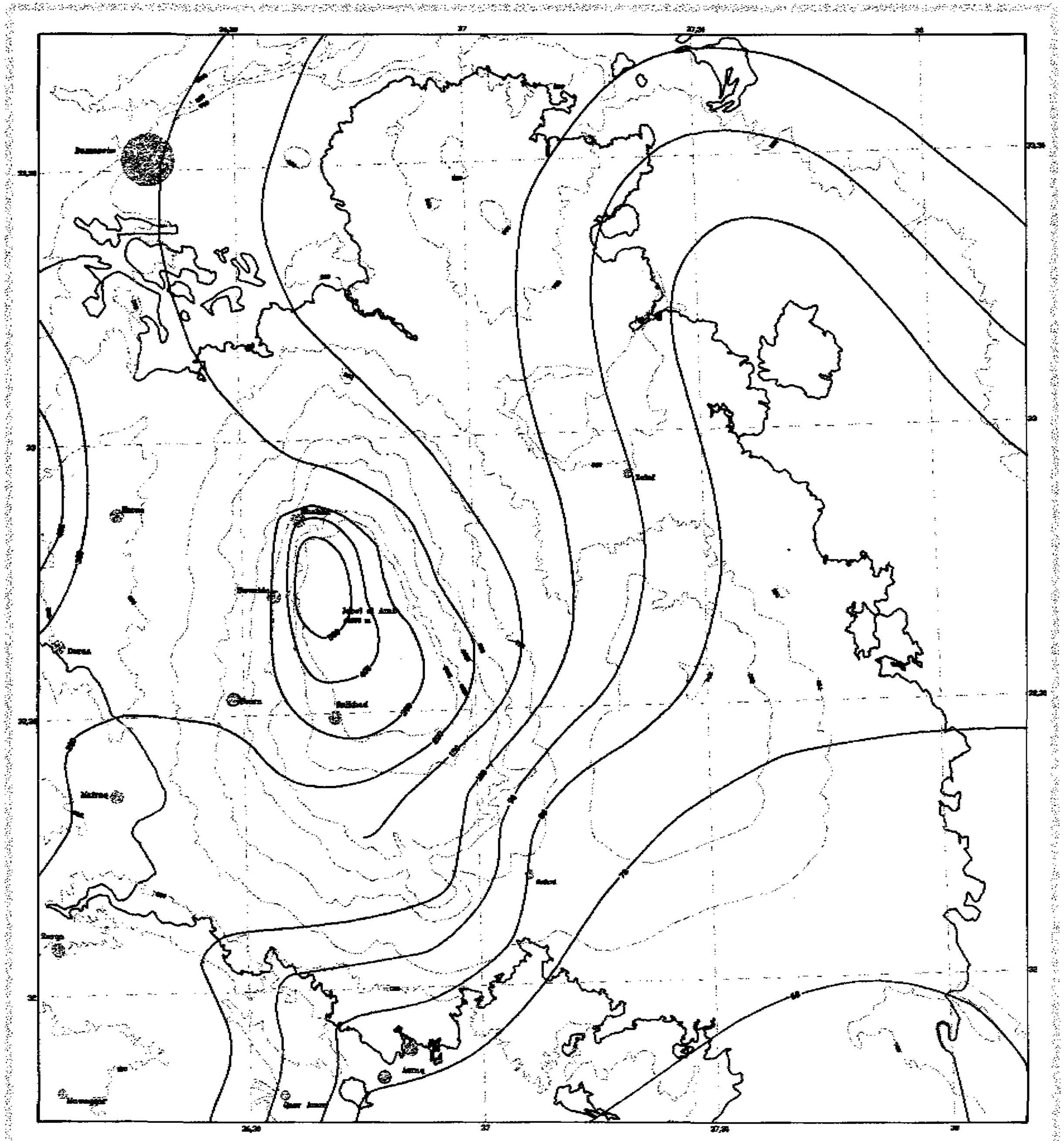
Drainage System

Map 4	Scale: 1:500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Distributation of Mean Annual Precipitation [mm]

after information by WAJ, ACSAD (1983) and KATTAN (1996)



topographic contour

basalt outcrop

isohyet of mean annual precipitation [mm]

0 10 20 30 km

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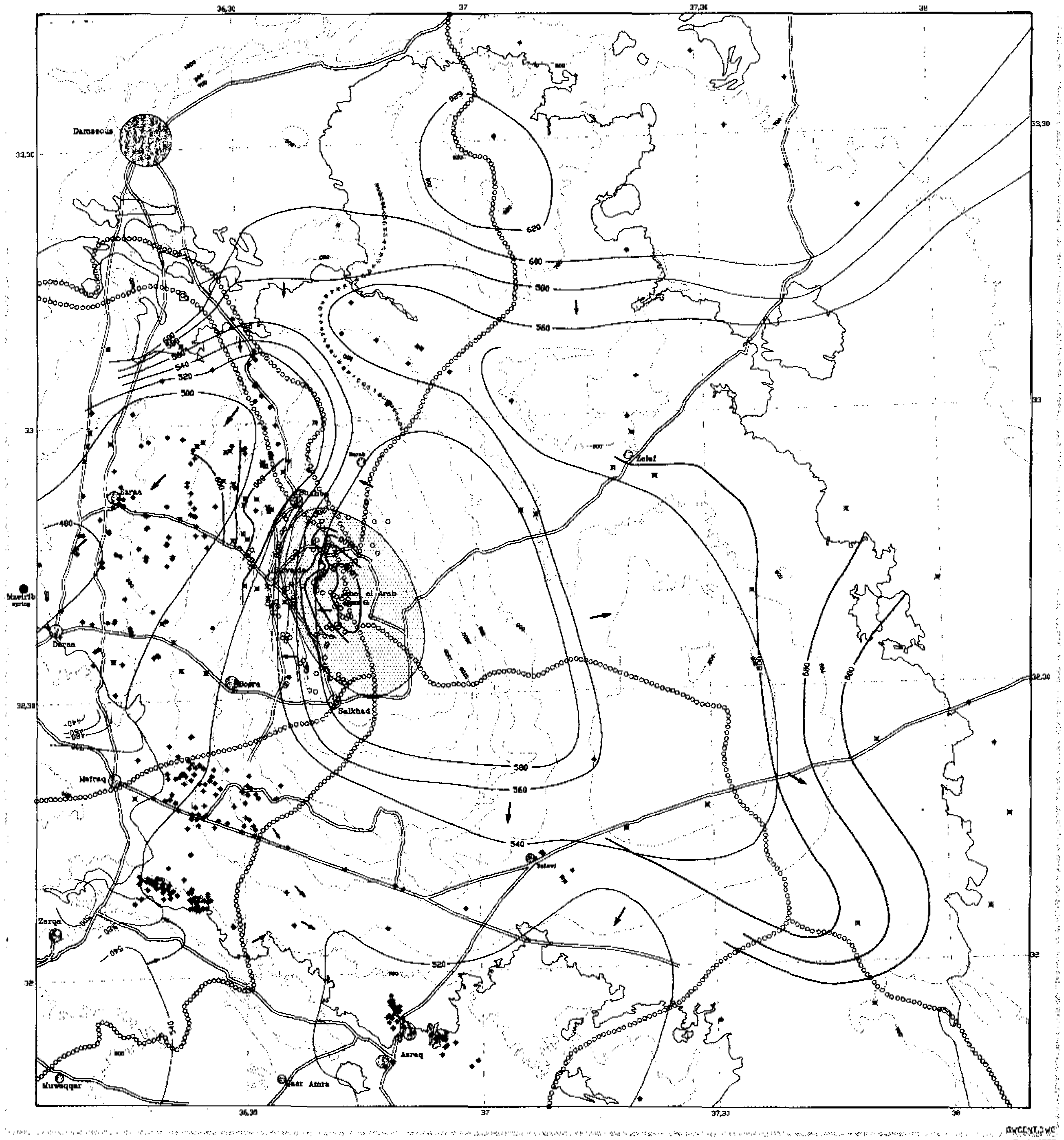
Mean Annual Precipitation

Map 5	Scale: 1 : 1000000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 6: Groundwater Contours



0 10 20 30 km

water table contour line (m above sea level)

- 500 — main basalt aquifer
- 700 — shallow or intermediate basalt aquifer (discontinuous)
- 540 — sedimentary aquifer (Upper Cretaceous – Tertiary)
- direction of groundwater flow (main aquifer)
- groundwater divide deviating from surface water divide
- surface water divide
- borehole, water level in main aquifer
- borehole, water level in shallow or intermediate aquifer
- spring ● Mzeirib spring
- basalt outcrop
- 600 topographic contour
- main basalt feeder zone (probably no deep groundwater)

N

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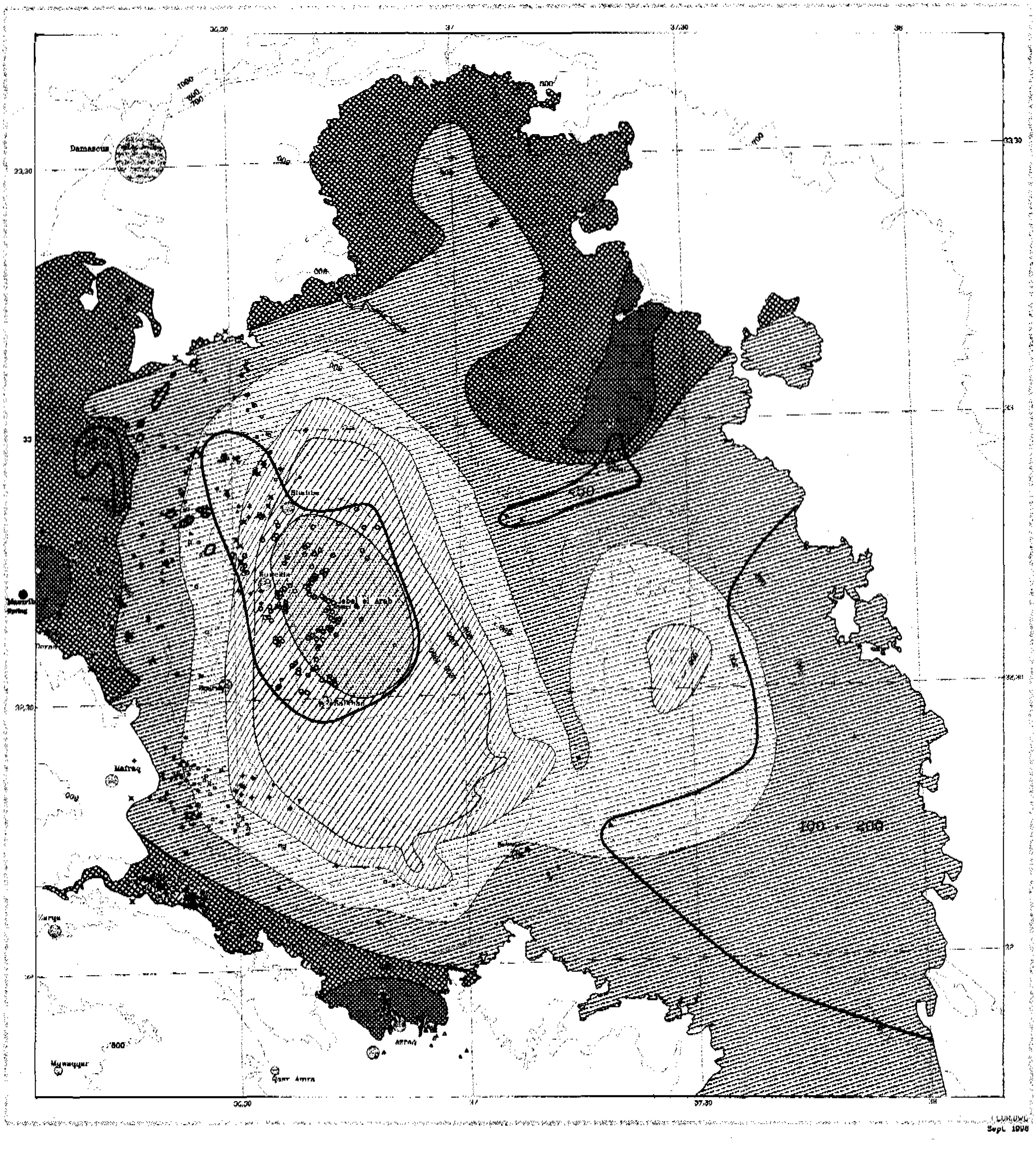
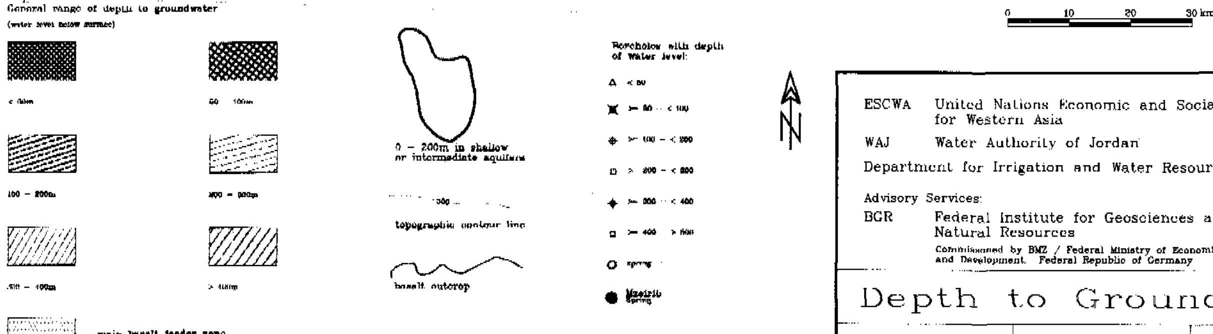
Groundwater Contours

Map 6	Scale: 1:500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 7: Depth to Groundwater





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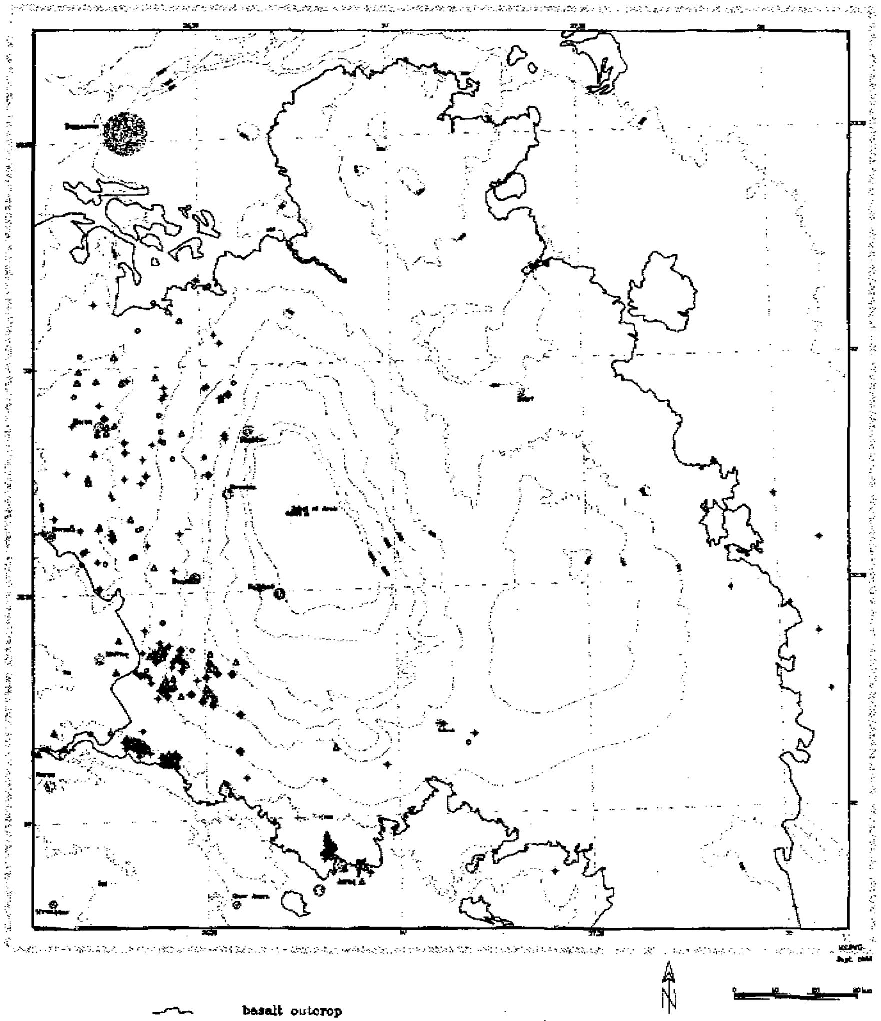
Depth to Groundwater

Map 7	Scale: 1:500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

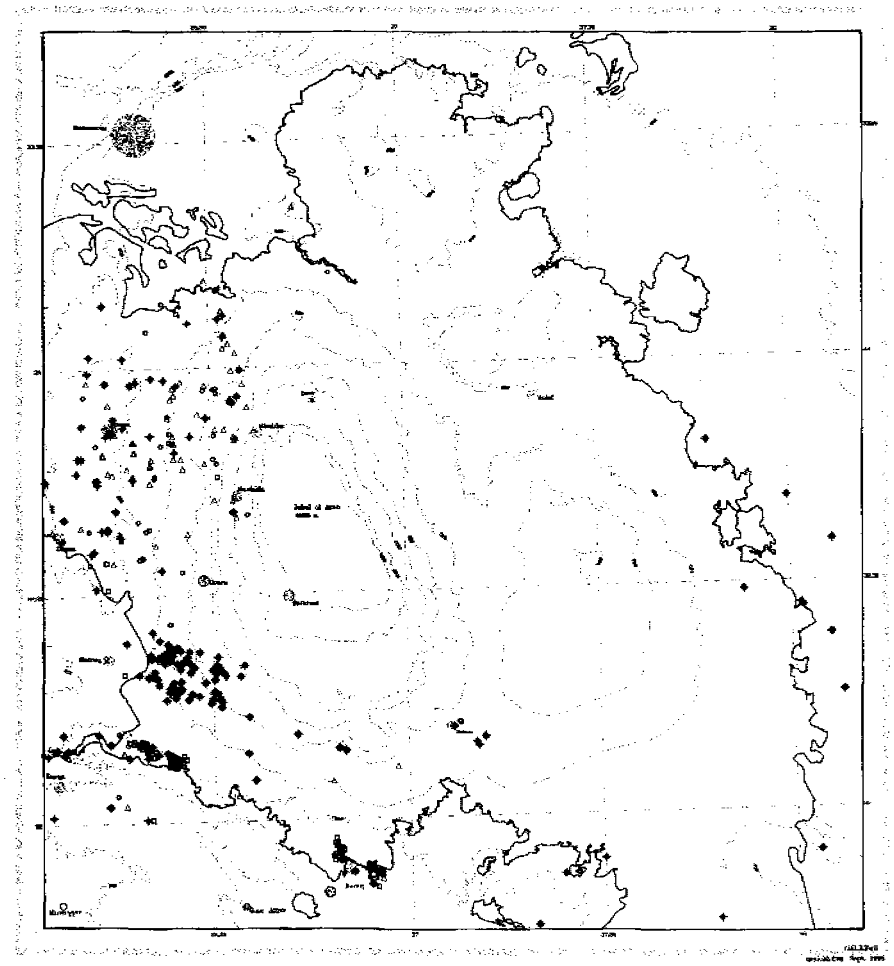
Map 8: Well Yield



basalt outcrop
topographic contour

specific capacity of wells, [m²/h]:

- o 0 – 1
- + ≥ 1 – < 10
- Δ > 10 – < 100
- ✦ ≥ 100



basalt outcrop
topographic contour

borehole yield [m³/h]

- o 0 – 10
- Δ ≥ 10 – 20
- + ≥ 20 – 30
- ✦ ≥ 30 100
- □ ≥ 100

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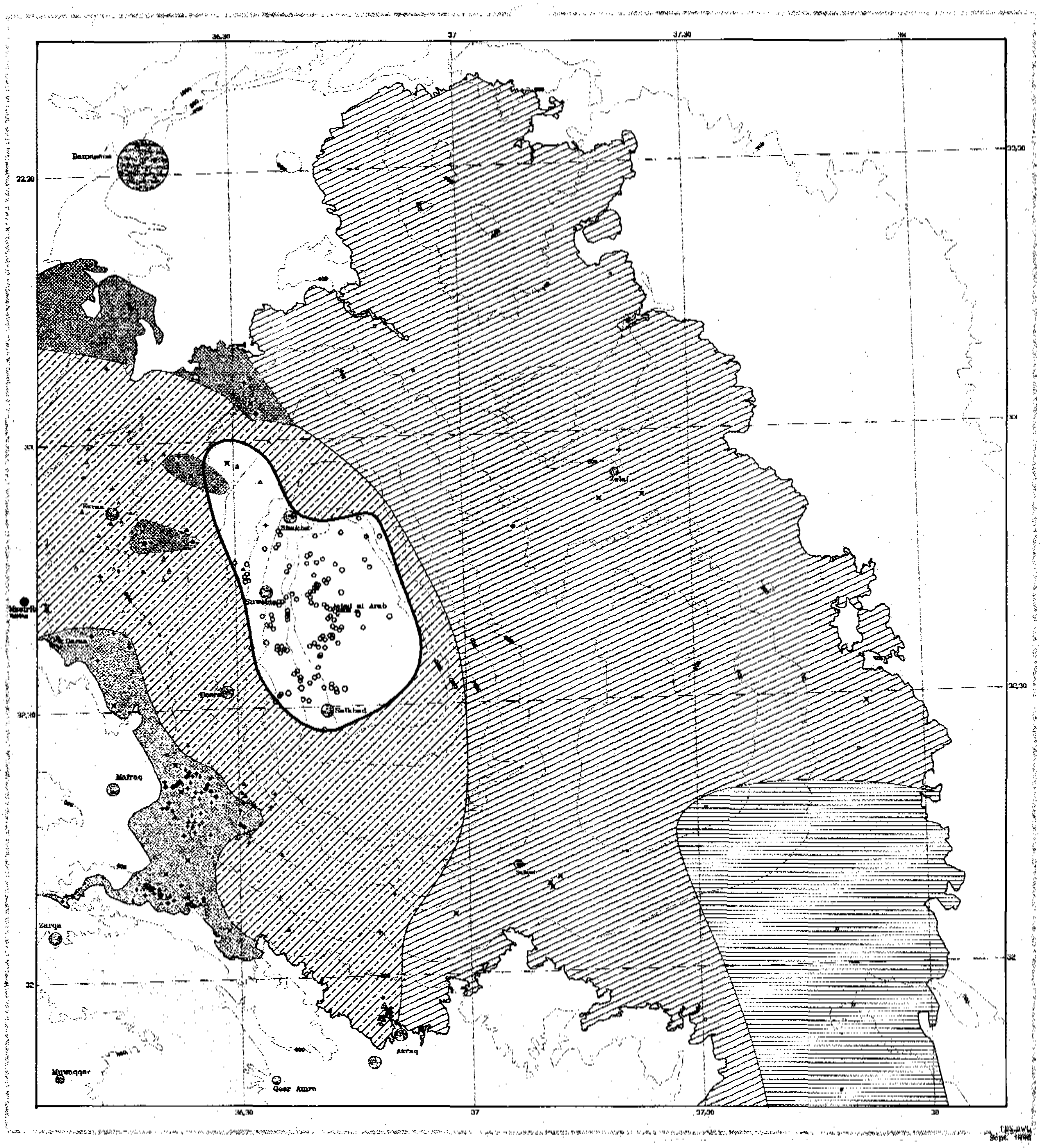
Well Yield

Map 8	Scale: 1:1000.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 9: Groundwater Salinity



General range of groundwater salinity (total dissolved solids in mg/l):

- < 250 mg/l TDS shallow or intermediate aquifers
- 100 – 1000 mg/l TDS shallow aquifer
- 200 – 400 mg/l TDS main basalt aquifer, locally shallow aquifers
- generally 200 – 400 mg/l TDS locally up to > 2000 mg/l TDS
- 300 – 1000 mg/l TDS main basalt aquifer
- 1000 – 1500 mg/l TDS main basalt aquifer locally < 1000 mg/l TDS
- 1500 – 6000 mg/l TDS underlying sedimentary aquifer below basalt

topographic contour

basalt outcrop

spring

Mzeirib spring

boreholes:	[g/l TDS]:
^	<= 0.3
+	> 0.3 <= 0.4
♦	> 0.4 <= 0.5
X	> 0.5 – <= 1
□	>1

0 10 20 30 km

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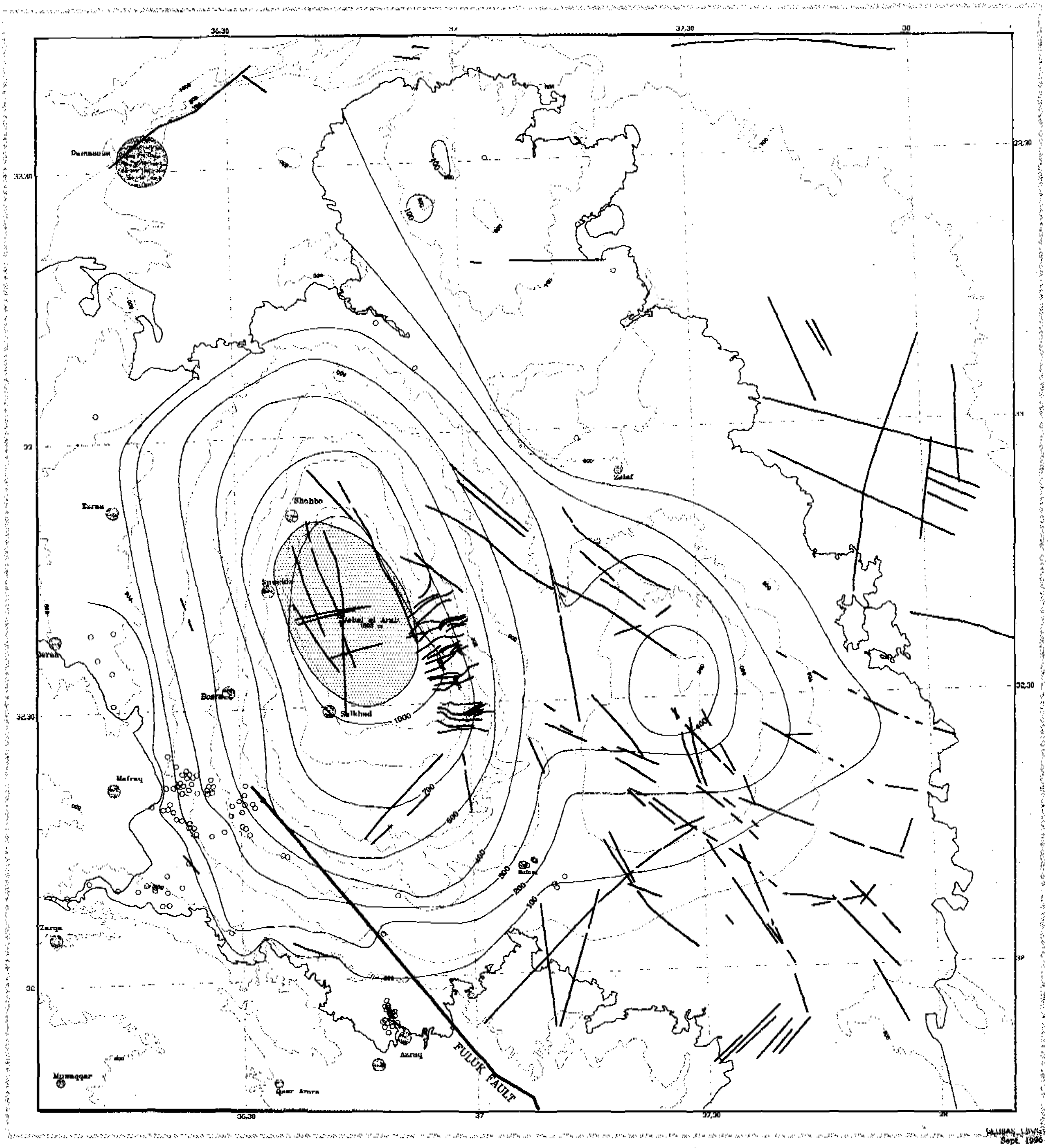
Groundwater Salinity

Map 9	Scale: 1:500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 10: Thickness of Neogene to Quaternary Basalt



0 10 20 30 km

isopach line of basalt [m]

basalt outcrop

borehole, information used for construction of isopachs

topographic contour

fault

main basalt feeder zone

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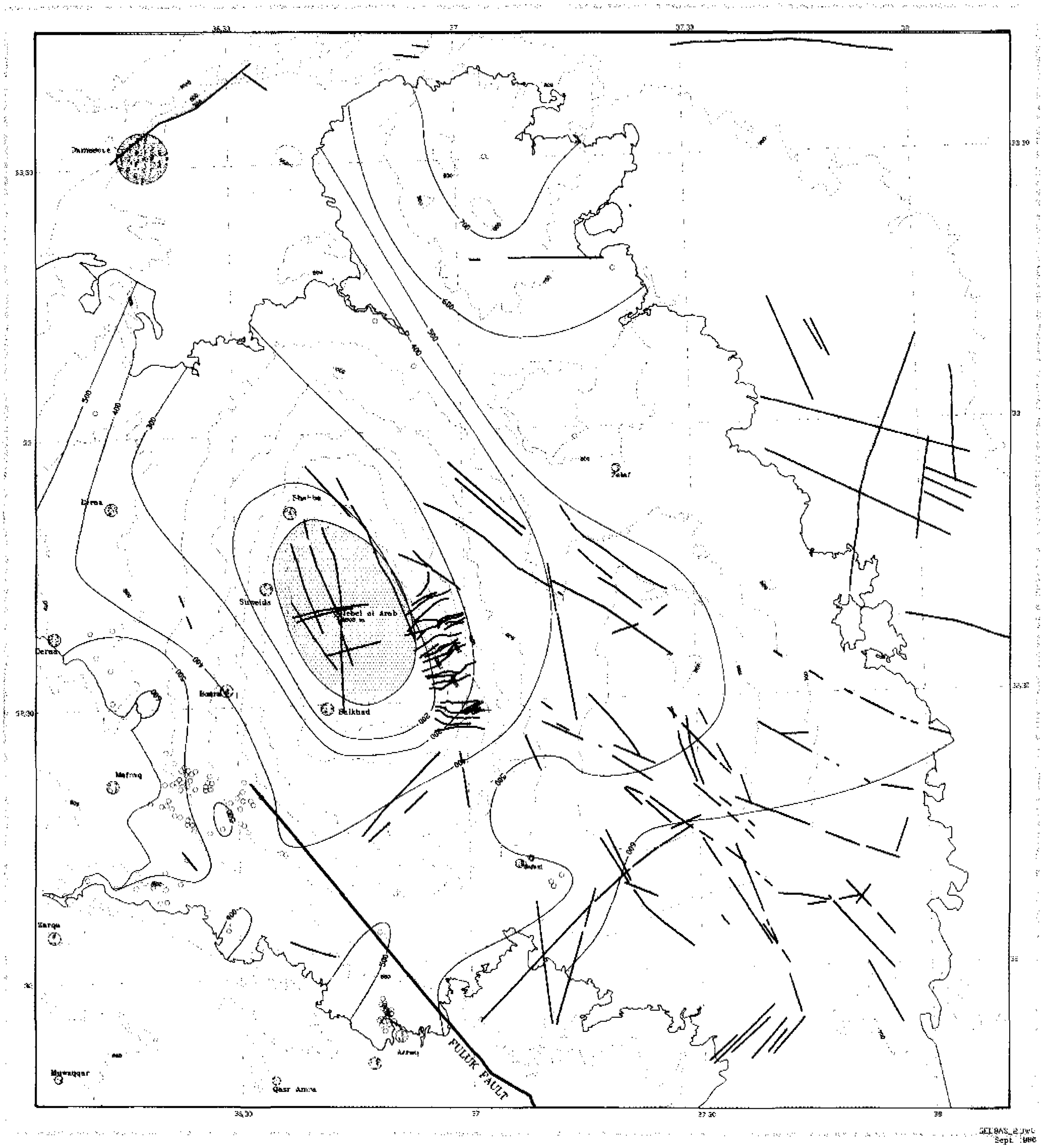
Thickness of Neogene to Quaternary Basalt

Map 10	Scale 1 : 500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 11: Structural Contours of Base of Basalt



contour line of basalt base [m] above sea level

basalt outcrop

borehole, information used for construction of contours

topographic contour

main basalt feeder zone

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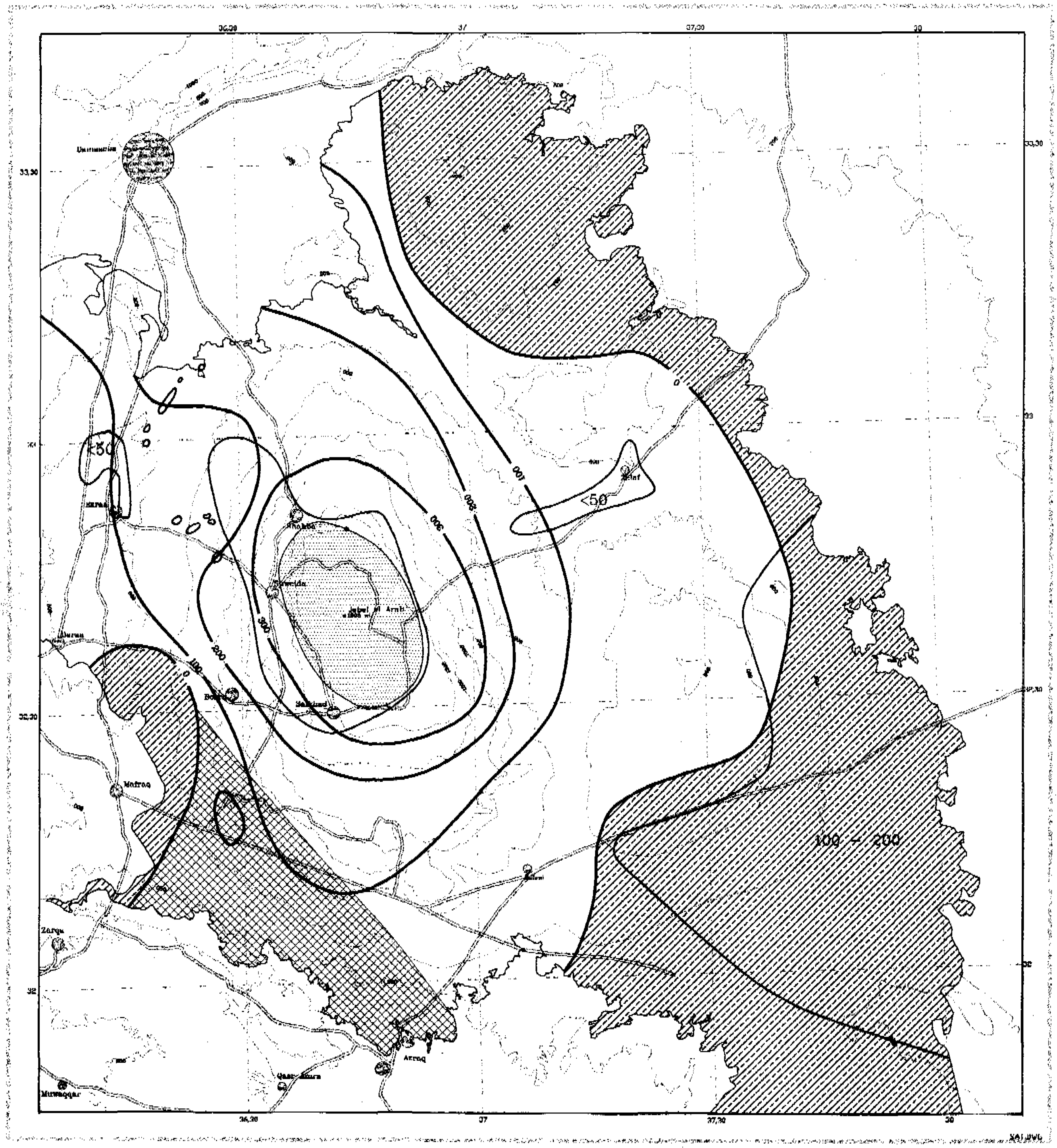
Structural Contours of Base of Basalt

Map 11	Scale: 1: 500.000	Amman 1996

BASALT AQUIFER SYSTEM IN JORDAN AND SYRIA

Map 12 : Saturated Thickness of the Basalt Aquifer



Sept. 1990

basalt base above water level of main regional aquifer system

basalt aquifer hydraulically connected with underlying carbonate aquifers

main basalt feeder zone

shallow or intermediate basalt aquifers

100 — contour of saturated thickness of main basalt aquifer (m)

800 — topographic contour

main road

0 10 20 30 km

N

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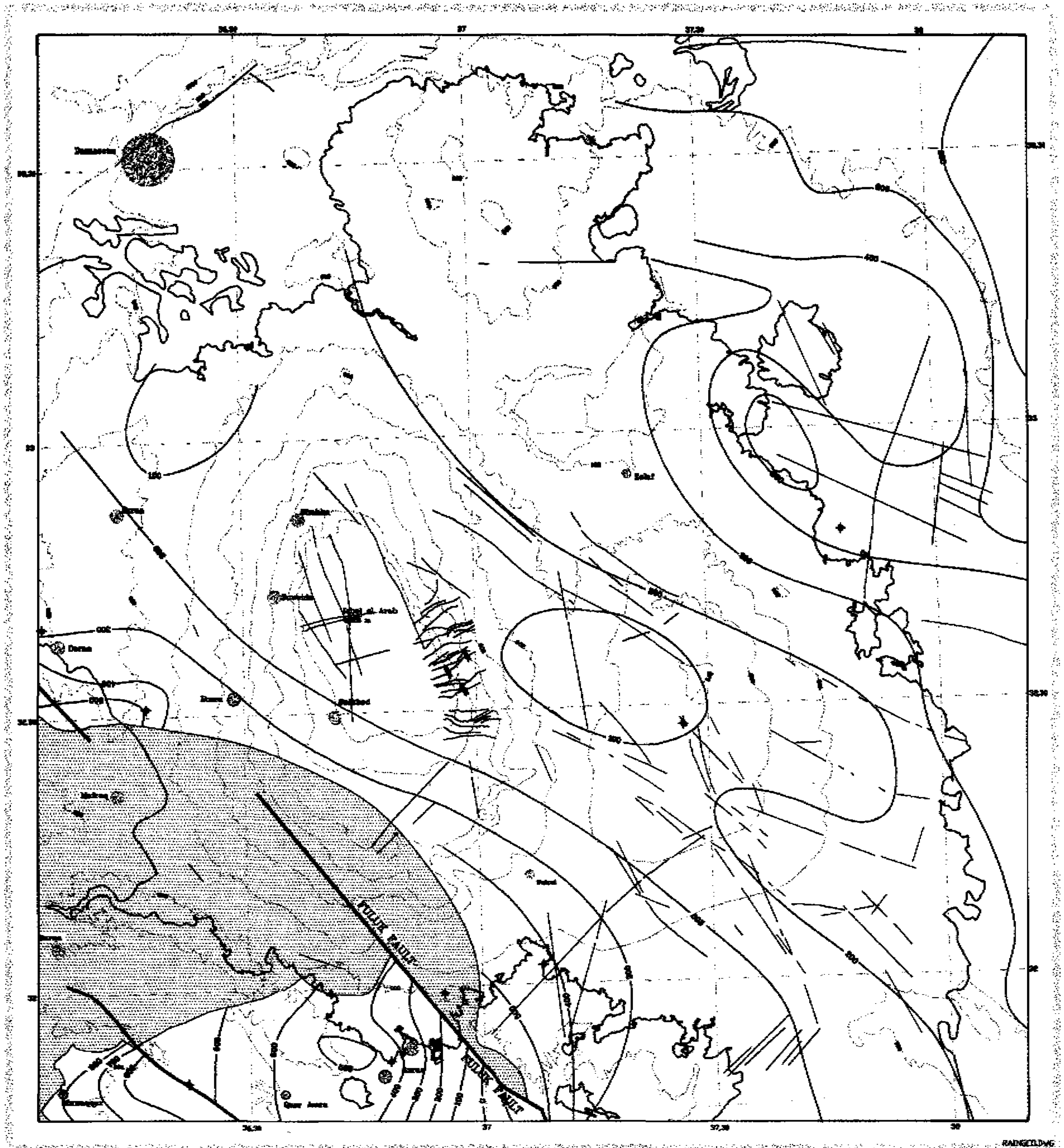
Saturated Thickness of the Basalt Aquifer

Map 12	Scale: 1: 500.000	Amman 1996

Structural Contours of Base of Paleogene Chalk Formation

(Top of Maastrichtian – Paleogene Marls)



fault

Paleogene missing

contour line of base of chalk formation [m above sea level] generalized after BGR, WAJ, 1994, WAJ 1995, Technoexport 1961, ACSAD 1963

topographic contour

basalt outcrop

borehole, information used for construction of isopachs

0 10 20 30 km

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Structural Contours of Base of Paleogene Chalk Formation

Map 13	Scale: 1 : 1000000	Amman 1996