4.4.2 Geology of recharge dams

Eleven damsites were preliminary selected from the map study (at scale 1/50,000). After examining both the site geology and the available flood water volume, eight potential damsites are screened out, and then after the geological mapping of the bedrock foundation along the dam axis are proceeded. No drillings were performed in this preliminary stage of the investigation.

The geological mapping along the dam axis was proceeded to examine the engineering geology of the bedrock foundation. The emphasis was put to the upper to middle Amman (B2) formation which is the major bedrock foundation for both dam axes and reservoirs. Following is the geological description of each damsite;

<u>A-1 Damsite</u>

The damsite is located on the Wadi Nijil, about 500 m Upstream from the Shoubak town. The left abutment rises at a uniform slope of 5-15 degrees from the bottom of the wadi to the top of the hill, while the right abutment rises steeply with a uniform slope of 30 to 45 degrees. No baseflow is recorded throughout the year.

The left abutment is covered with thin unconsolidated loose sediment of debris of which thickness is estimated to be about 1 to 2 m. The B2 Formation, which is composed of alternating silicified limestone, chert and marly Limestone, outcrops extensively along the steep cliff of the left abutment. The bed strikes N5W and dips 10S.

On the other hand, successive fresh outcrops are found in the right abutment. The bed rock of the lower right abutment up to 3 m from the road is composed of chalky marl and thin chert bed of the B2 Formation. The higher right abutment above to 3 m level consists of silicified limestone, chert and some chalky marl of the B2 Formation. These silicified limestone and chert layers are fractured with some open cracks. The bed strikes N35W and dips 2N. Alluvial wadi deposits of gravel and sand, widely cover the wadi with a thickness of about 5 m.

Estimated geological profile along the proposed dam axis is shown on Fig.4.62.

A-2 Damsite

The damsite is located on the Wadi Marma, which is a tributary of Wadi Nijil, and located about 3 km south of Shoubak town. The left abutment rises steeply with a slope of 45 to 50 degrees. The right abutment rises gently with a slope of 10 to 15 degrees. No baseflow is recorded throughout the year.

Successive fresh outcrops with stratified silicified limestone unit and phosphorite unit are found in and around the damsite area. The bedrock of the lower left abutment up to 5 m from the wadi bed is composed of highly fractured chert, silicified limestone and some marl of the B2 Formation. The higher left abutment above the 5 m level consists of phosphate, silicified phosphate and chert of the B2 Formation. The bed strikes N20E and dips 10N.

The right abutment below the 5 m level consists of chert and silicified limestone of B2 Formation. The bed strikes N75W and dips 5W. These chert and silicified limestone layer are fractured with some open cracks. The higher right abutment above the 5 m level is covered with thin unstable debris.

The wadi channel is covered with thin alluvial deposit of 1 to 2 m in thickness.

Estimated geological profile along the proposed dam axis is shown on Fig.4.62.

A-3 Damsite

The damsite is located on the Wadi El Arja, and located about 16 km south of Shoubak town. The left abutment rises gently with a slope of 15 to 20 degrees. The right abutment rises steeply with a slope of 40 to 45 degrees. No baseflow is recorded throughout the year.

The left abutment is covered mostly with thin unstable debris. Outcrops are found only near the bottom of the wadi within a height of 10 m. The Highly fractured chert bed at the wadi bottom strikes N65E and dips 10E.

The B2 Formation, which is composed of alternating silicified limestone, chert, outcrops extensively along the steep cliff of the right abutment. The bed strikes N45E and dips 5S. The chert layers are fractured with some open cracks.

Alluvial wadi deposits of gravel and sand, widely cover the wadi with a thickness of about 3 m.

Assumed geological profile along the proposed dam axis is shown on Fig.4.62.

<u>B-1 Damsite</u>

The damsite is located on the Wadi Wuheida, and located about 18 km southwest of Ma'an. The left abutment rises steeply with a slope of 35 to 40 degrees, while the right abutment rises with a moderate slope of 25 to 30 degrees. No baseflow is recorded throughout the year.

Successive fresh outcrops with stratified silicified limestone unit are found in and around the damsite area. The bedrock of the higher left abutment is composed of silicified limestone and fractured chert of the B2 Formation. The bed strikes N5E and dips 2S. The lower left abutment below the 10 m level covered with thin unconsolidated loose sediment of debris. The lower right abutment composed of fractured chert and some silicified limestone of the B2 Formation.

The bedrock of the higher right abutment consist of silicified limestone and some chert of the B2 Formation. The bed strikes N10E and dips 2N. The lower right abutment below the 15 m level covered with thin overburden.

A part of the wadi bed is covered with alluvial wadi deposit 2 to 3 m thick.

Assumed geological profile along to proposed dam axis is shown on Fig.4.63

B-2 Damsite

The Damsite is located on the Wadi Wuheida, and located about 17 km southwest of Ma'an. The left abutment rises gently with a slope of 5 to 10 degrees, while the right abutment rises with a moderate slope of 15 to 20 degrees. No baseflow is recorded throughout the year.

The bedrock of the lower left abutment, up to 5 m height above the wadi bed, is composed of alternating fractured chert and silicified limestone of the B2 Formation. The bed strikes EW and dips 5S. The upper part, above 5 m dam height, covered with thin top soil and debris, therefore no outcrops are found both at the left abutment and on the reservoir rim.

The bedrock of the lower right abutment, less than the 15 m height, is consist of alternating silicified phosphate and fractured chert of the B2 Formation. The bed strikes EW and dips 5N. The gentle slope of upper right abutment, more than 15 m in height, is covered with thin top soil or debris, and no outcrops are found on the slope of the left abutment.

A part of the wadi bed is covered with alluvial wadi deposit 5 to 10 m thick.

Estimated geological profile along the proposed dam axis is shown on Fig.4.63.

B-3 Damsite

The damsite is located on the Wadi el Huseinàn, about 14 km southwest of Ma'an. The left abutment rises steeply with a slope of 45 to 50 degrees, while the right abutment rises rather gently with a slope of 10 to 15 degrees. No baseflow is recorded throughout the year.

The upper left abutment is covered with thin unconsolidated loose sediment of debris of which thickness is estimated to be about 1 to 2 m. The B2 Formation, which is composed of alternating silicified limestone, chert and phosphate, outcrops extensively along the steep cliff of the right abutment. The bed strikes N60E and dips 5E. The chert layers are highly fractured with some open cracks.

The bedrock of the lower right abutment, less than the 15 m height, is composed of alternating silicified limestone, chert and phosphate of the B2 Formation. The bed strikes N45E and dips to 5E. The upper part, above 15 m dam height, covered with thin top soil and debris.

Alluvial wadi deposits of gravel and sand, widely cover the wadi with a thickness of about 3 m.

Assumed geological profile along the proposed dam axis is shown on Fig.4.63.

C-1 Damsite

The damsite is located on the Wadi esh Shidiya, and is situated 17 km upstream from the Ma'an-Mudawwara road crosses the wadi. The left abutment rises steeply with a slope of 35 to 40 degrees while the right abutment rises gently with a slope 5 to 10 degrees. No baseflow is recorded throughout the year.

The bedrock of the upper left abutment, at a height above 10 m is consist of Coquina bed. The middle part of the abutment is composed of alternating highly fractured chert and silicified limestone. A part of the wadi bed at the left bank is consist of silicified phosphate. The bed strikes N5E and dips 5N. The bedrock of the lower right abutment, less than 2 m height, is composed of alternating silicified limestone and chert. The upper part, above 2 m dam height, is covered with thin top soil or debris.

A part of the wadi bed is covered with alluvial wadi deposit 1 to 2 m thick.

Assumed geological profile along the proposed dam axis is shown on Fig.4.64.

<u>C-2 Damsite</u>

The damsite is located on the Wadi el Ghubeya, and is situated 2 km upstream from the Ma'an-Mudawwara road crosses the wadi. Both left and right abutment rise with a uniform slope of 5 to 10 degrees. No baseflow is recorded throughout the year.

The bedrock of the lower left abutment, up to 8 m height above the wadi bed, is composed of alternating chert, silicified limestone and silicified phosphate of the B2 Formation. The upper part higher than 8 m covered with top soil and debris. The bed strikes N20E and dips 12E.

The B2 Formation, which is composed of alternating highly silicified limestone, chert and Coquina limestone, outcrops intensively along of the lower right abutment. The higher right abutment, above to 10 m level covered with top soil and unconsolidated loose sediment of debris. The bed strikes N75E and dips 10W.

A part of wadi bed is covered with alluvial wadi deposit 5 to 10 m thick.

Estimated geological profile along the proposed dam axis is shown on Fig.4.64.

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4.2 United Nation (FAO), 1970, "Investigation of the Sandstone Aquifers of East Jordan, Main Report and Annex I"

4.3 German Agency for Technical Cooperation Ltd., Federal Republic of Germany, 1977, "National Water Master Plan", Vol.I,II,III,IV,V,VI and VII

4.4 Howard Humphreys, 1986, "Groundwater Resources Study in the Shidiya Area"

4.5 The government of Jordan, 1958, "Geological Map of Jordan (Aqaba-Ma'an, S=1/250,000)

4.6 The government of Jordan, 1975, "Geological Map of Jordan (S=1/500,000)"

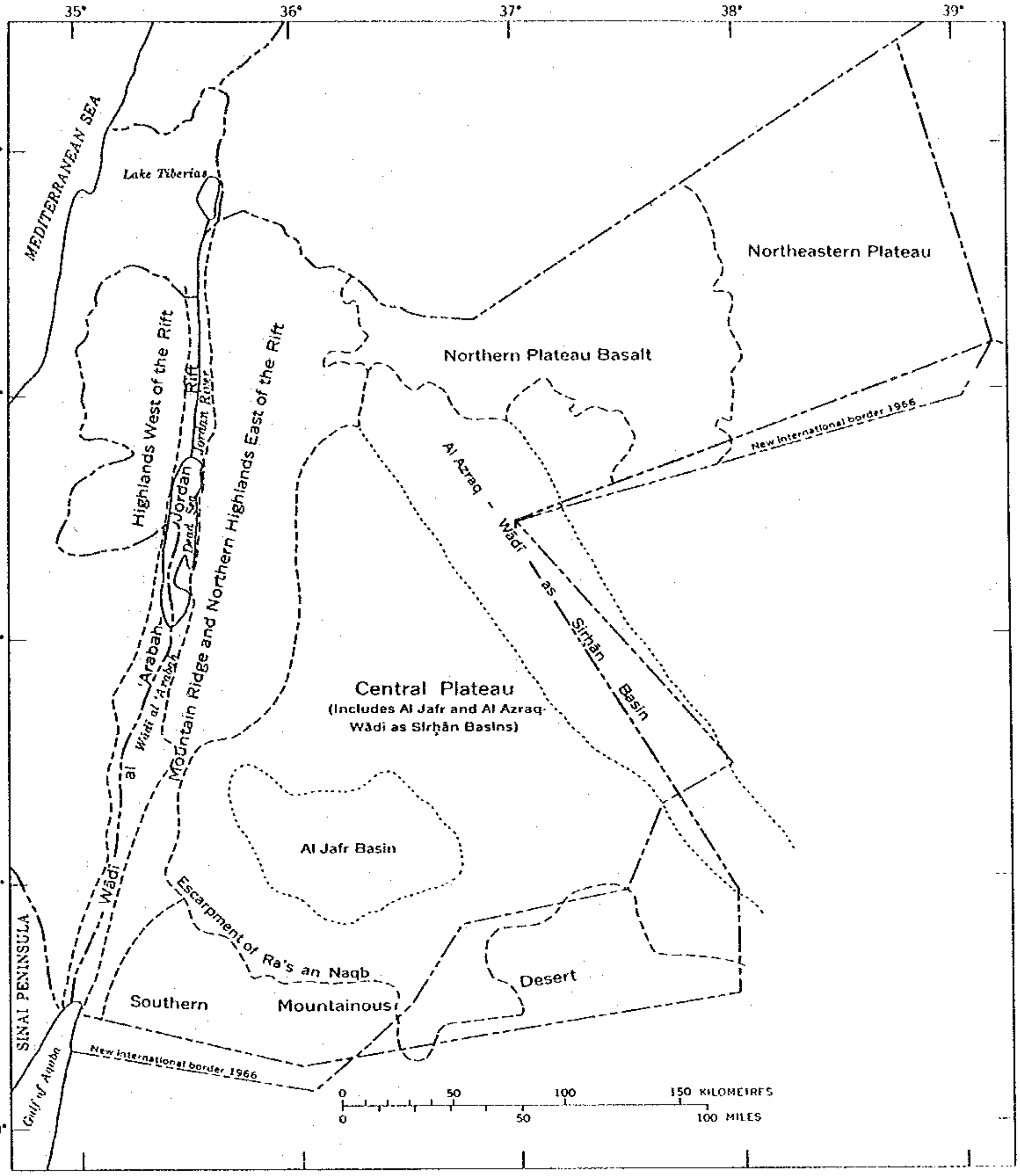
TABLES

Table 2.2 STRATIGRAPHIC SECTION

ERA	PERIOD		EPOCH	GROUP	FORMATION		SYMBOL	GENERAL LITHOLOGY
Cainozoic	Quaternary		Recent	–	–		R	Fluviatile deposits - sands, gravels etc. aeolean sands
Cainozoic	Quaternary		Pleistocene	Plateau	Jafr		Ja	Lacustrine limestone
Cainozoic	Tertiary		Eocene Paleocene	Belqa	Rijam		B4※	Limestone with chert, Nummulitic Limestone.
Mesozoic	Cretaceous	Upper	Maestrichtian	Belqa	Muwaqqar		B3	Chalky marls, bituminous, Limestones and marls
Mesozoic	Cretaceous	Upper	Campanian Santonian	Belqa	Amman Ruseifa		B1 - 2	Silicified and chert limestone Phosphorites, coquina - Minor marl Marl and marly limestone
Mesozoic	Cretaceous	Middle	Turonian	Ajlun	Fassua	Wadi Sir	A7※	Sandy limestones dolomites calcareous sandstone and marl
Mesozoic	Cretaceous	Middle	Cenomanian	Ajlun	Fassua	undifferentiated Lower Ajlun	A1 - 6※	Nodular limestones, clays, marls, interbedded sandstones change laterally to dominantly sandstones
Mesozoic	Cretaceous	Lower	Albian Aptian Neocomian	Kurnub	Subeihi Aarda		K2 K1※	Varicoloured sandstones, silts ; brown coarse sands minor shales clays and marls interbeded Massive light coloured sandstones with minor shales clays and marls interbeded
Palaeozoic	Silurian		Llandovery	Khreim	Mudawwara		Kh2	Flaggy micaceous greenish grey argillaceous sandstones and shales

Remark ; ※ Aquifer

FIGURES



Source : Geology of the Arabian Peninsula Jordan
By FRIEDRICH BENDER (1975)

Fig.4.1

Index Map of Physiographic-Geologic Provinces, Jordan

THE HASHEMITE KINGDOM OF JORDAN
WATER RESOURCES STUDY OF THE JAFR BASIN
JAPAN INTERNATIONAL COOPERATION AGENCY

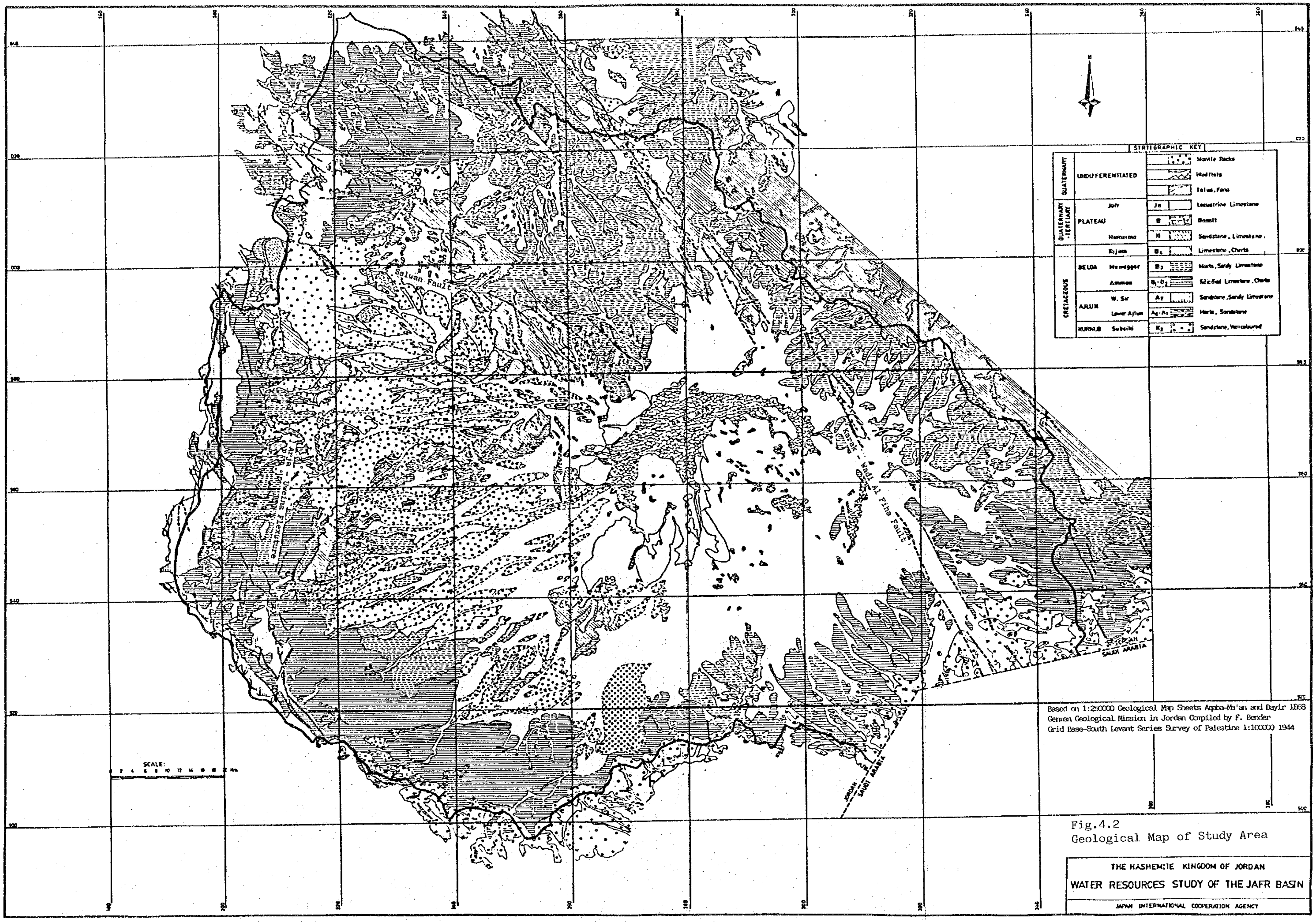


Fig.4.2
Geological Map of Study Area

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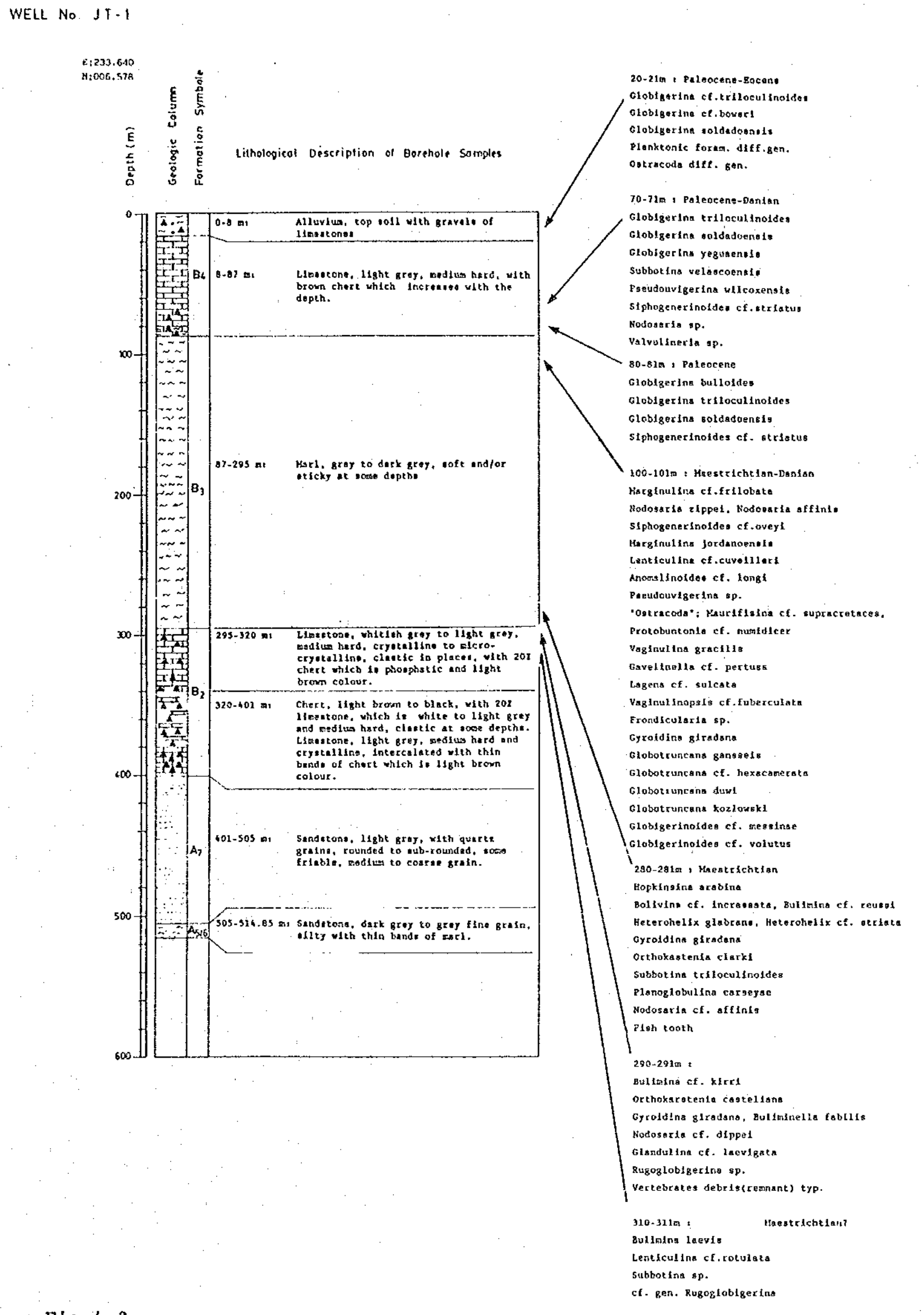

Fig.4.3

Micro-fossil Analysis (1/4) ; JT-1

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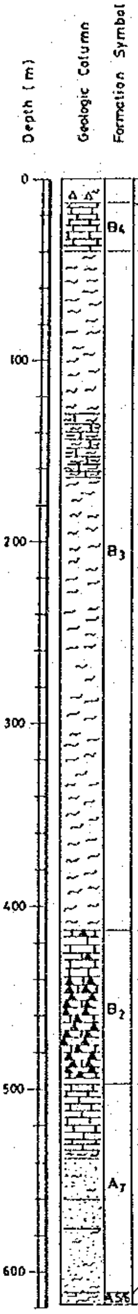
WELL No. JT-2

E;232.364
N;992.392



Lithological Description of Borehole Samples

0-12 m:	Alluvium, with boulders of gravel and basalt.
12-40 m:	Limestone, some weathered, light beige, hard.
40-130 m:	Marl, light grey, soft, intercalating thin bands of limestone which is beige colour and hard.
130-164 m:	Marly limestone, dark grey, intercalating black chert layers.
164-413 m:	Marl, grey to dark grey, bitminous.
413-440 m:	Limestone, beige, hard, intercalating chert.
440-497 m:	Chert, black, intercalating thin bands of limestone which is beige colour and hard.
497-530 m:	Marl, dark grey, with limestone which is sandy.
530-610 m:	Marl, grey to dark grey, sticky, with sand which is light grey with argillaceous materials.
610-617 m:	Marl, grey, soft, with sands.

50-51m :
Diff. benthic foraminifera
Cristaelebris sp.
Lenticulina sp.

440-441m :
Orthokarstenia clarki
Siphogenerinoides cf. plummerae
Heterohelix globulosa
Nodosaria affinis

490-491m : Maestrichtian
Siphogenerinoides oveyi
Heterohelix navarroensis
Subbotina trilocuiinoides
Globigerina sp.
Dentalina sp.

510-511m : Maestrichtian
Bulimina cf. peiroleana
Orthokarstenia sp.
Globigerinoides diff. sp.
Gen. diff. benthic foraminifera

590-591m : Middle Maestrichtian
Vaginulina trilobata
Robulus cf. mellahensis
Siphogenerioides oveyi
Ostracoda dif. gen.

Fig.4.4

Micro-fossil Analysis (2/4) ; JT-2

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WATER RESOURCES STUDY OF THE JAFR BASIN
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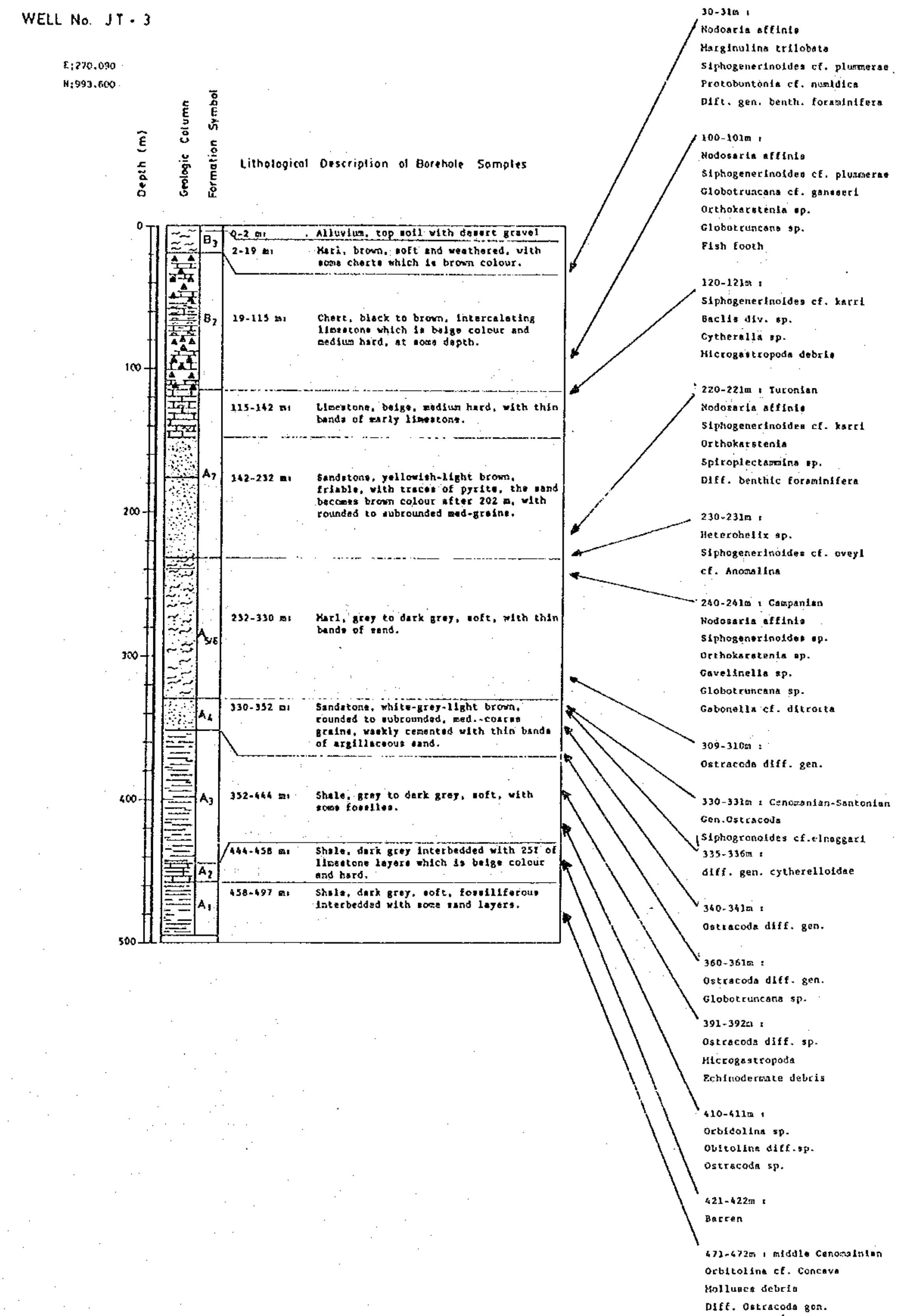

Fig.4.5

Micro-fossil Analysis (3/4) ; JT-3

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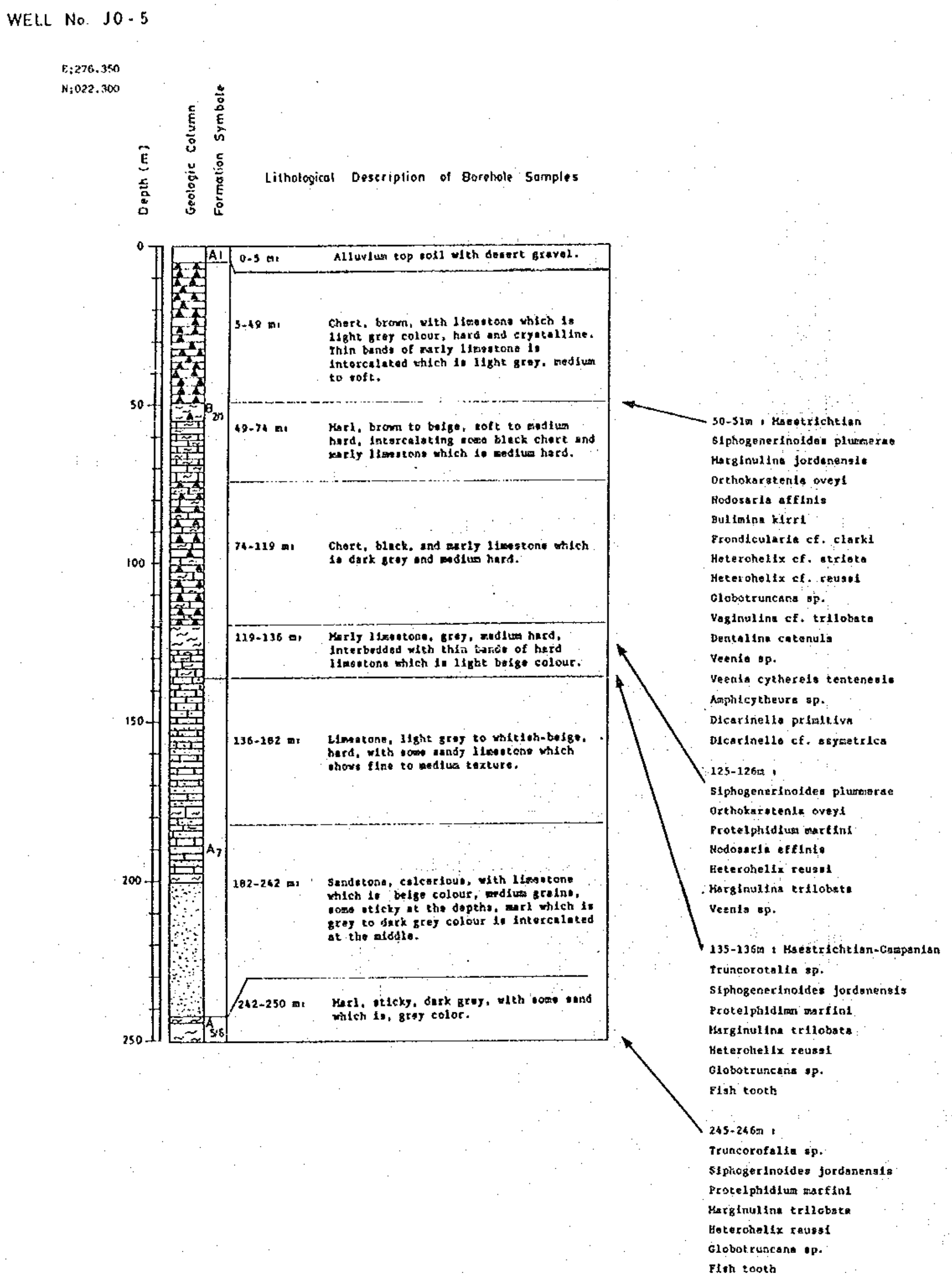

Fig.4.6

Micro-fossil Analysis (4/4) ; JO-5

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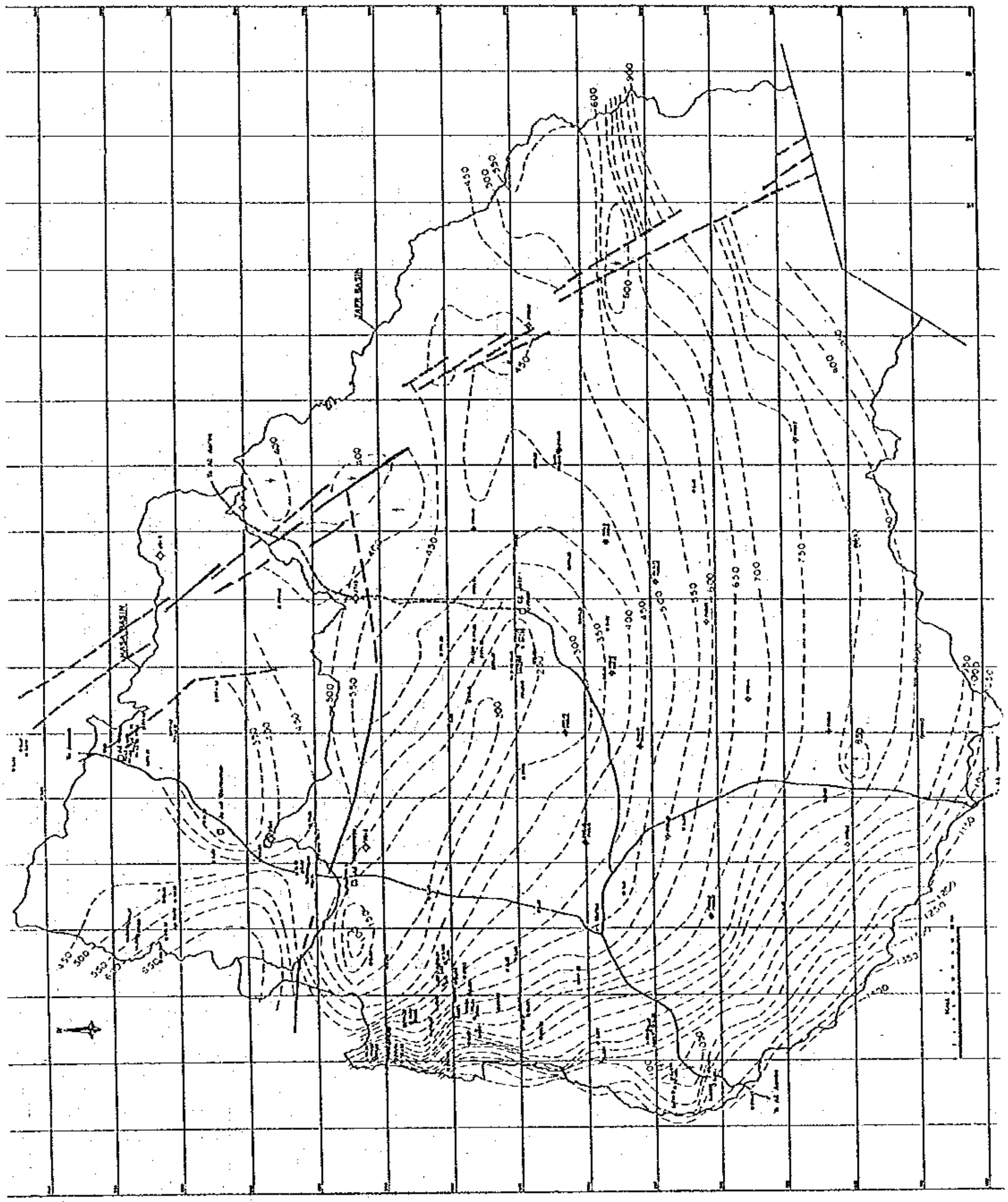

Fig.4.7

Structural Contour Map of Top of Kurnub (K) Formation

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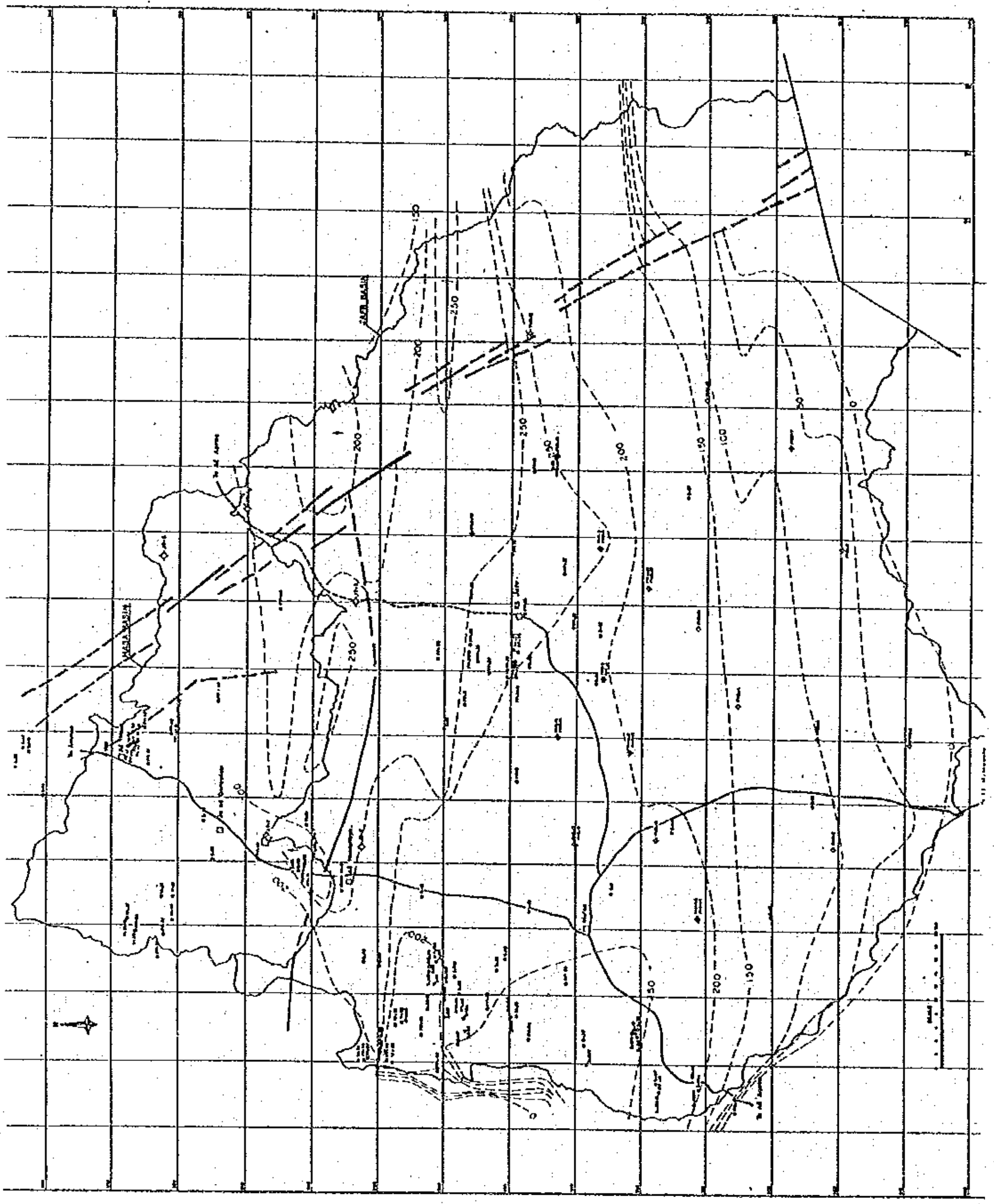

Fig.4.8

Isopach Contour Map of Lower Ajlun (A1-6) Formation

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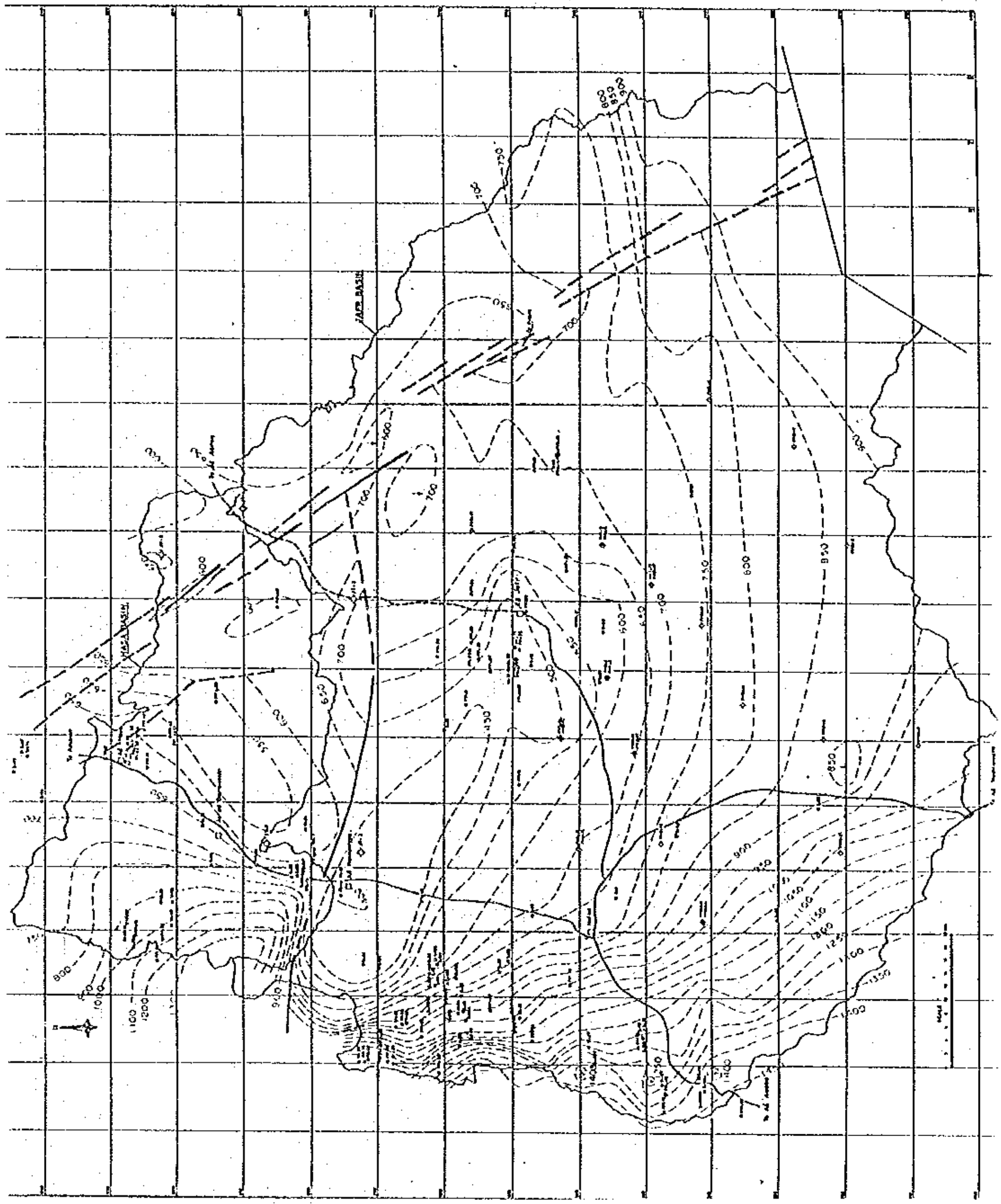

Fig.4.9

Structural Contour Map of Top of Lower Ajlun (A1-6) Formation

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WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

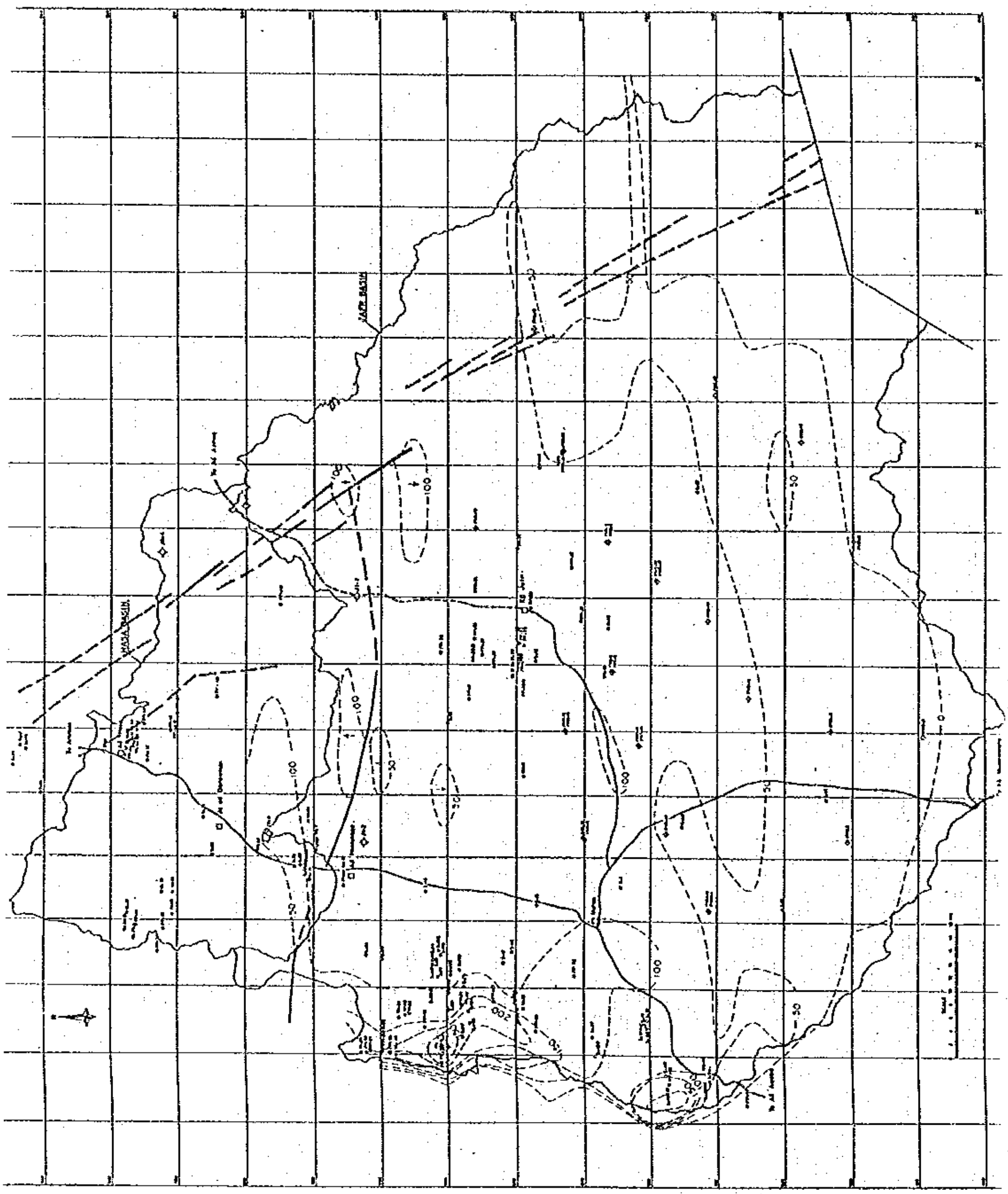

Fig.4.10

Isopach Contour Map of Wadi Sir (A7) Formation

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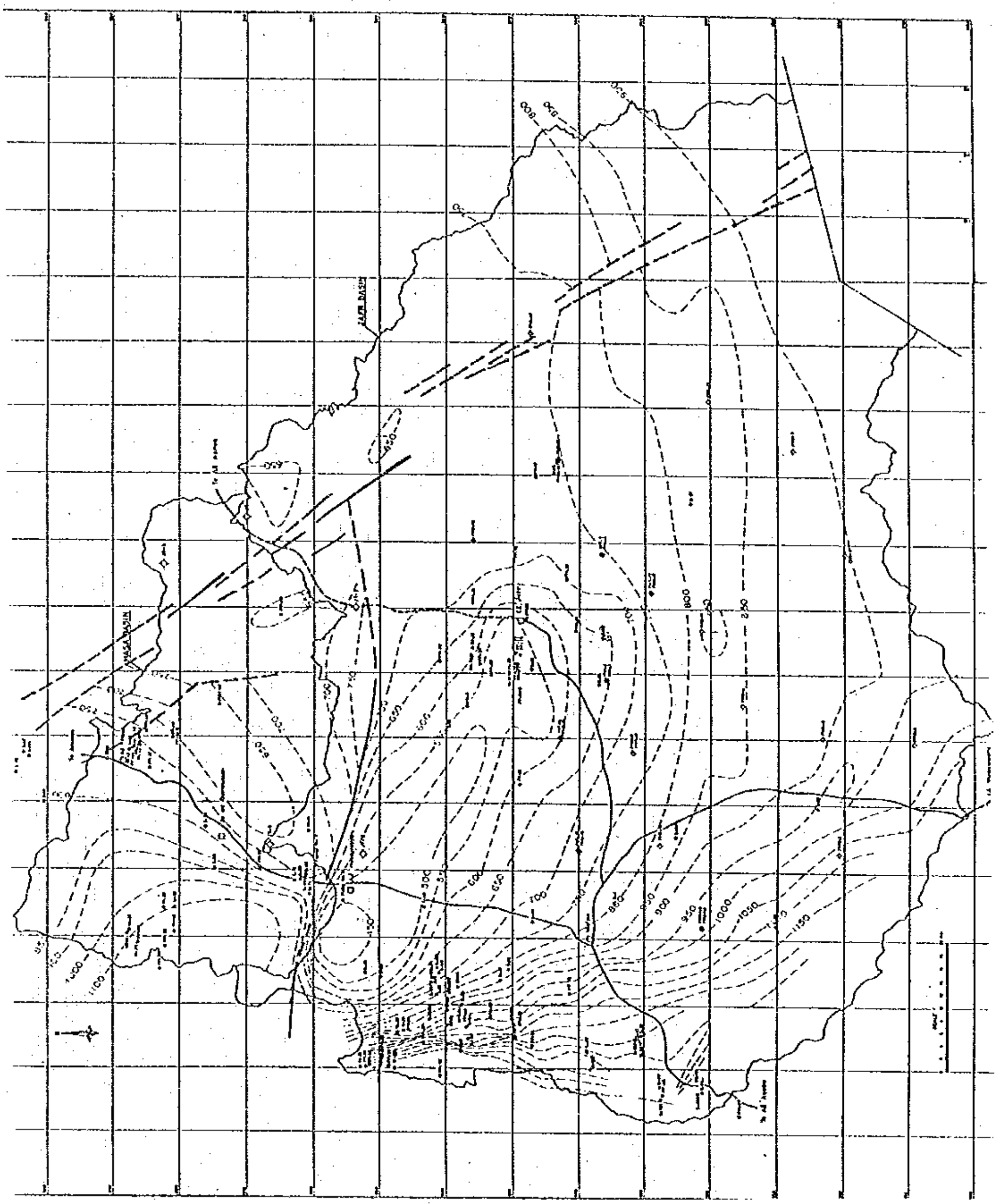

Fig.4.11

Structural Contour Map of Top of Wadi Sir (A7) Formation

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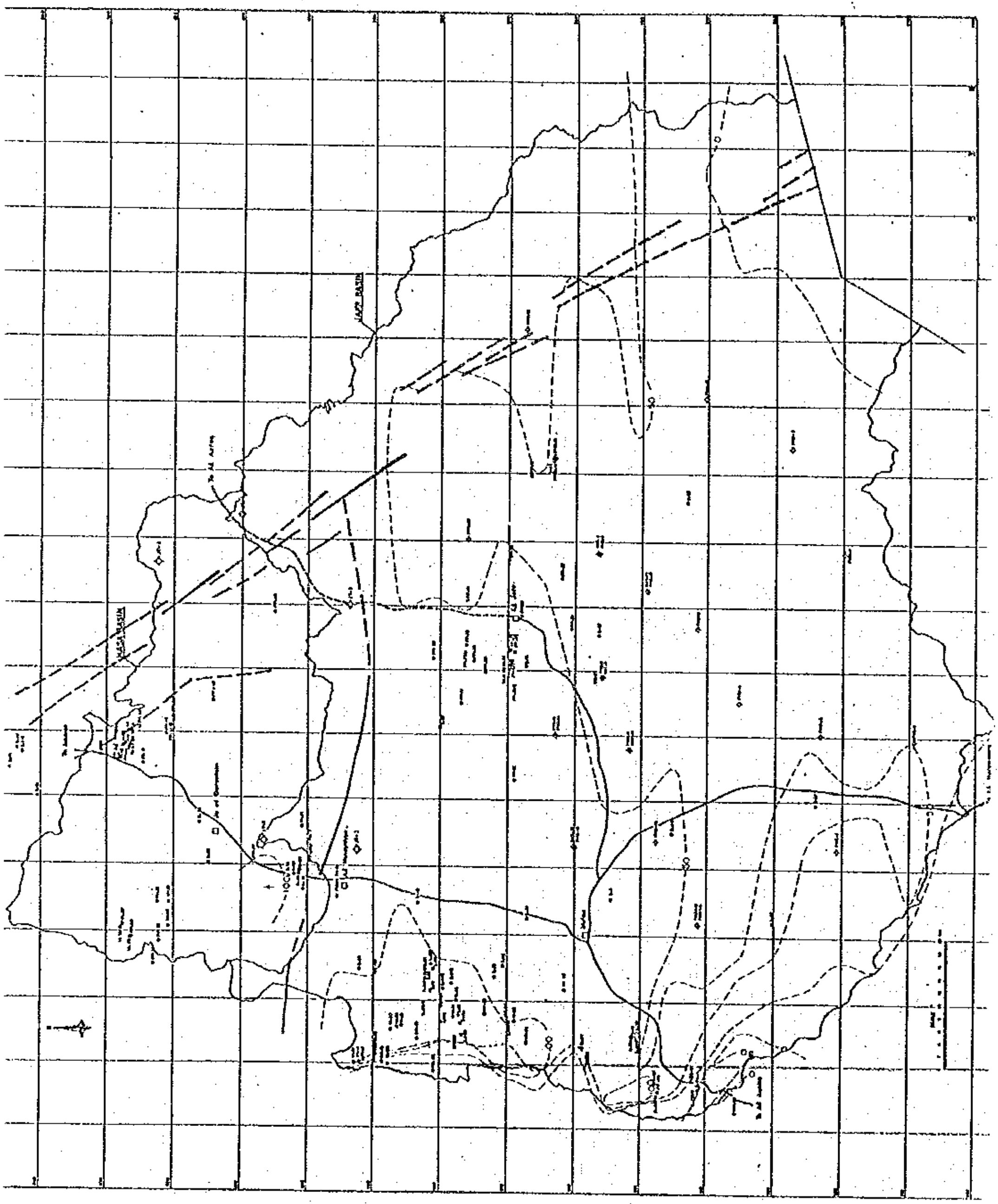

Fig.4.12

Isopach Contour Map of Amman-Ruseifa (B1/2) Formation

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WATER RESOURCES STUDY OF THE JAFR BASIN

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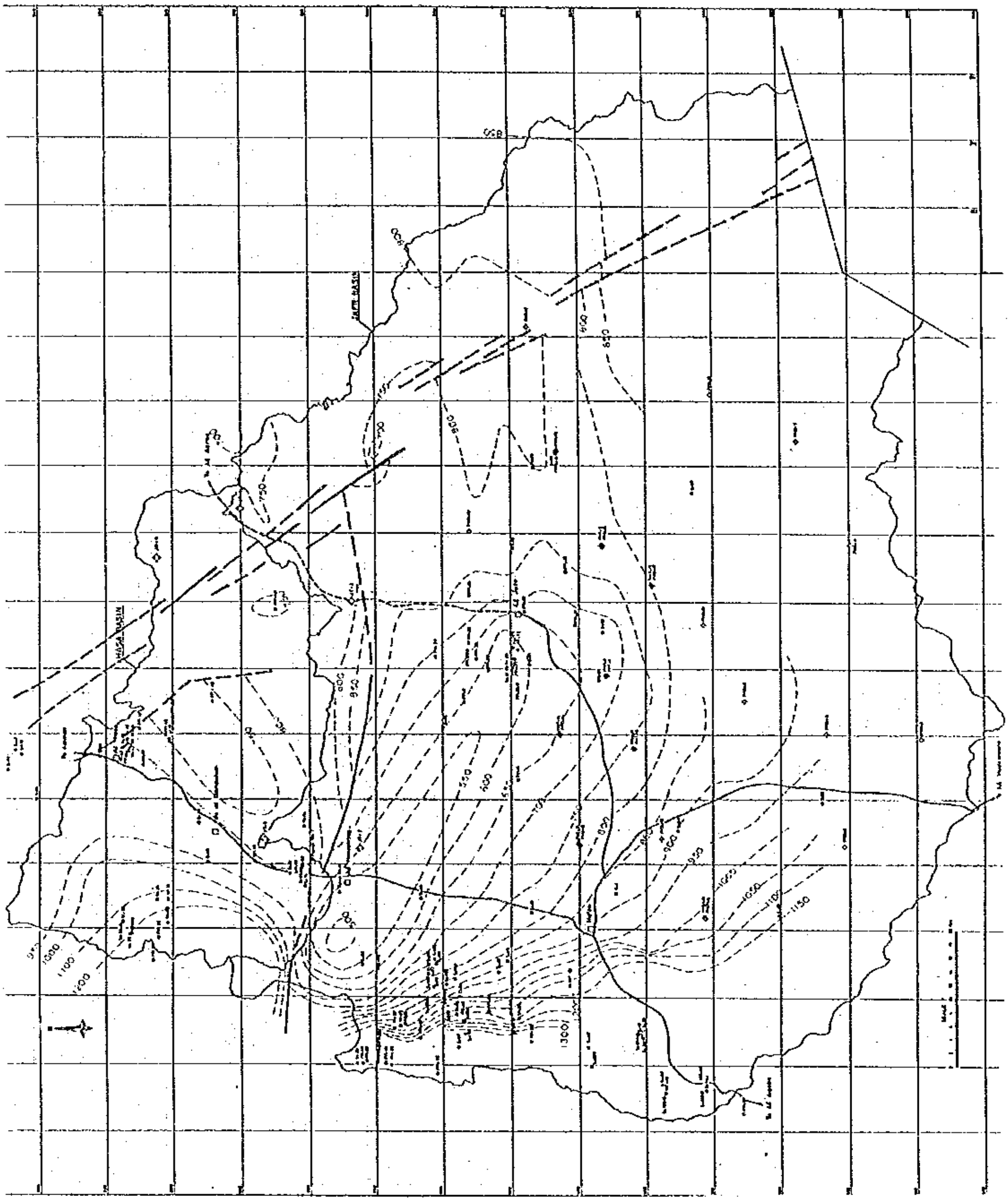

Fig.4.13

Structure Contour Map of Top of Amman-Ruseifa (B1/2) Formation

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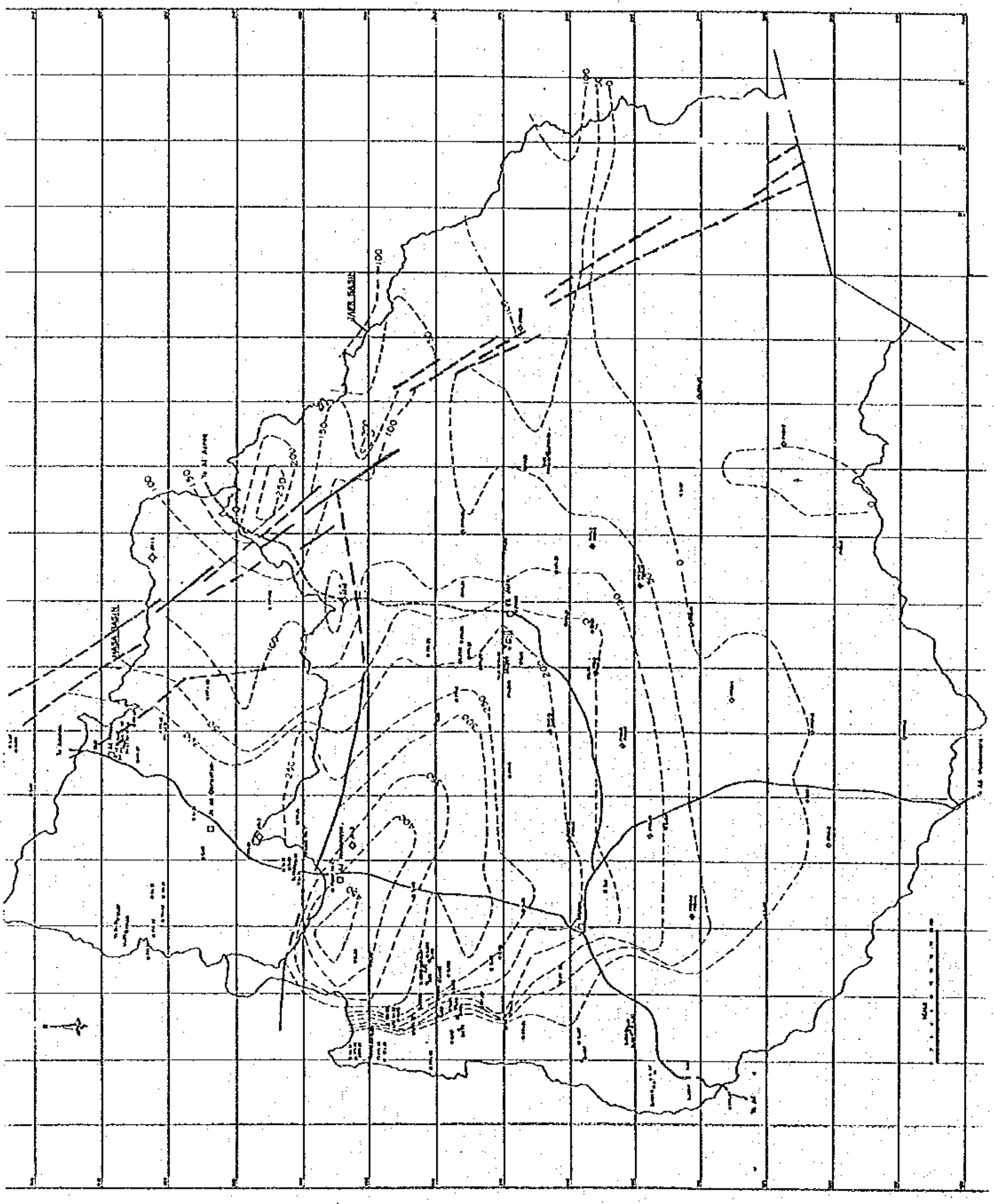

Fig.4.14

Isopach Contour Map of Muwaqqar

(B-3) Formation

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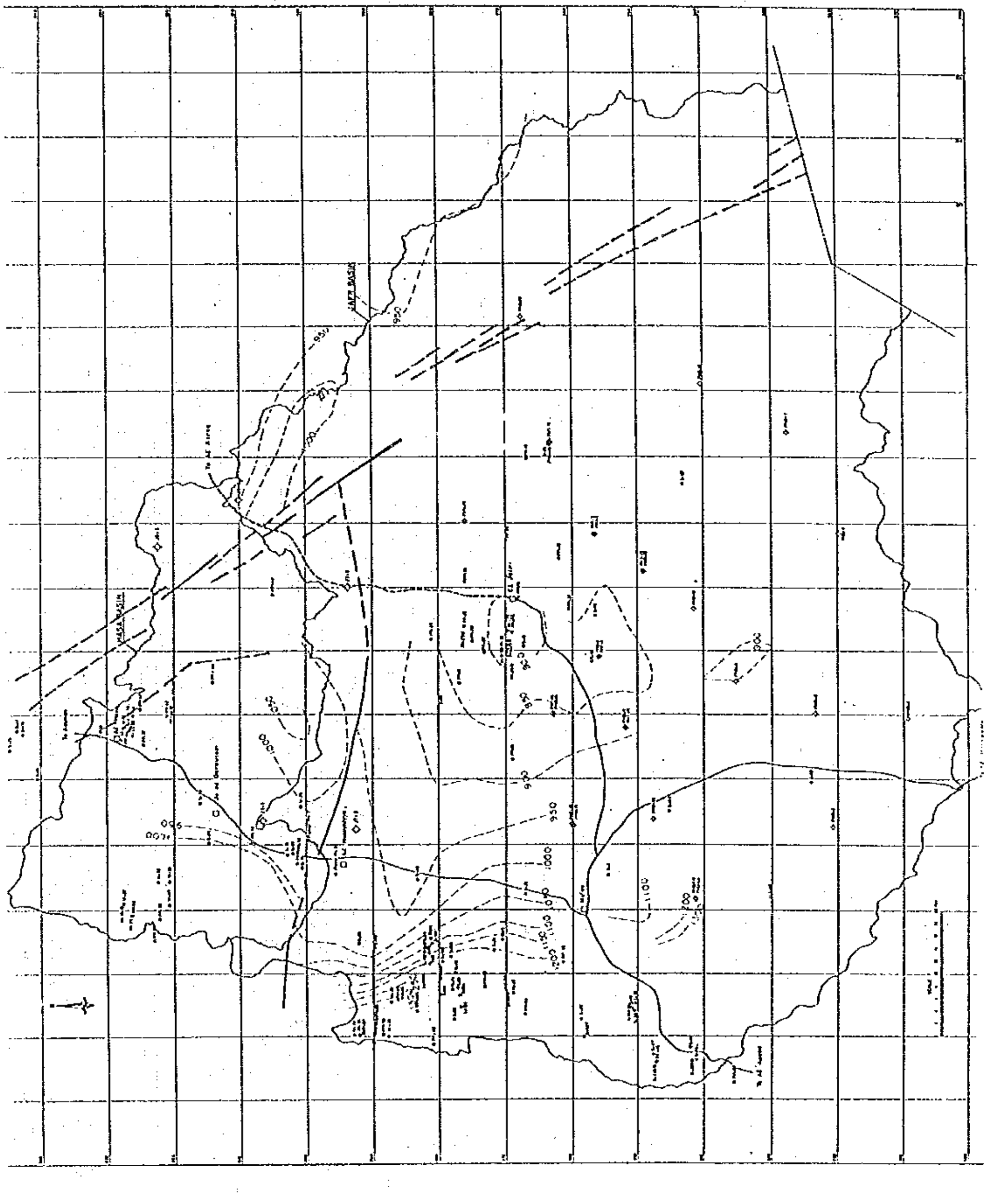

Fig.4.15

Structural Contour Map of Top of Muwaqqar (B-3) Formation

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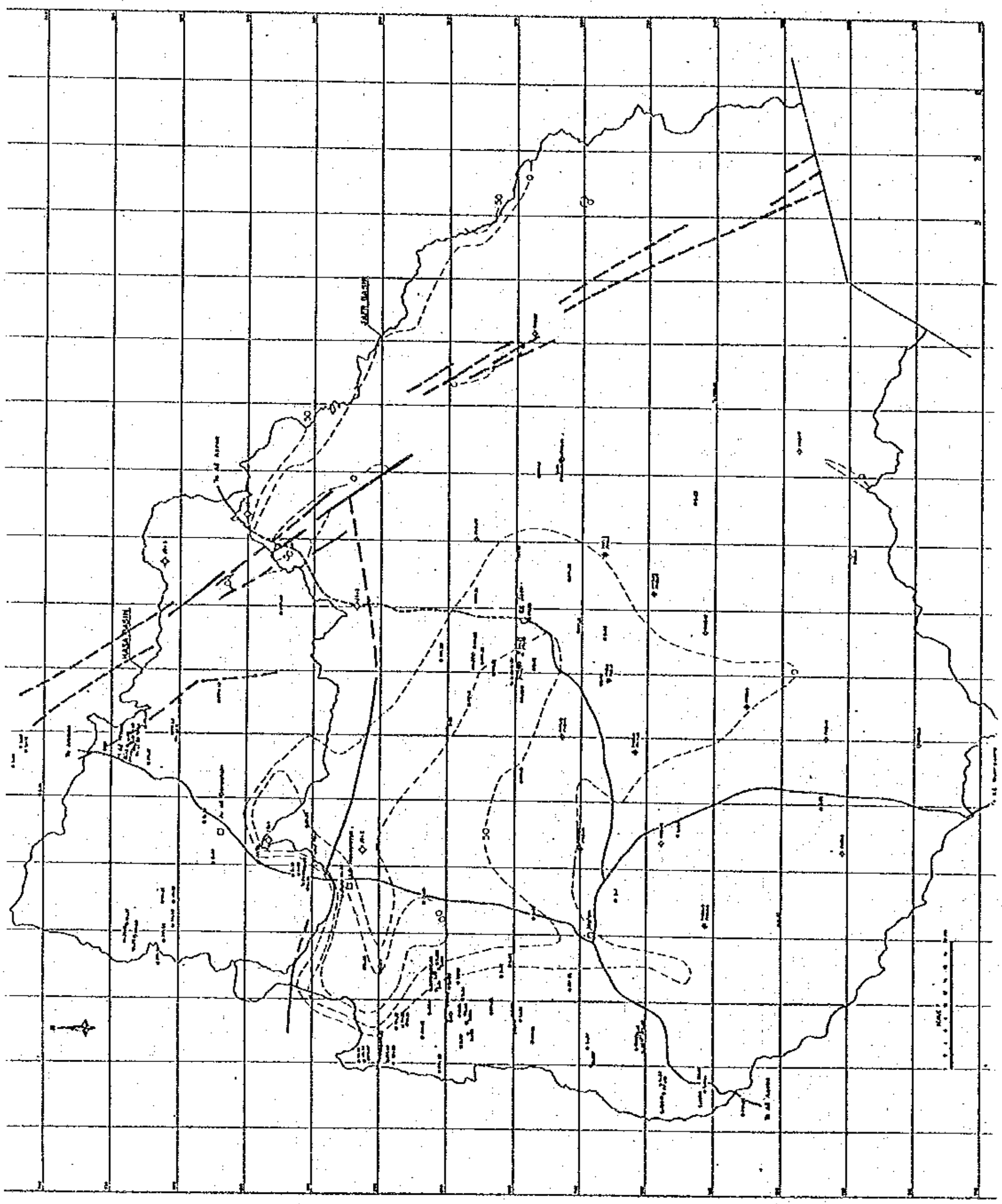

Fig.4.16

Isopach Contour Map of Rijam (B-4) Formation

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

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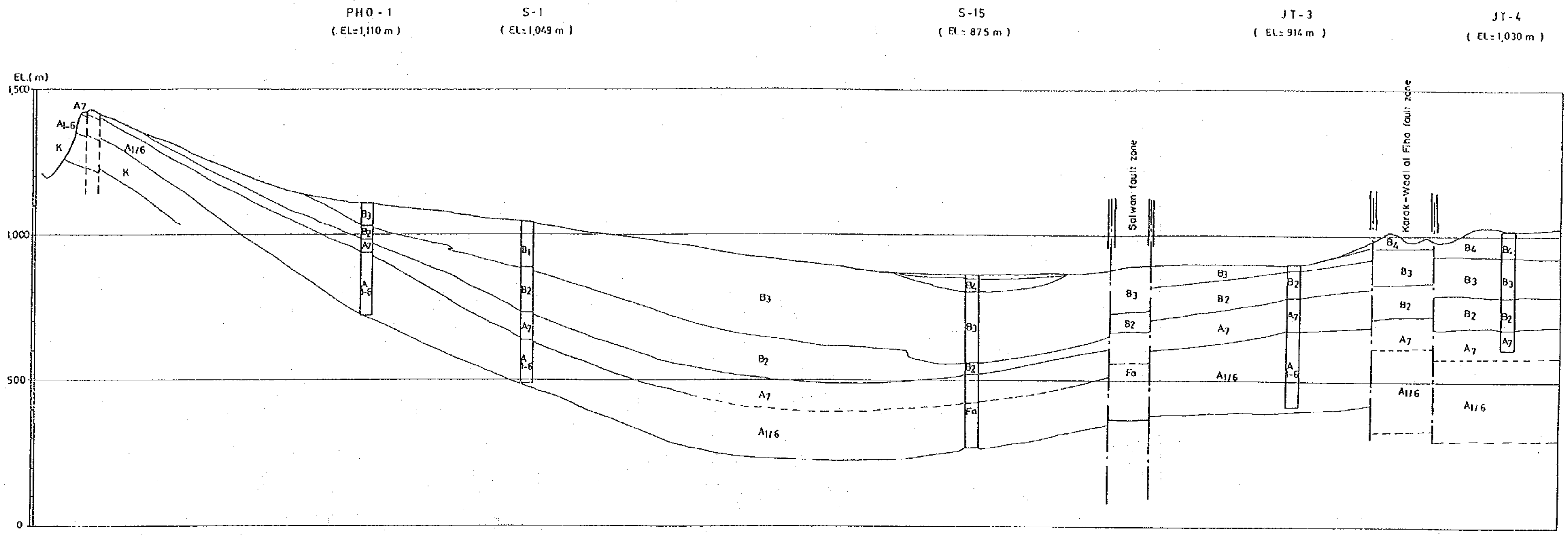
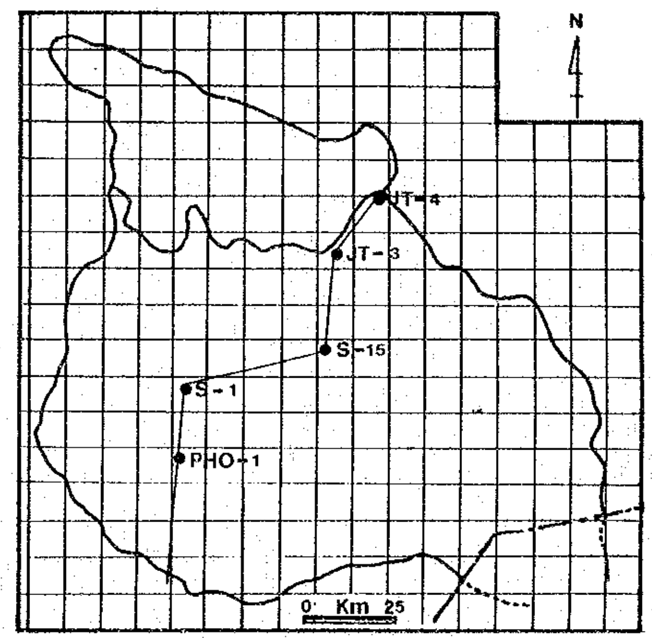




STRATIGRAPHIC KEY

QUATERNARY	UNDIFFERENTIATED			Mantle Rocks
				Mudflats
				Talus, Fans
QUATERNARY -TERTIARY	PLATEAU	Jafr	Ja	Locustrine Limestone
			B	Basalt
		Humeima	H	Sandstone, Limestone
CRETACEOUS	BELQA	Rijam	B_4	Limestone, Cherts
		Muwaggar	B_3	Marls, Sandy Limestone
		Ammon	B_1-B_2	Silicified Limestone, Cherts
	AJLUN	W. Sir	A_7	Sandstone, Sandy Limestone
		Lower Ajlun	A_6-A_1	Marls, Sandstone
	KURNUB	Subeihi	K_2	Sandstone, Varicoloured

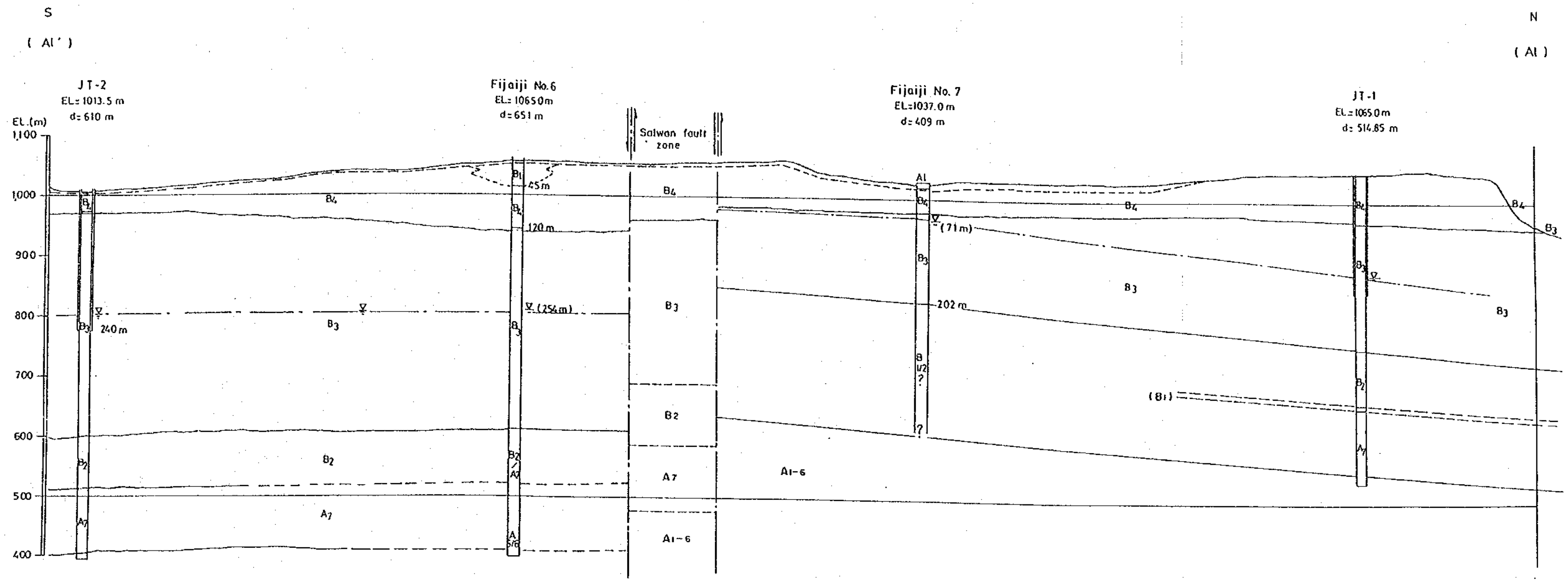
Fig.4.17

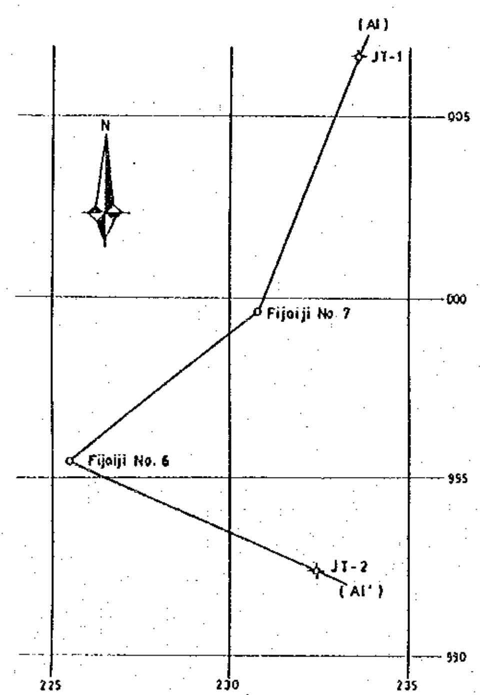
Geological Profile of the Jafr Basin

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





STRATIGRAPHIC KEY

QUATERNARY	UNDIFFERENTIATED			Mantle Rocks
				Mudflats
				Talus, Fans
QUATERNARY -TERTIARY	PLATEAU	Jafr	Ja	Lacustrine Limestone
			B	Basalt
		Humeima	H	Sandstone, Limestone
CRETACEOUS	BELQA	Rijam	B_4	Limestone, Cherts
		Muwaggar	B_3	Marls, Sandy Limestone
		Amman	B_1-B_2	Silicified Limestone, Cherts
	AJLUN	W. Sir	A_7	Sandstone, Sandy Limestone
		Lower Ajlun	A_6-A_1	Marls, Sandstone
	KURNUB	Subeihi	K_2	Sandstone, Varicoloured

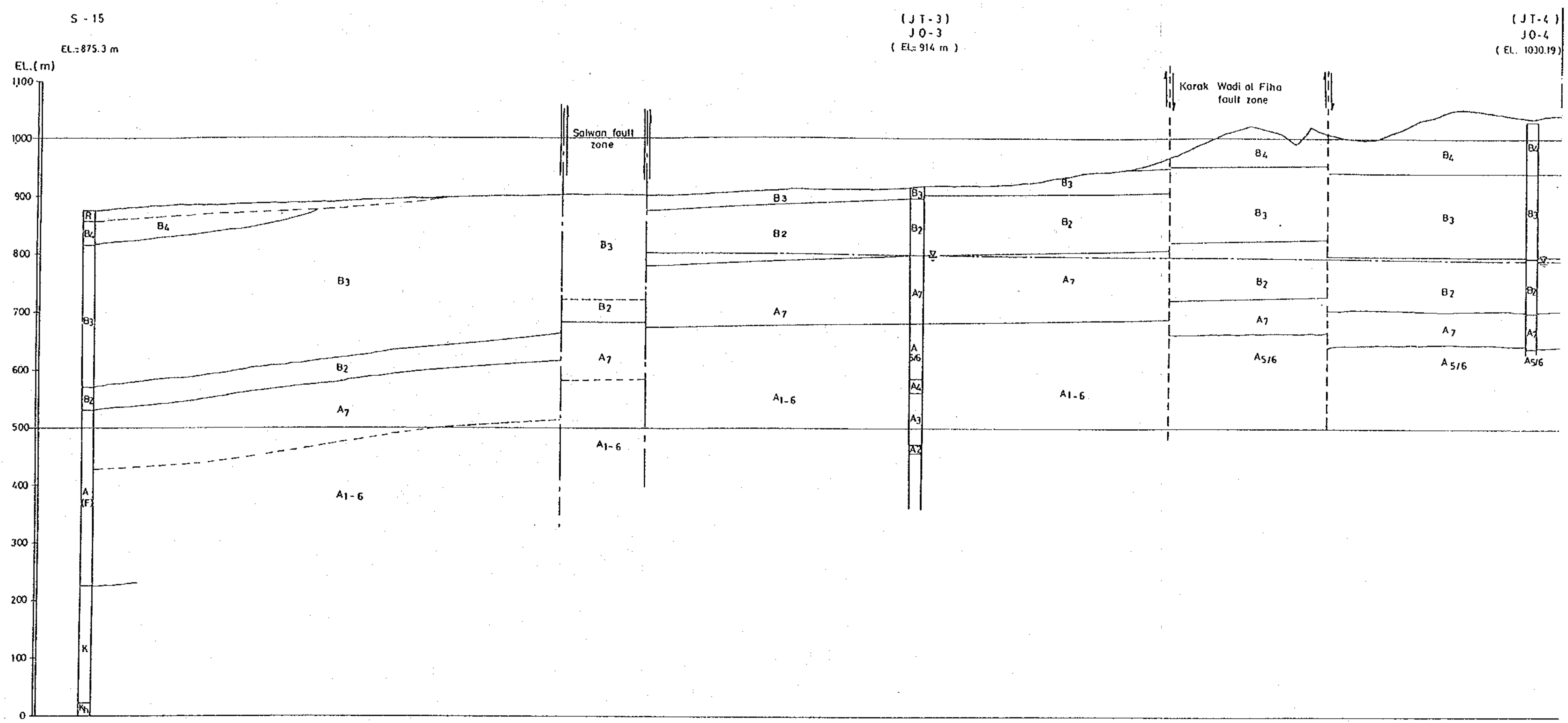
Fig.4.18

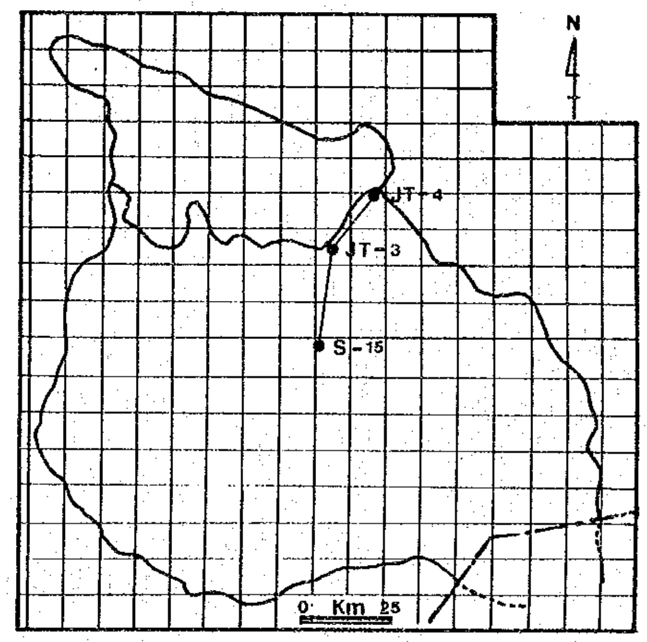
Geological Profile of Northwest Jafr Basin ; JT1-JT2

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





STRTIGRAPHIC KEY

QUATERNARY	UNDIFFERENTIATED			Mantle Rocks
				Mudflats
				Talus, Fans
QUATERNARY -TERTIARY	PLATEAU	Jafr	Ja	Lacustrine Limestone
			B	Basalt
		Humeima	H	Sandstone, Limestone
CRETACEOUS	BELQA	Rijam	B_4	Limestone, Cherts
		Muwaggar	B_3	Marls, Sandy Limestone
		Amman	B_1-B_2	Silicified Limestone, Cherts
	AJLUN	W. Sir	A_7	Sandstone, Sandy Limestone
		Lower Ajlun	A_6-A_1	Marls, Sandstone
	KURNUB	Subeihi	K_2	Sandstone, Varicoloured

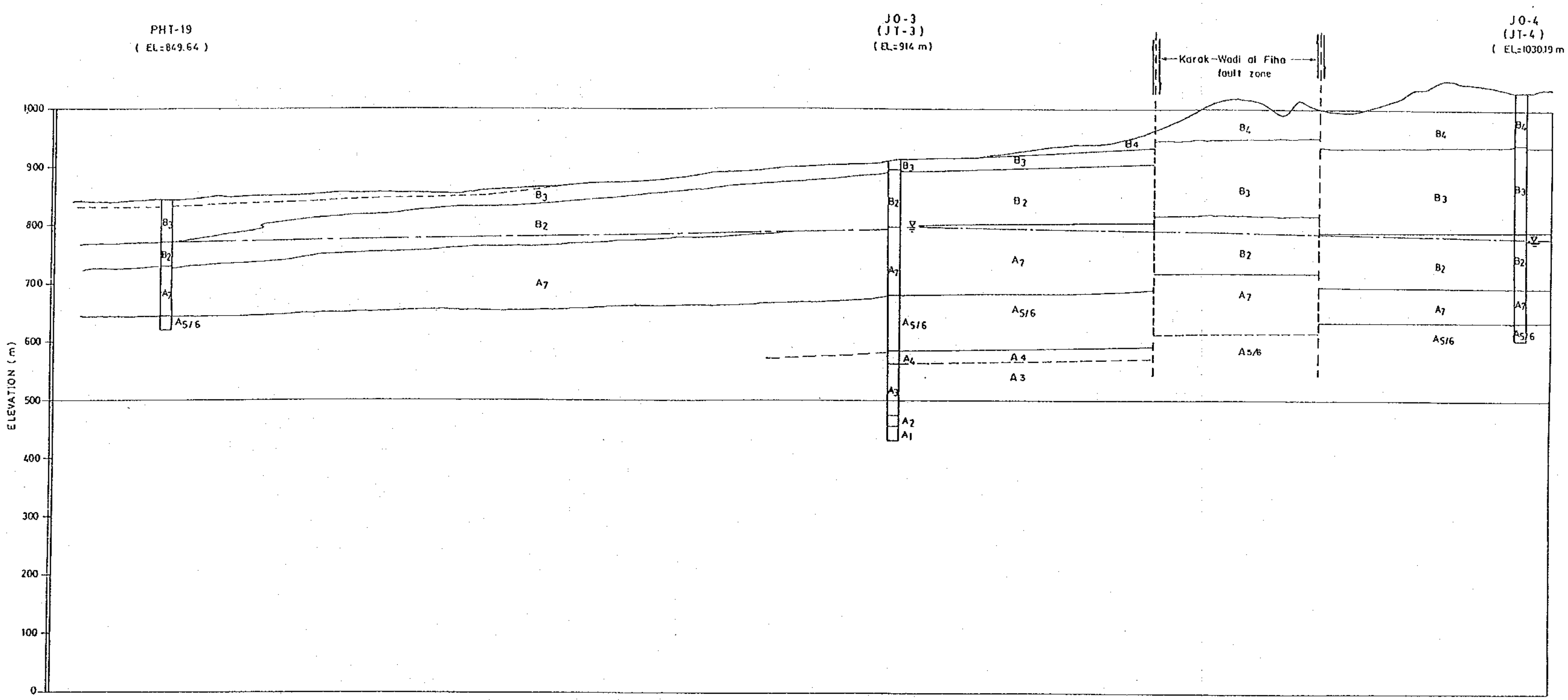
Fig.4.19

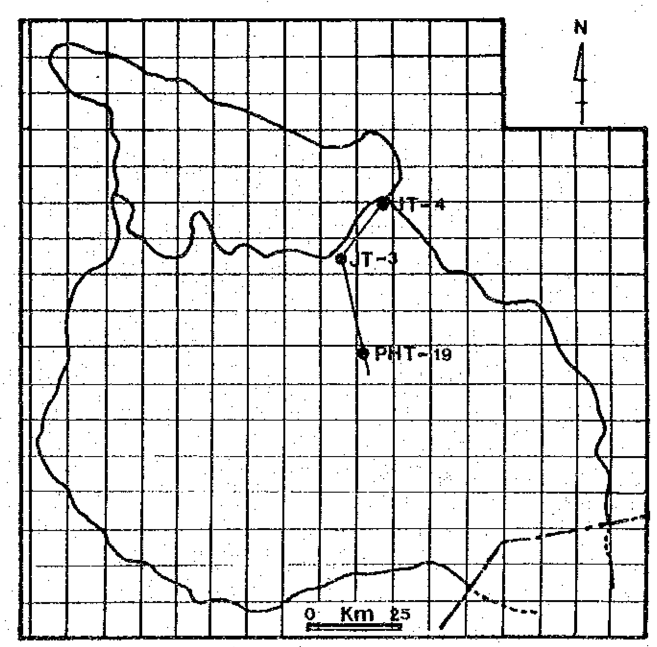
Geological Profile of Northeast Jafr Basin (1/2) ; JT3-JT4

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





STIRTIGRAPHIC KEY

QUATERNARY	UNDIFFERENTIATED			Mantle Rocks
				Mudflats
				Talus, Fans
QUATERNARY -TERTIARY	PLATEAU	Jafr	Ja	Locustrine Limestone
			B	Basalt
		Humeima	H	Sandstone, Limestone
CRETACEOUS	BELQA	Rijam	B_4	Limestone, Cherts
		Muwaggar	B_3	Marls, Sandy Limestone
		Amman	B_1-B_2	Silicified Limestone, Cherts
	AJLUN	W. Sir	A_7	Sandstone, Sandy Limestone
		Lower Ajlun	A_6-A_1	Marls, Sandstone
	KURNUB	Subeihi	K_2	Sandstone, Varicoloured

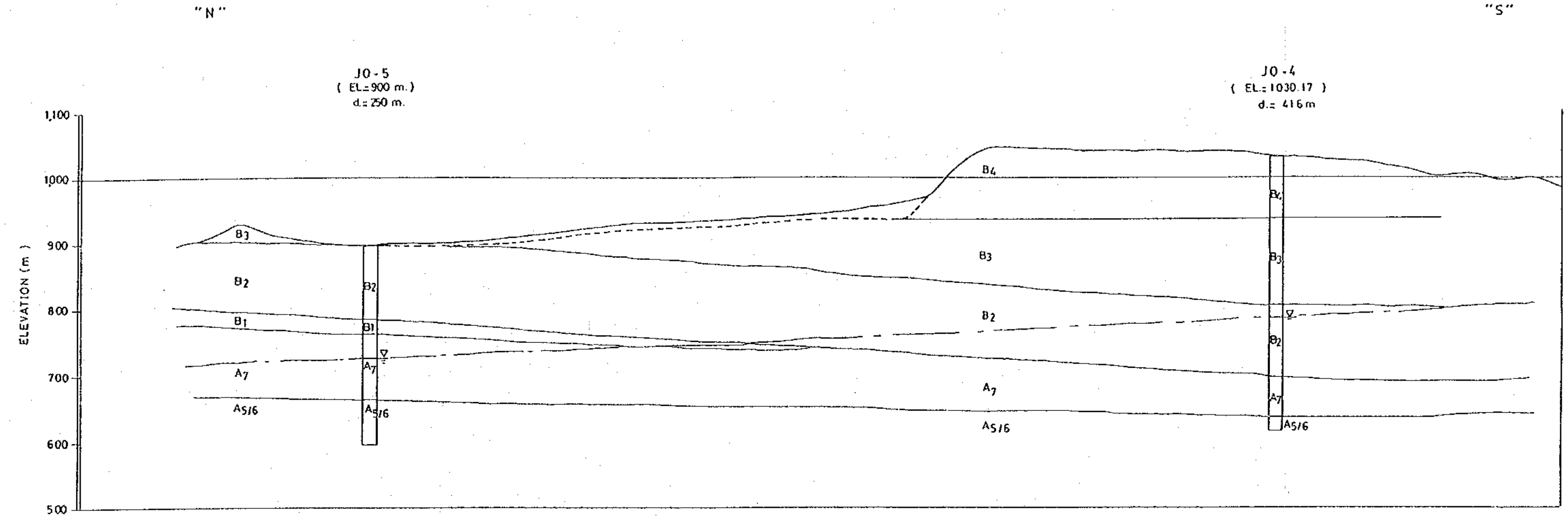
Fig.4.20

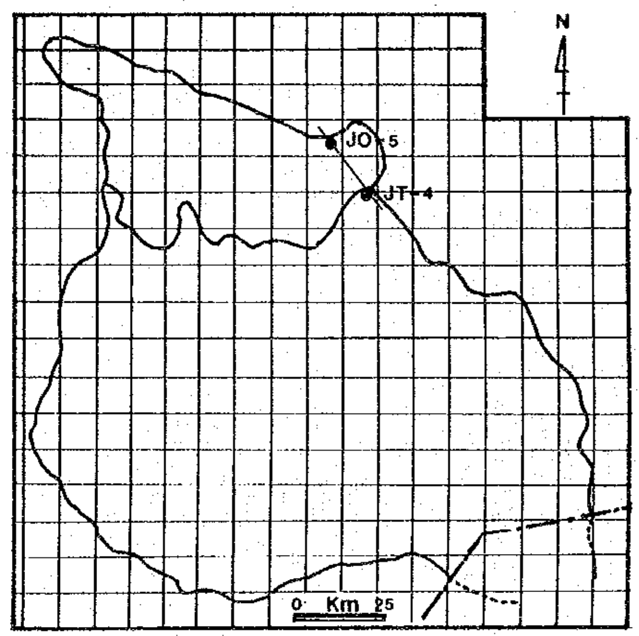
Geological Profile of Northeast Jafr Basin (2/2) : JT3-JT4

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





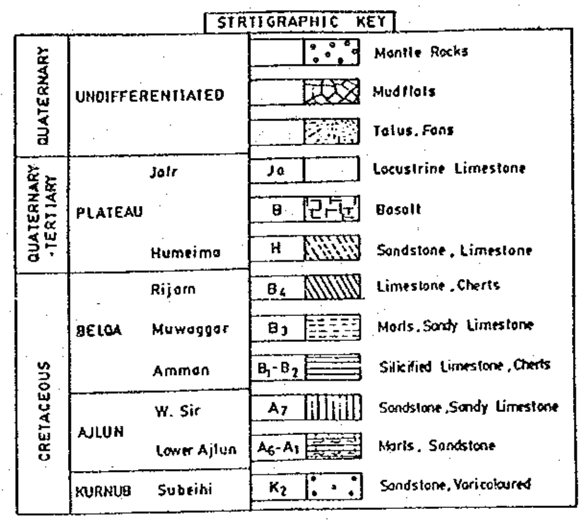


Fig.4.21

Geological Profile of East

Upper Hasa Basin : JO-5

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

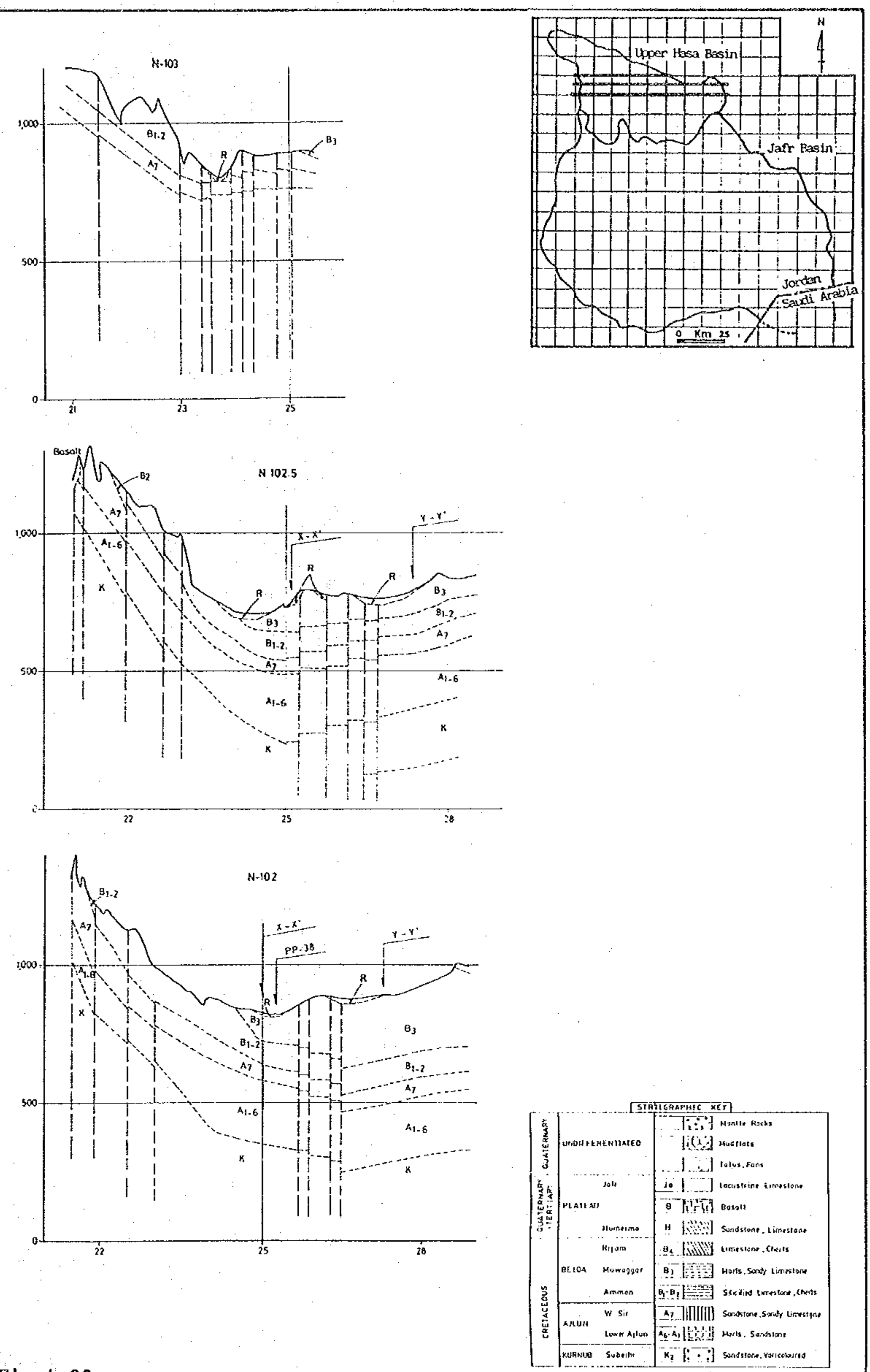


Fig.4.22

Geological Profile 1

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

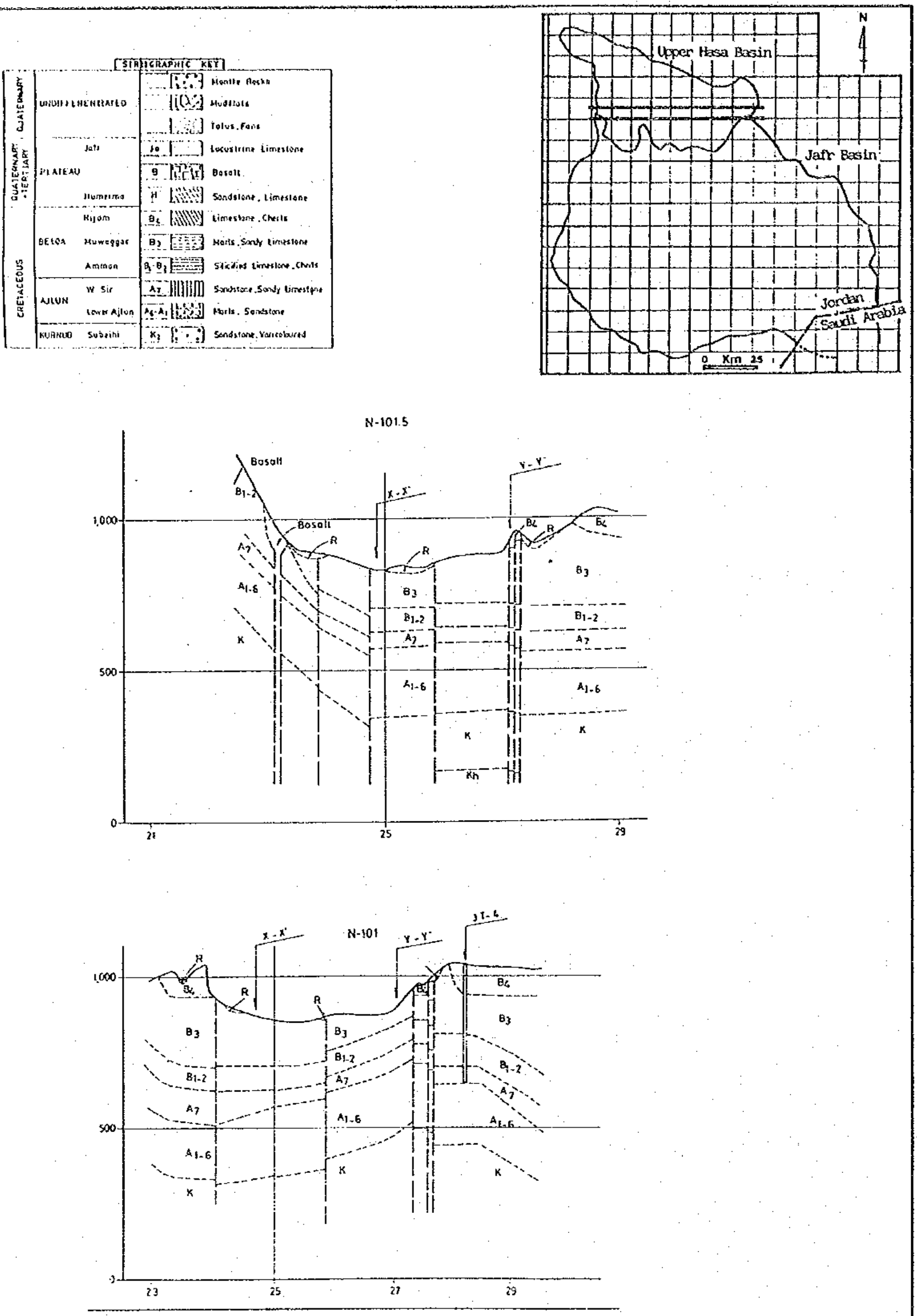


Fig.4.23

Geological Profile 2

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

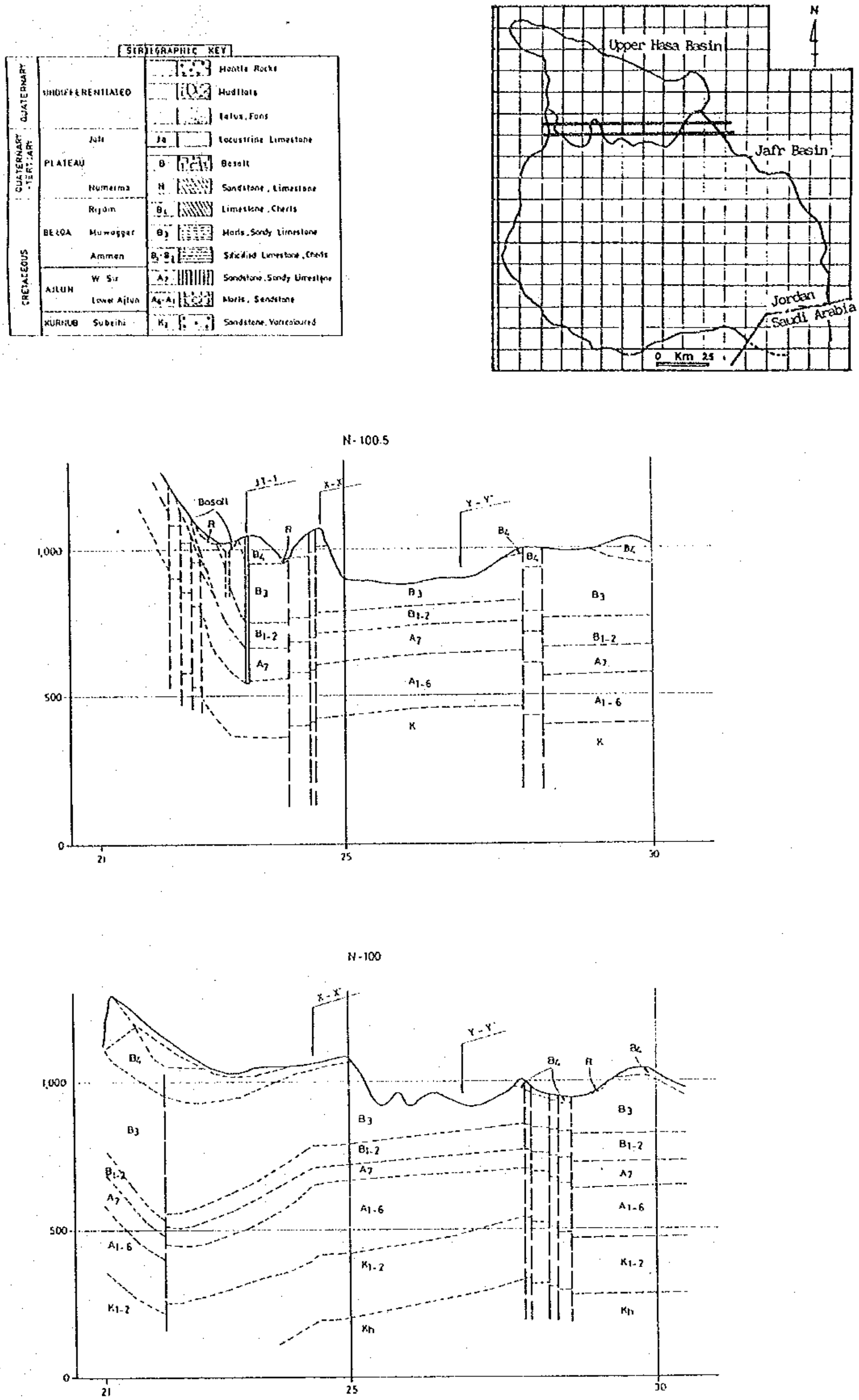


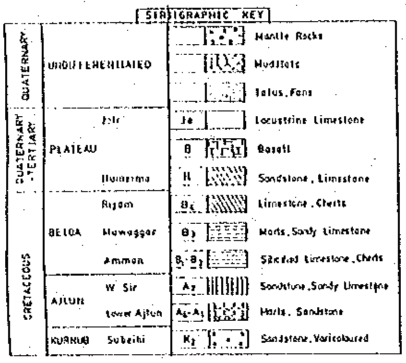
Fig.4.24

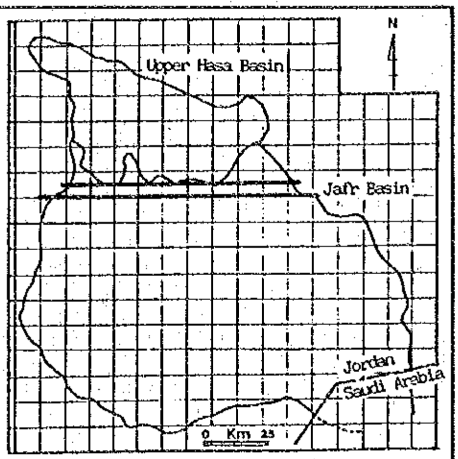
Geological Profile 3

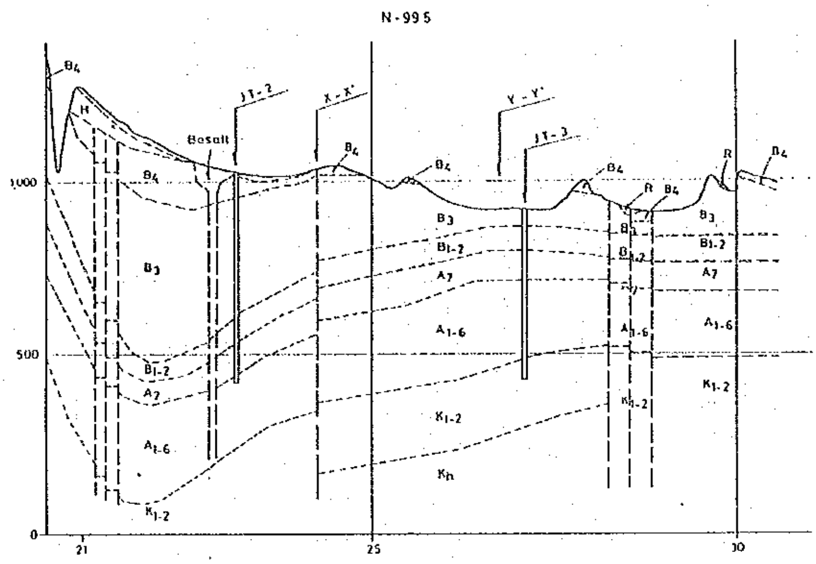
THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY







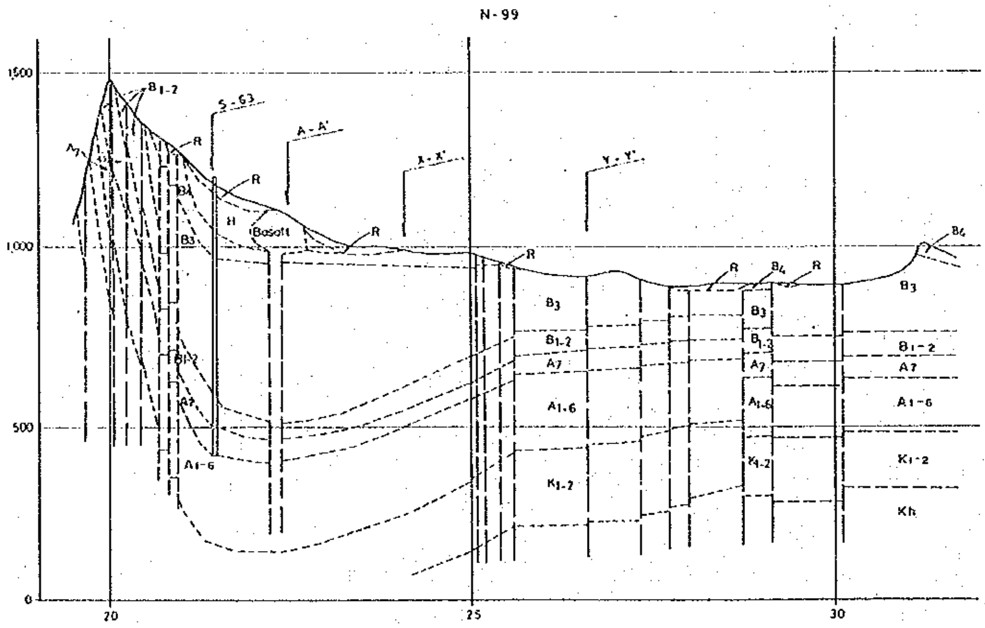


Fig.4.25

Geological Profile 4

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

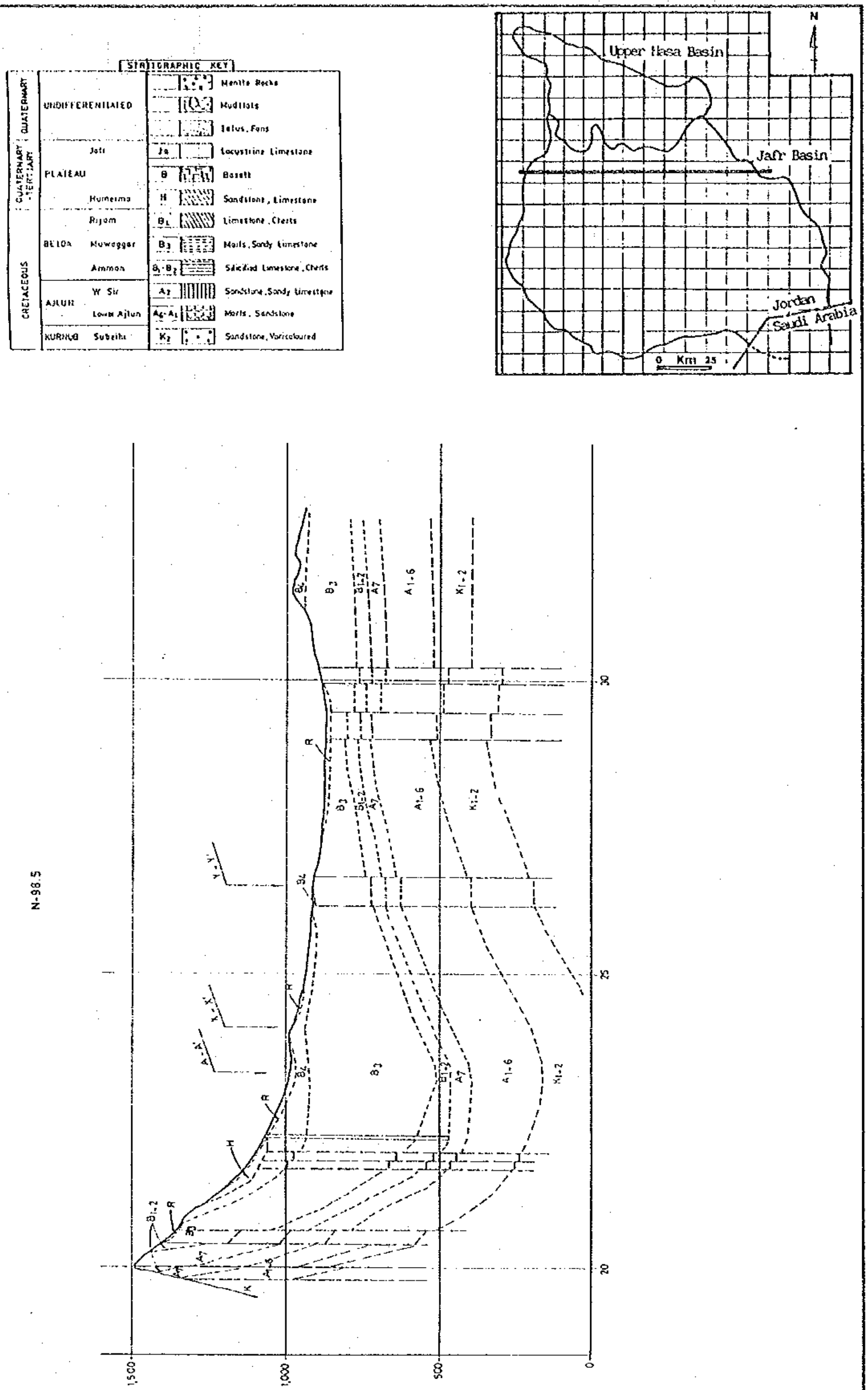


Fig.4.26

Geological Profile 5

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

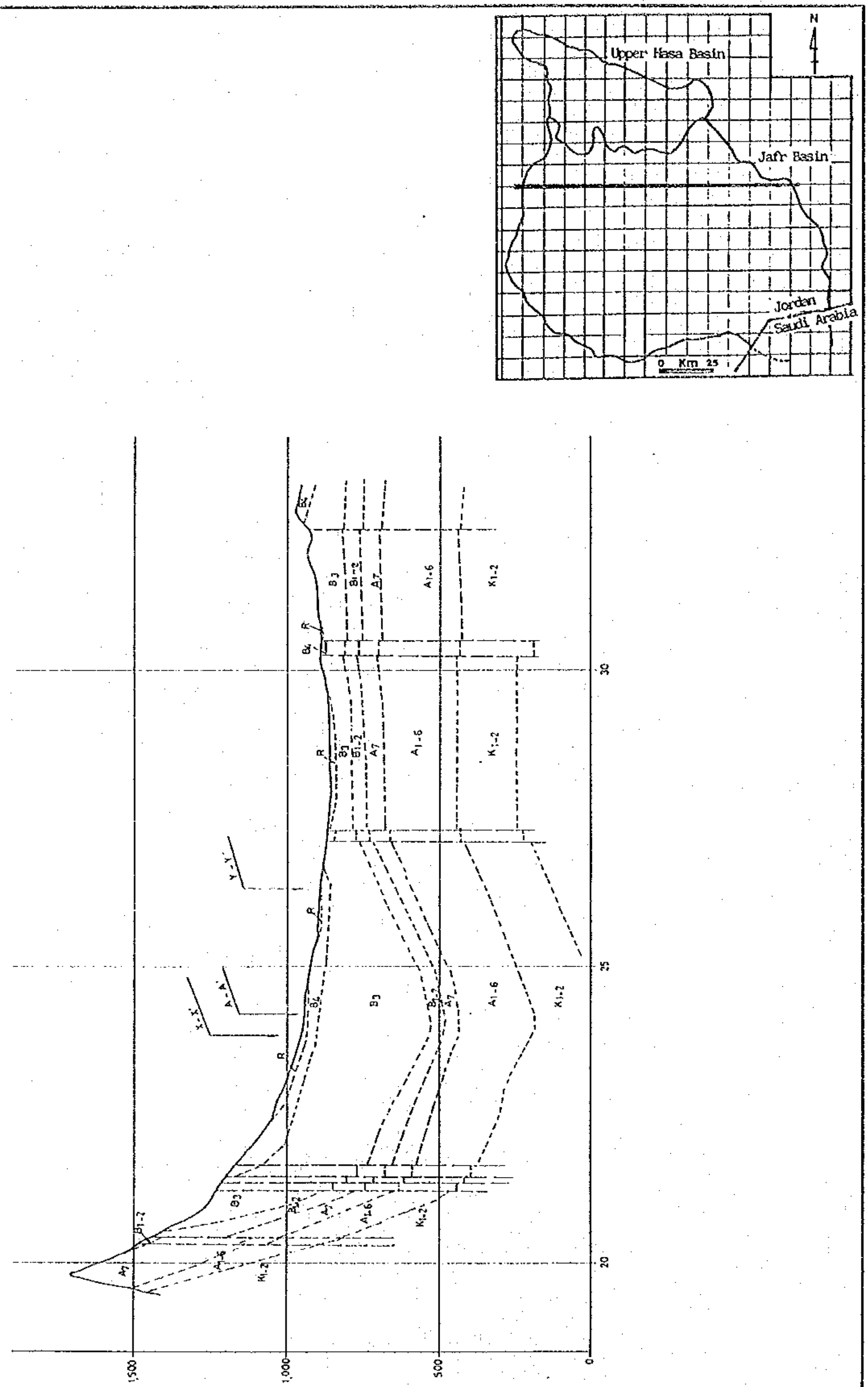


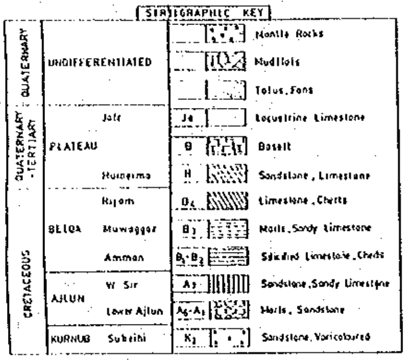
Fig.4.27

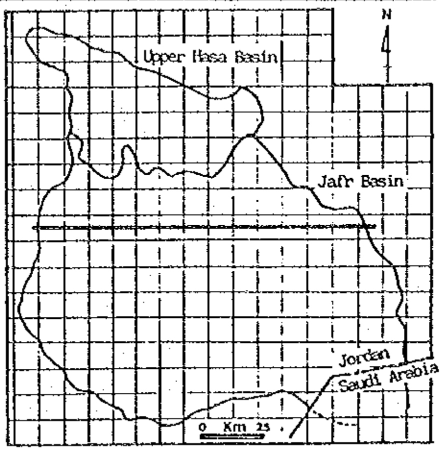
Geological Profile 6

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





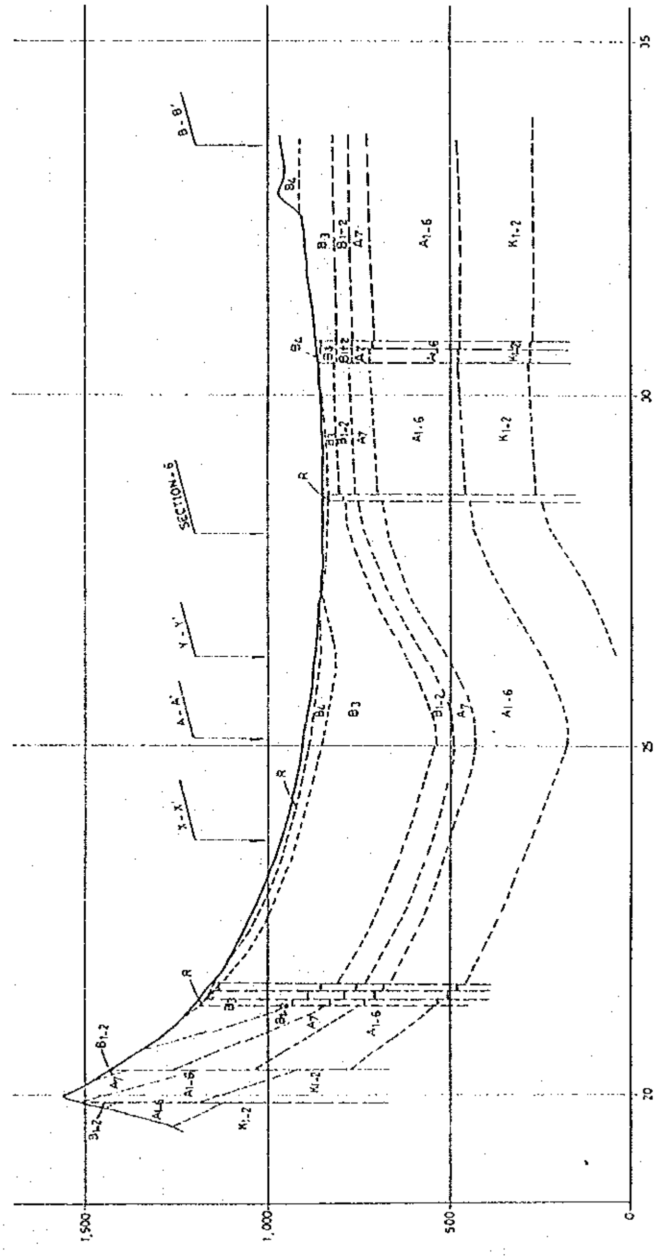


Fig.4.28

Geological Profile 7

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

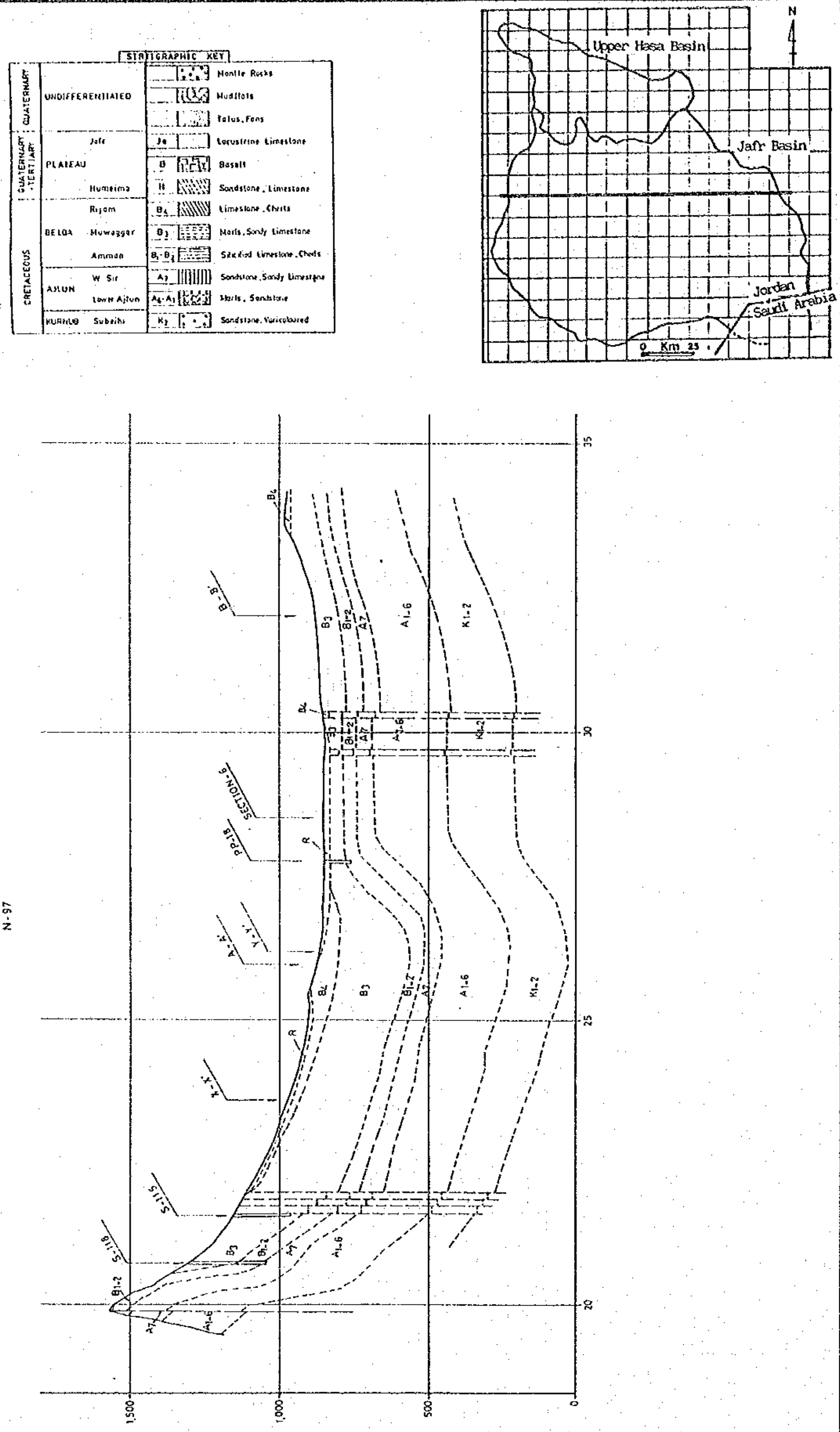


Fig.4.29

Geological Profile 8

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

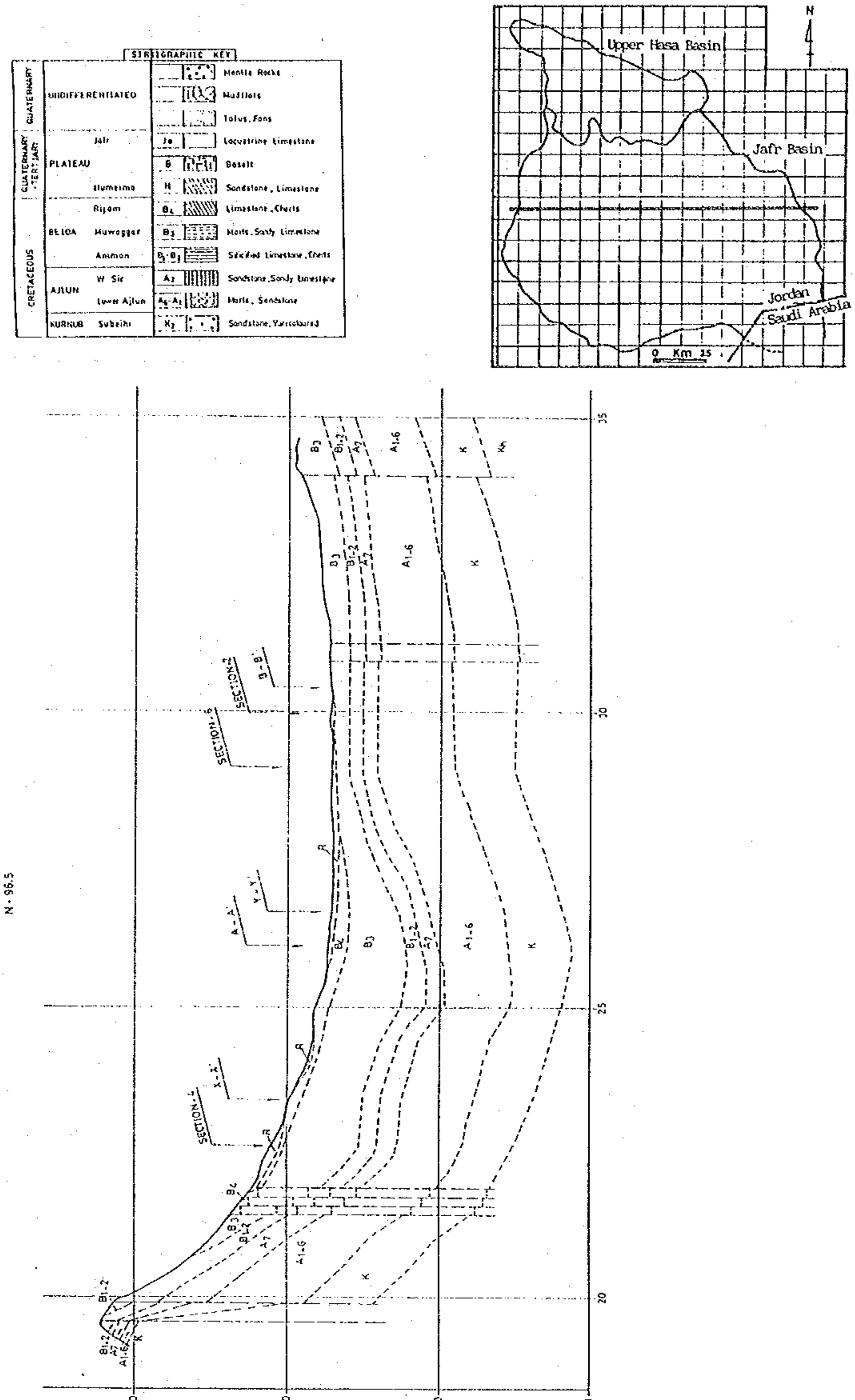


Fig.4.30

Geological Profile 9

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

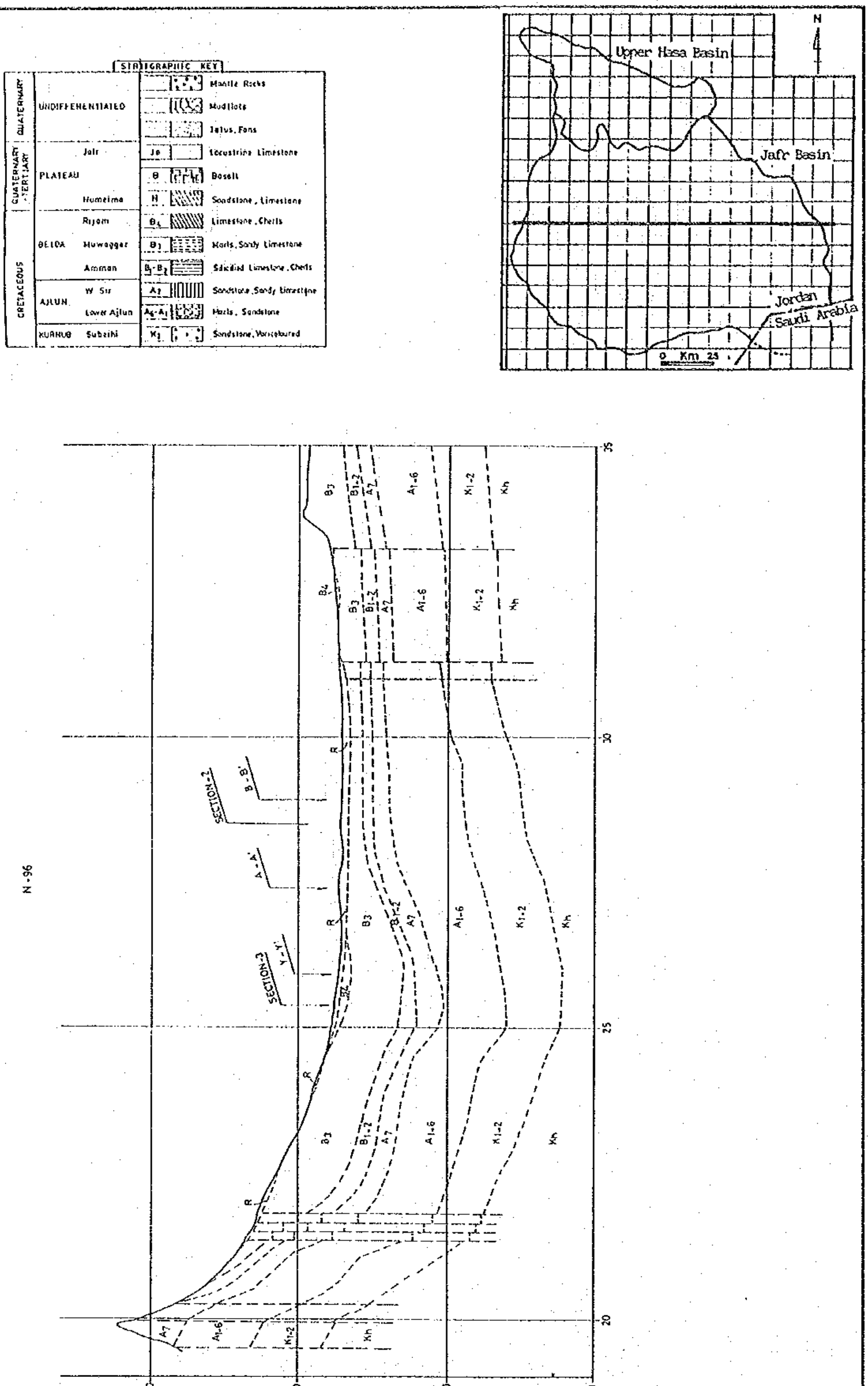


Fig.4.31

Geological Profile 10

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

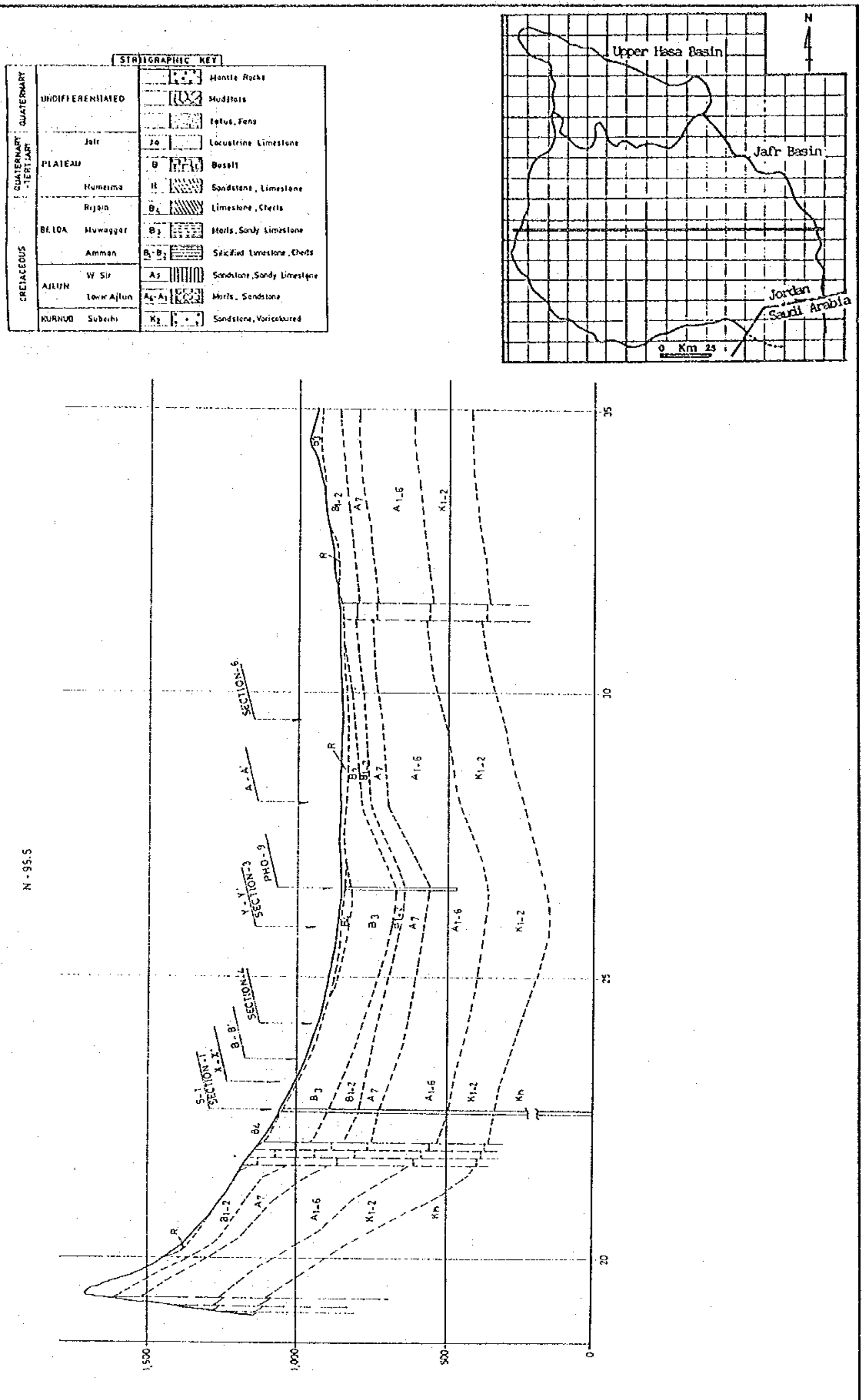


Fig.4.32

Geological Profile 11

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

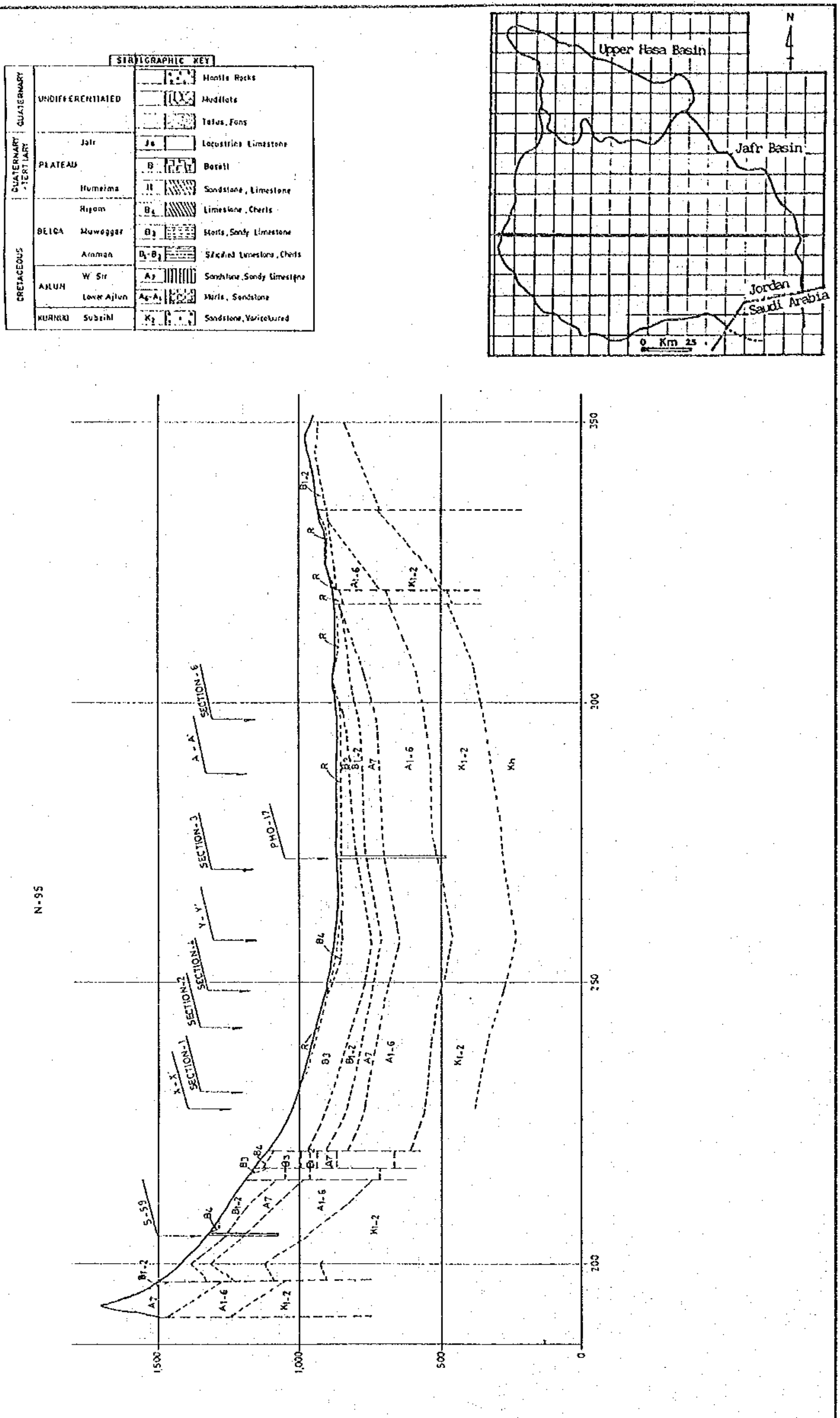


Fig.4.33

Geological Profile 12

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

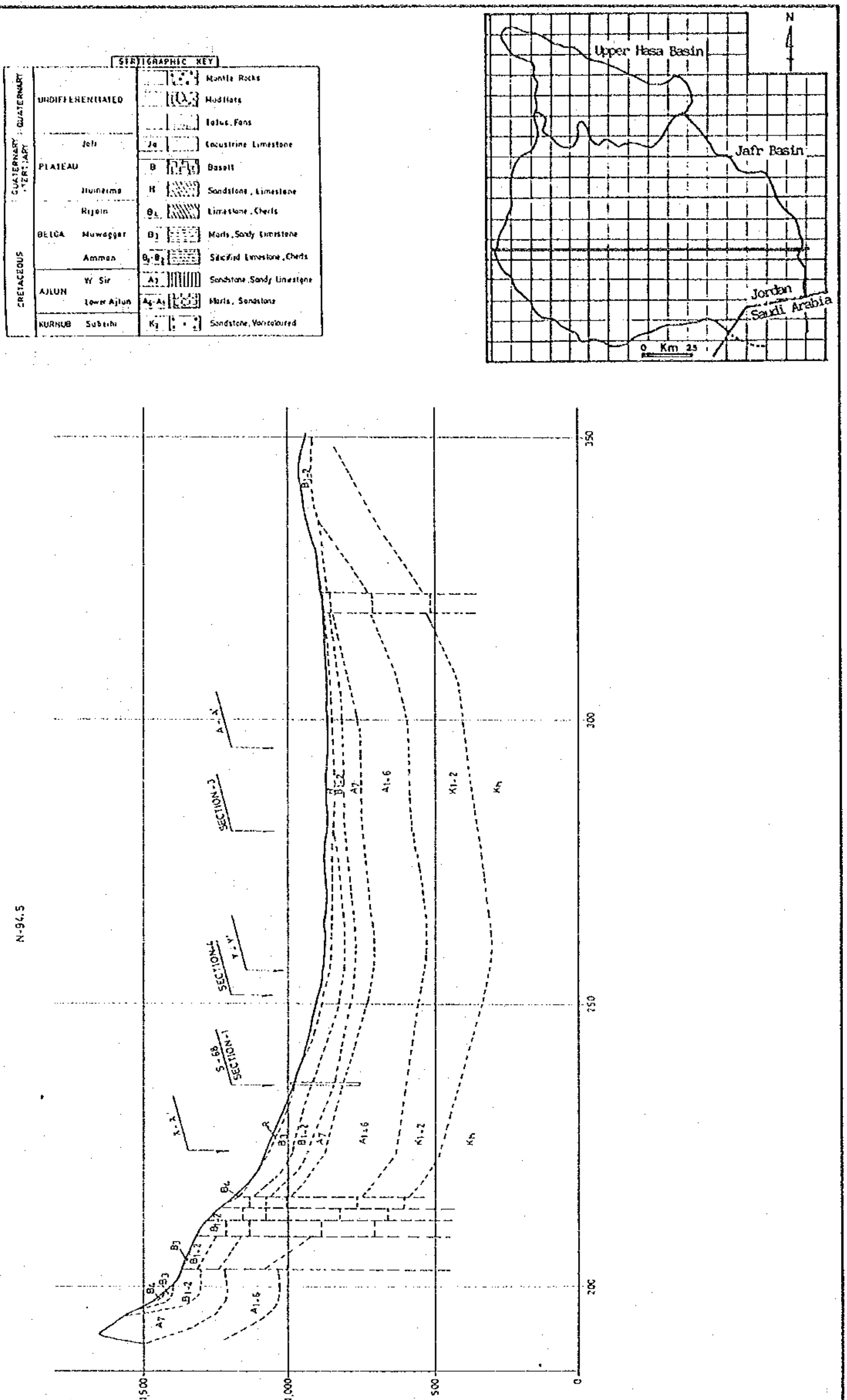


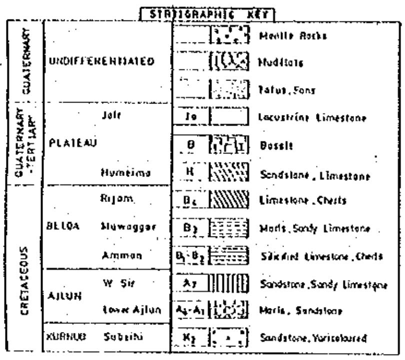
Fig.4.34

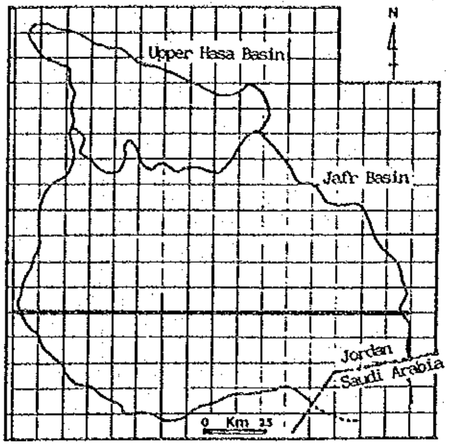
Geological Profile 13

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





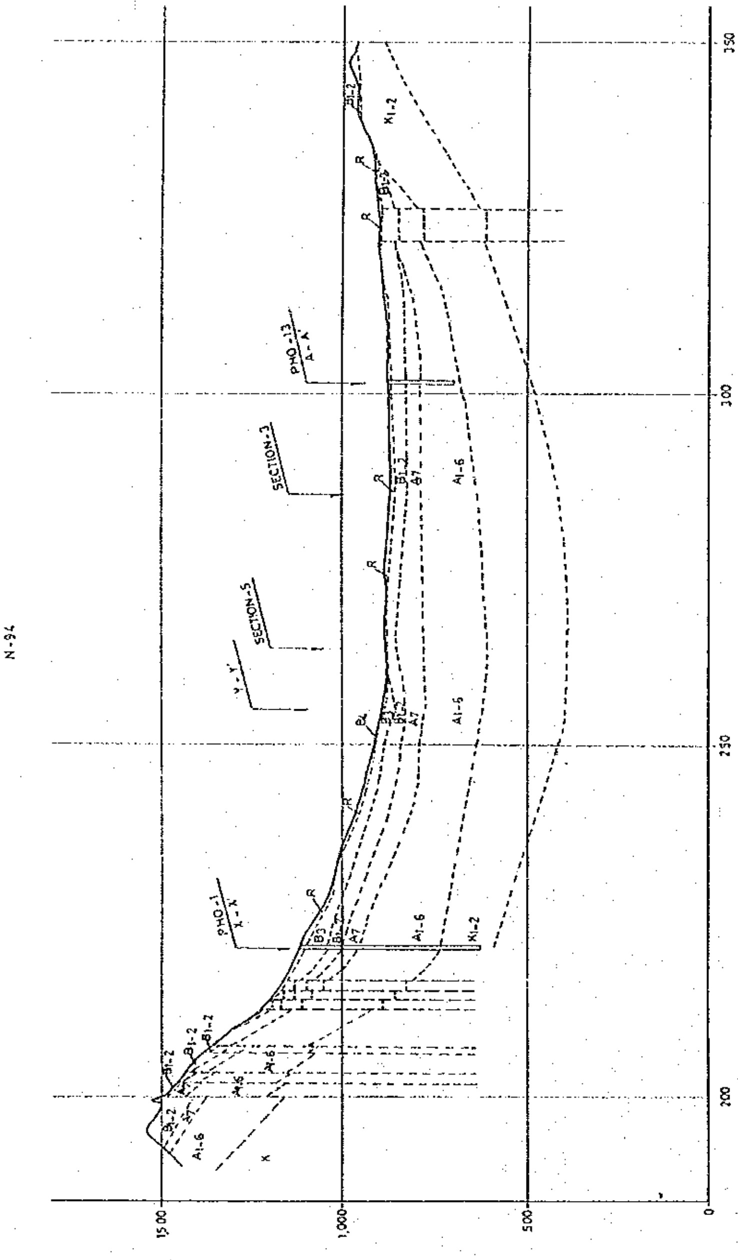


Fig.4.35

Geological Profile 14

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

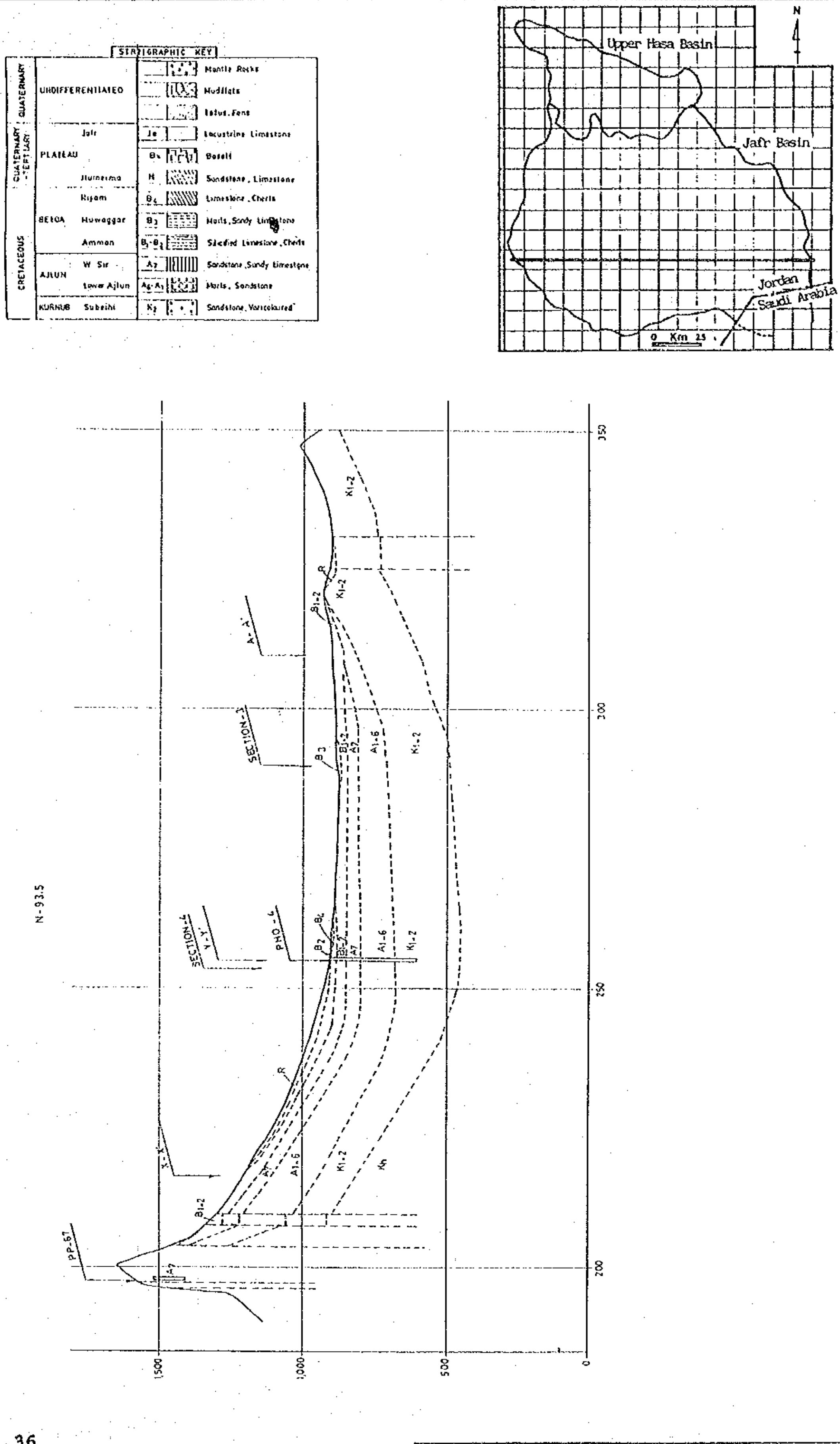


Fig.4.36

Geological Profile 15

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

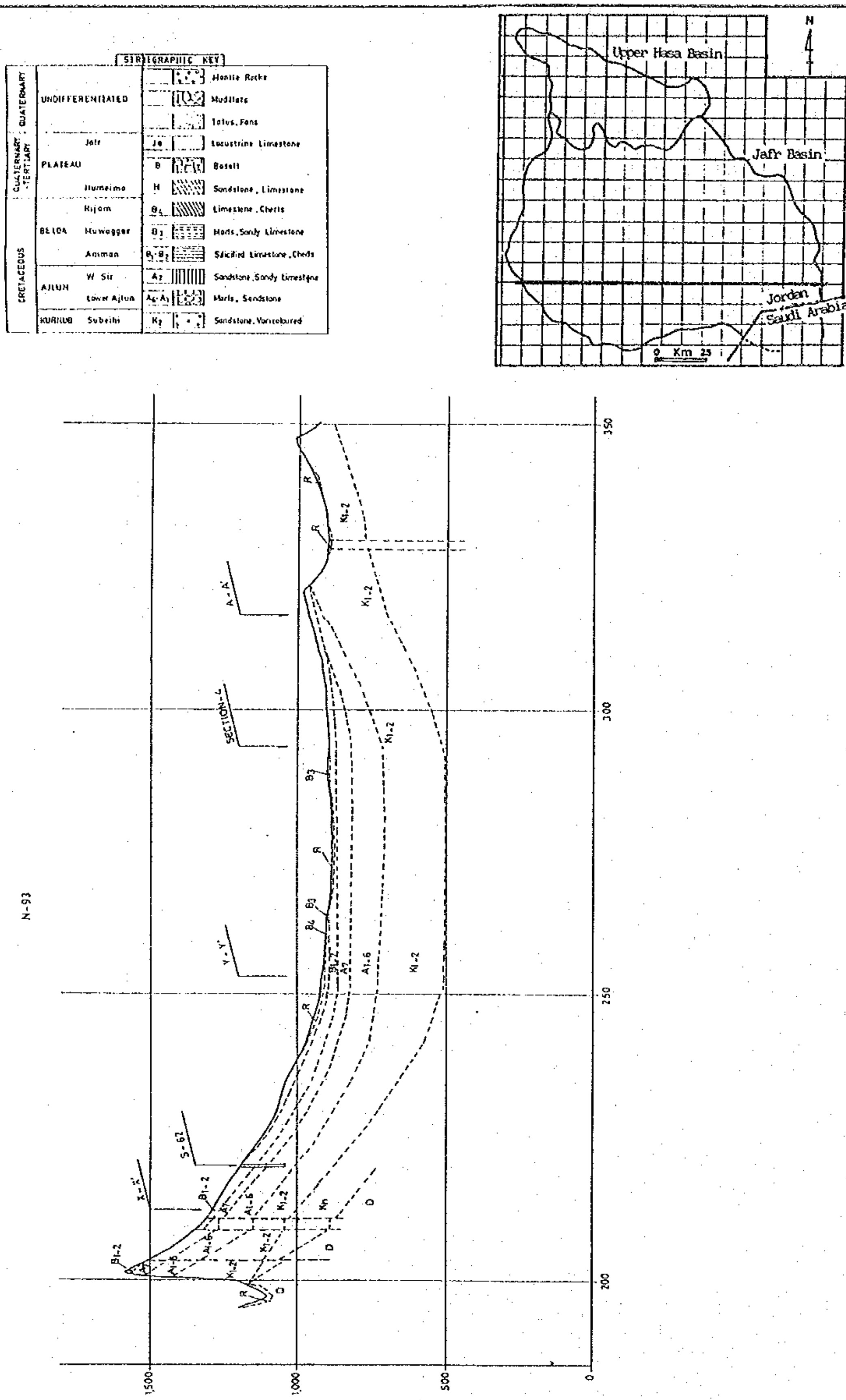


Fig.4.37

Geological Profile 16

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

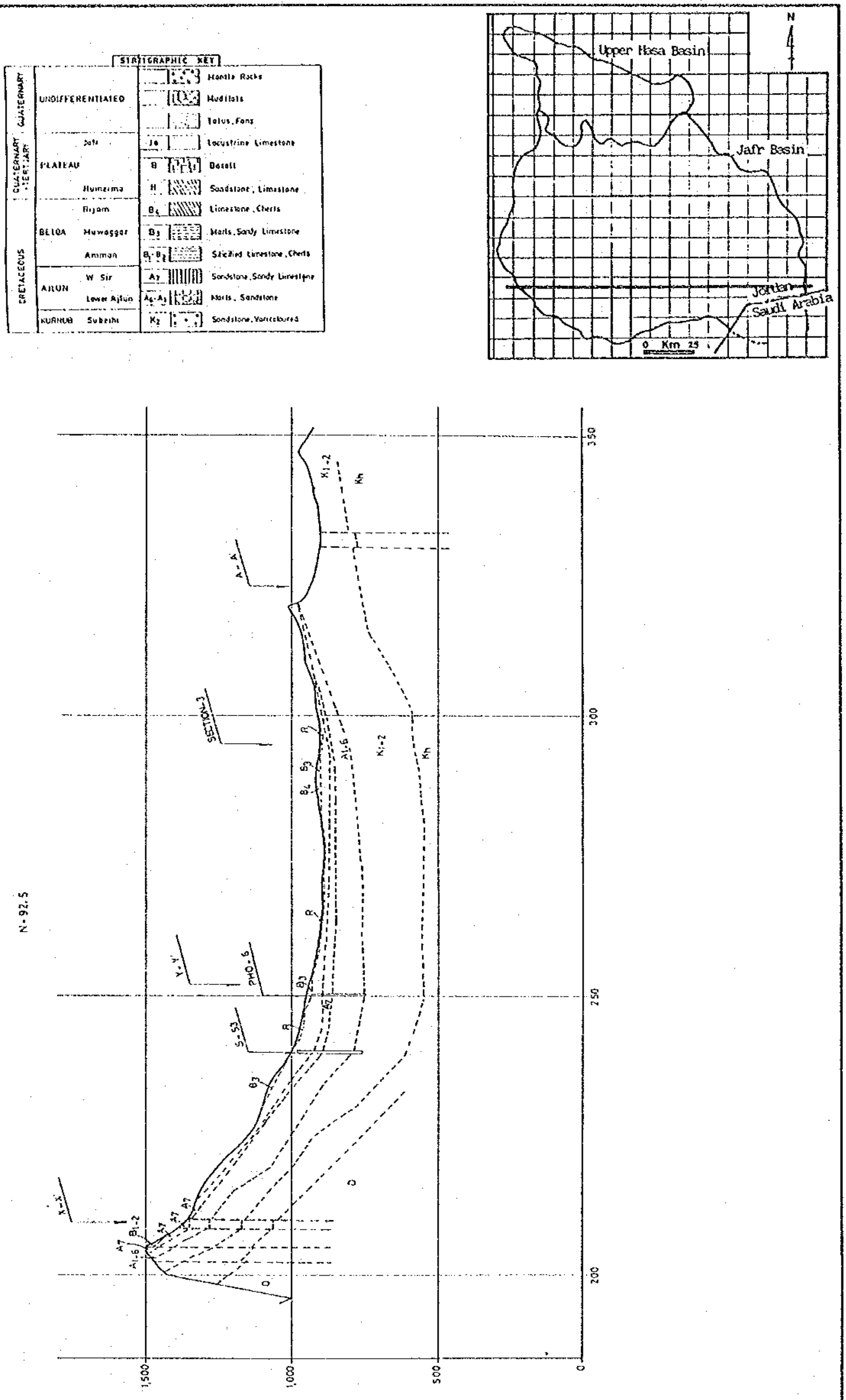


Fig.4.38

Geological Profile 17

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

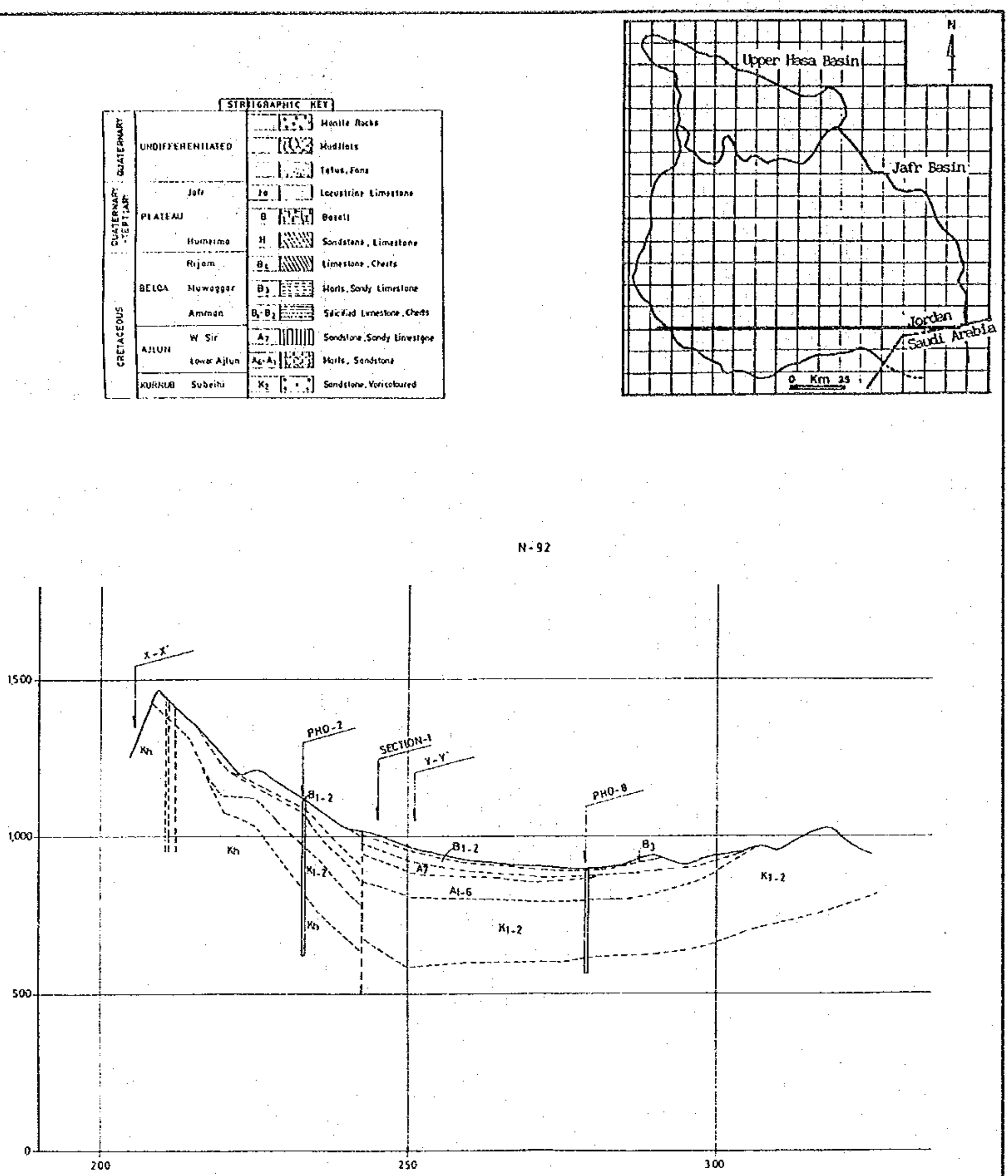


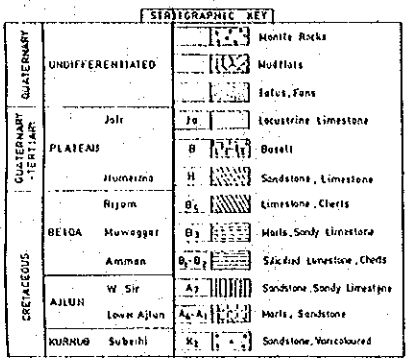
Fig.4.39

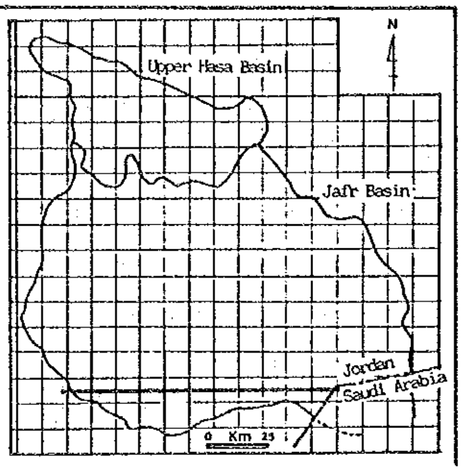
Geological Profile 18

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





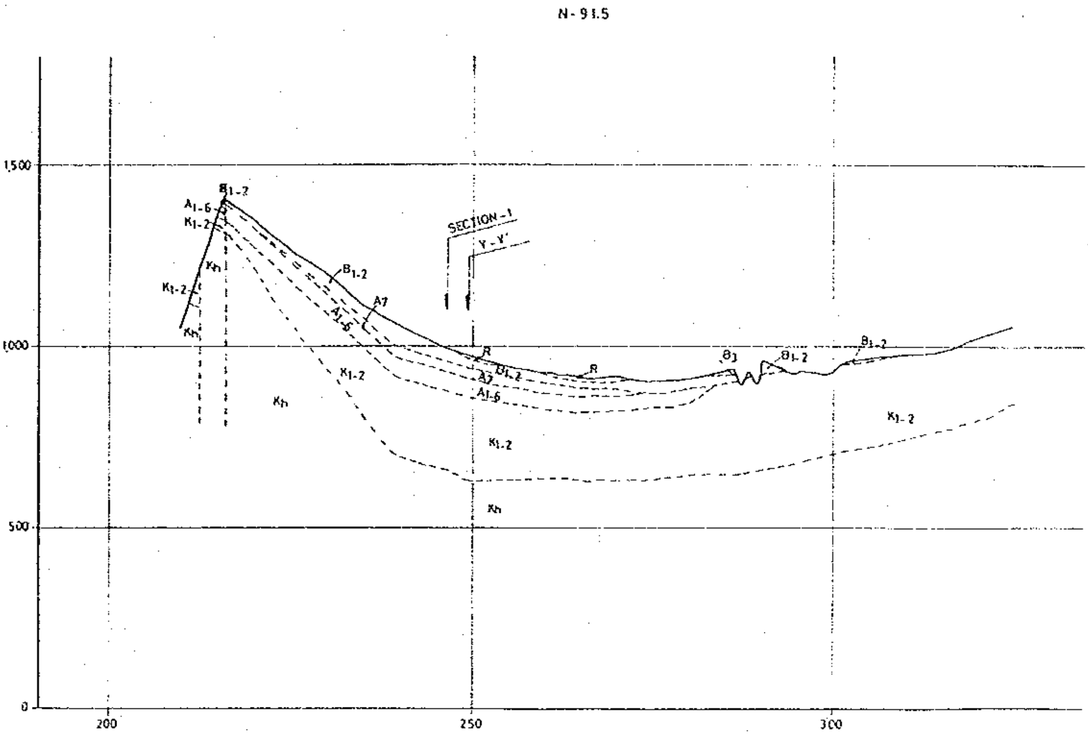


Fig.4.40

Geological Profile 19

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

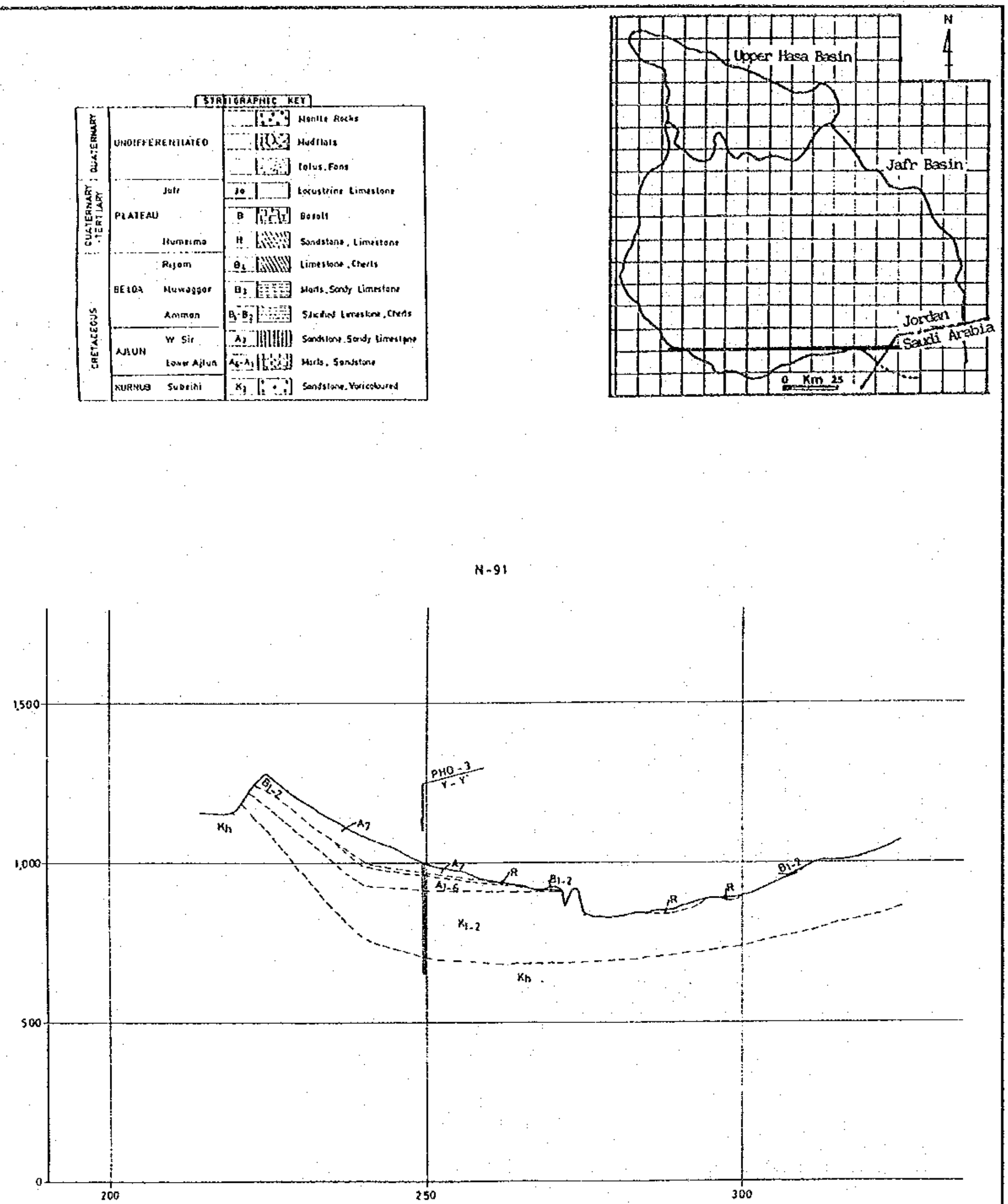


Fig.4.41

Geological Profile 20

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

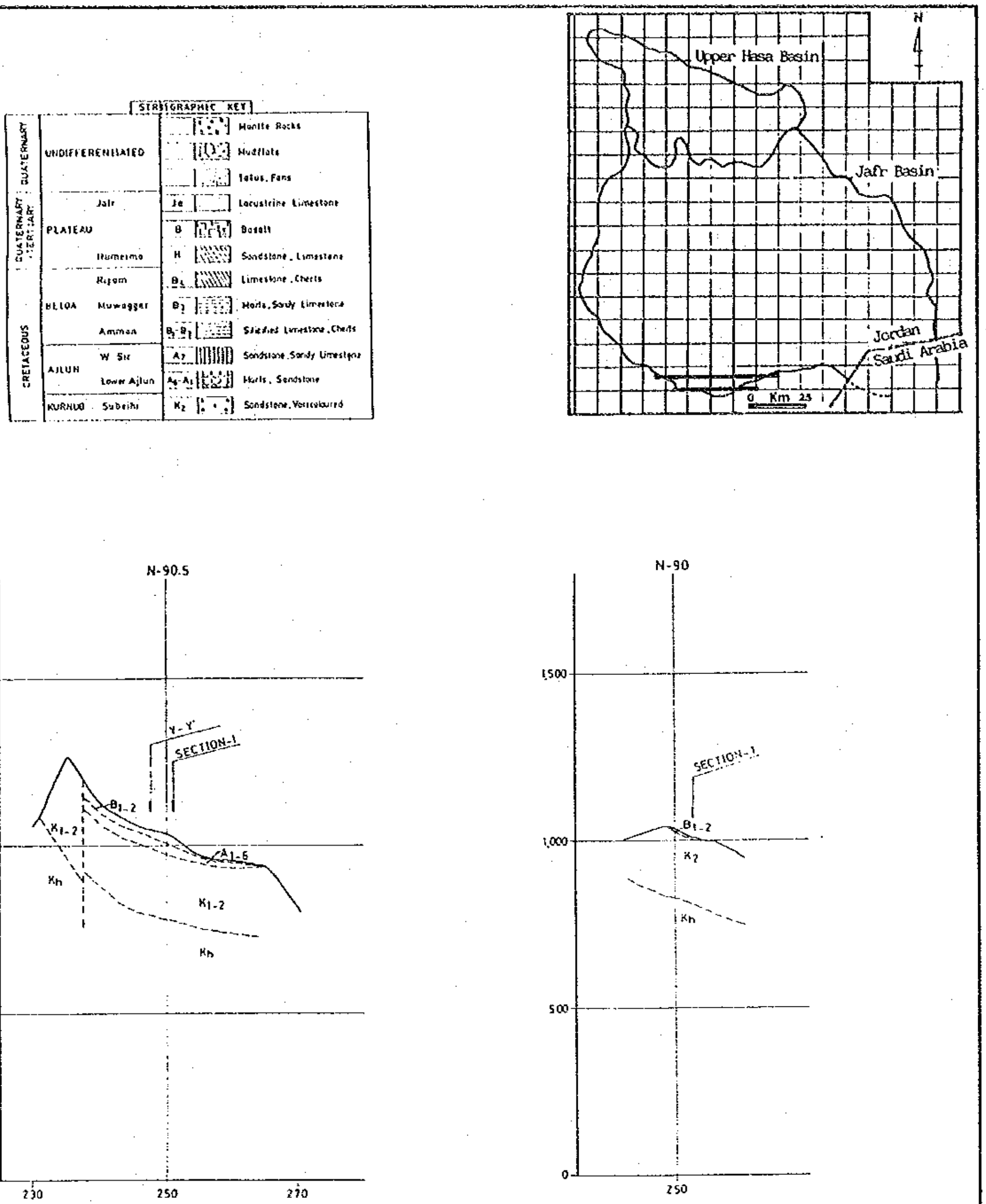


Fig.4.42

Geological Profile 21

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

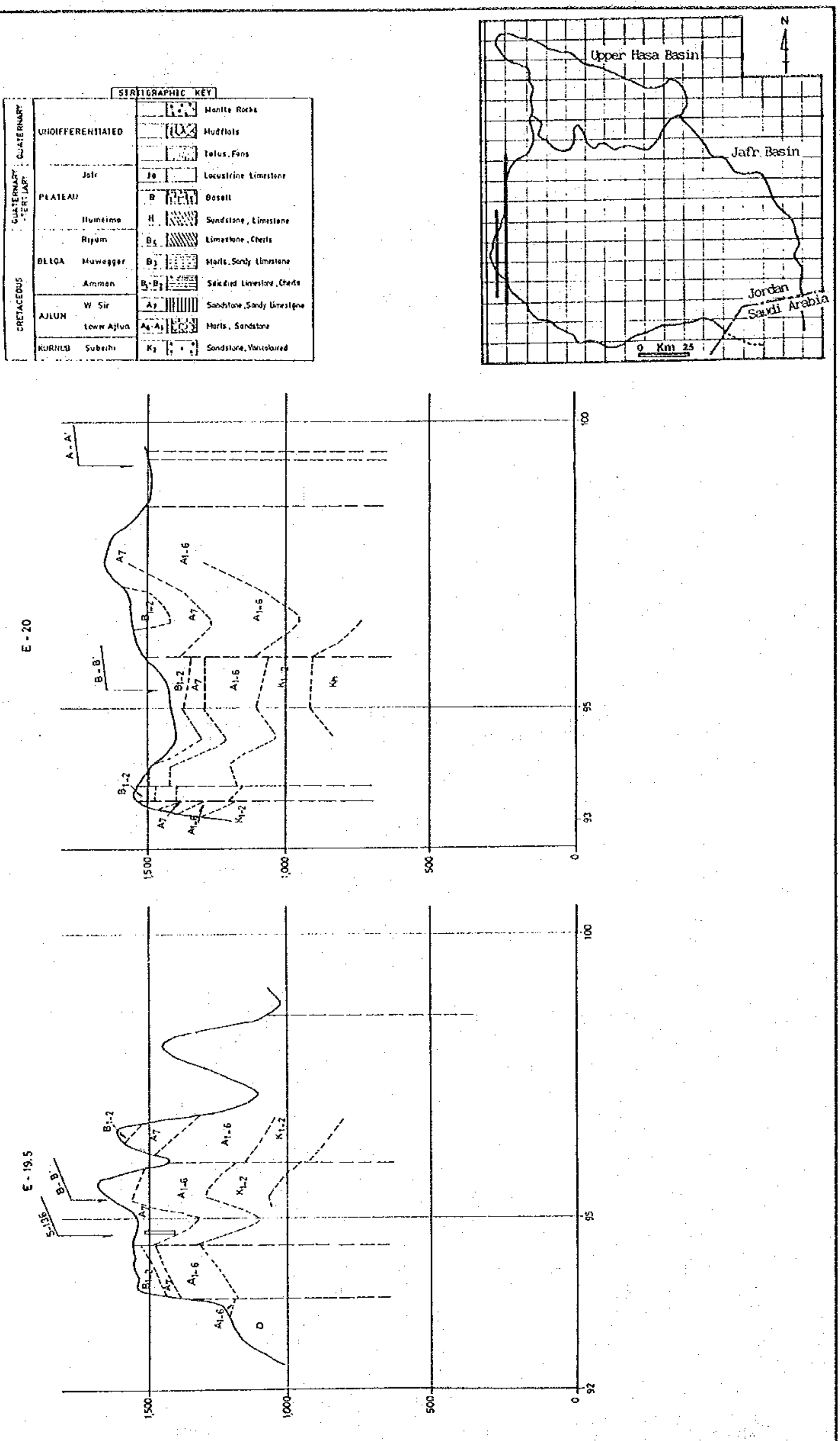


Fig.4.43

Geological Profile 22

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

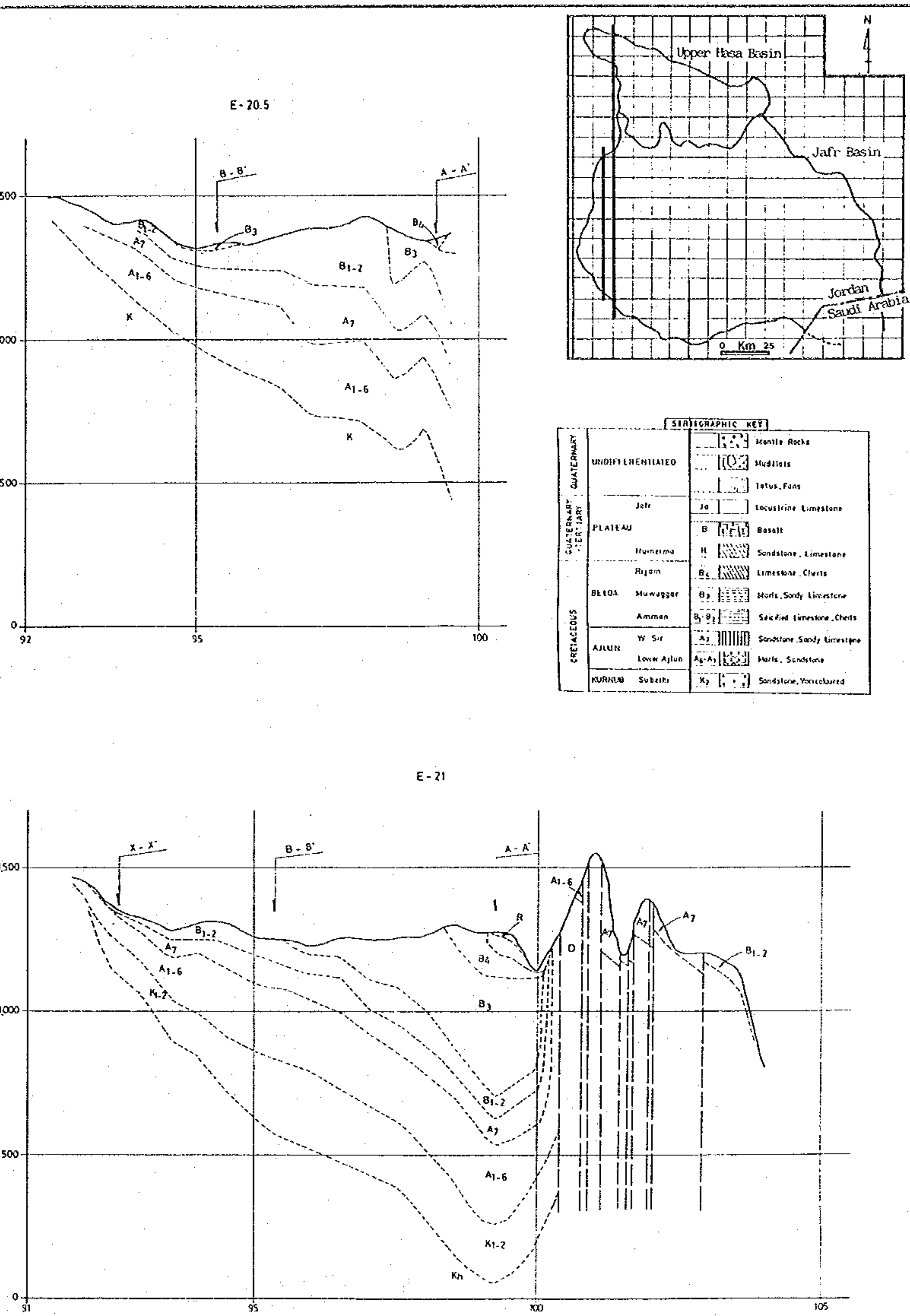


Fig.4.44

Geological Profile 23

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

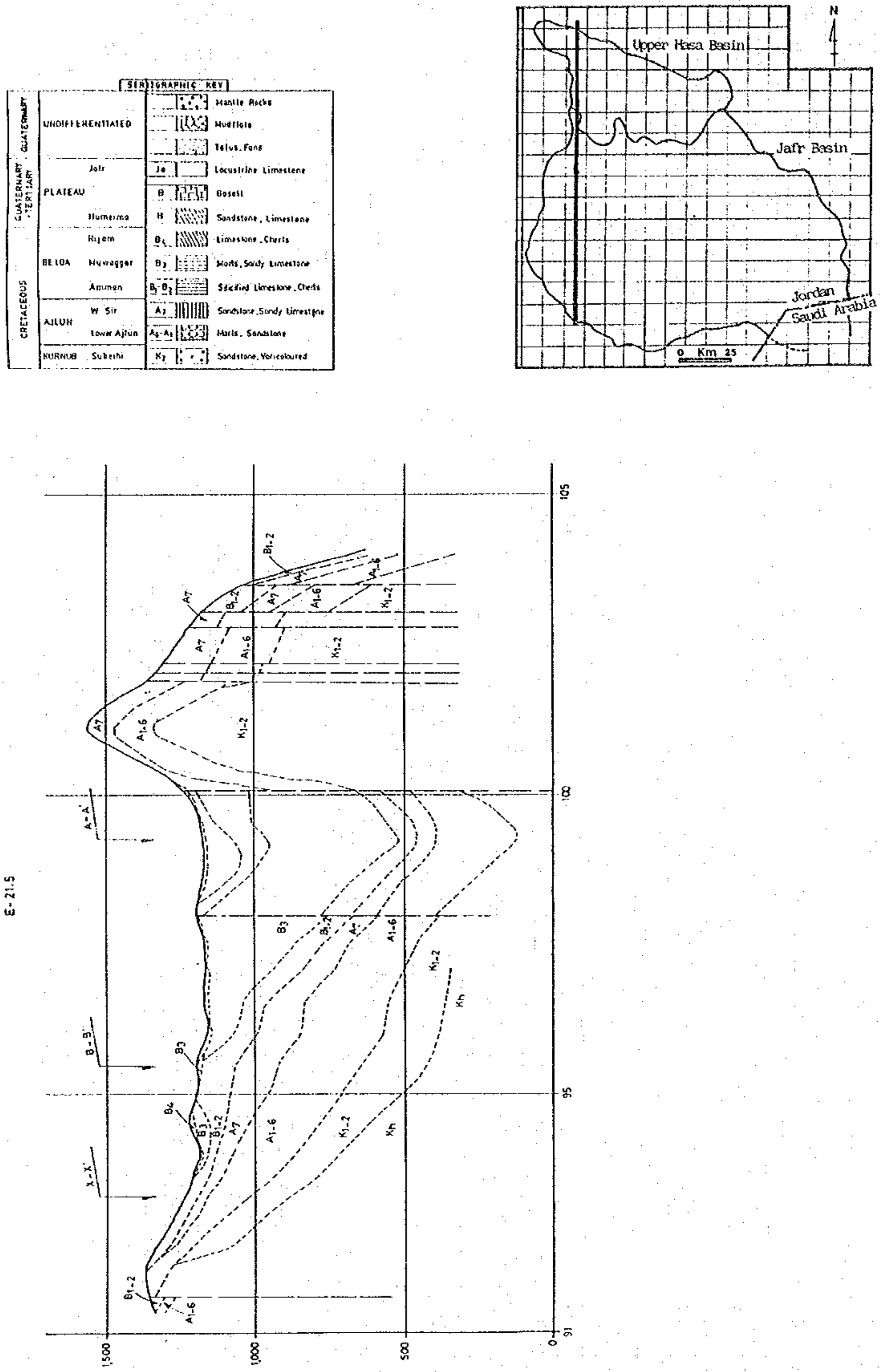


Fig.4.45

Geological Profile 24

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

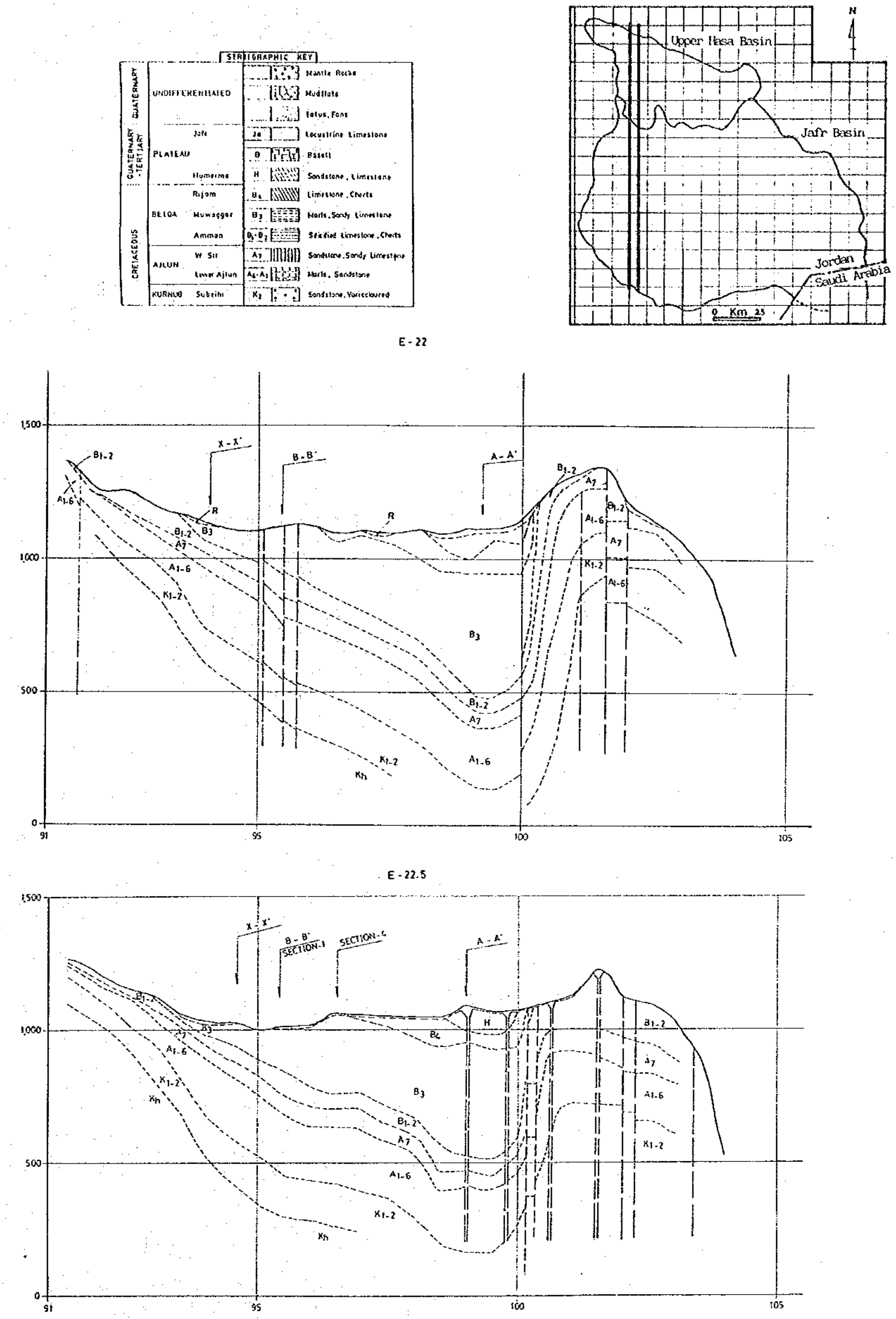


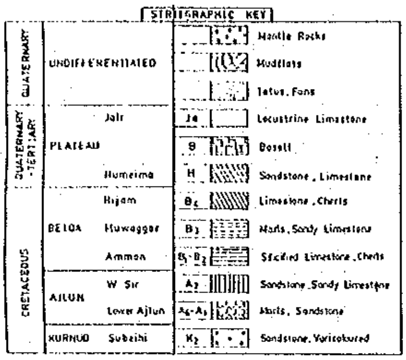
Fig.4.46

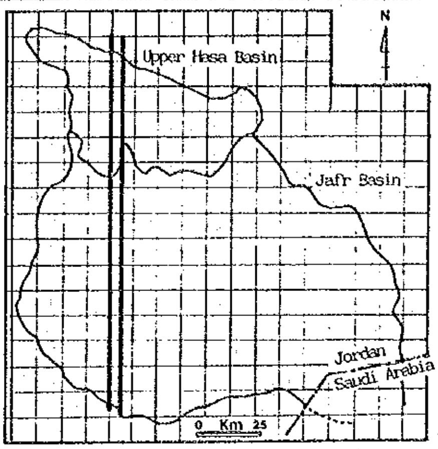
Geological Profile 25

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





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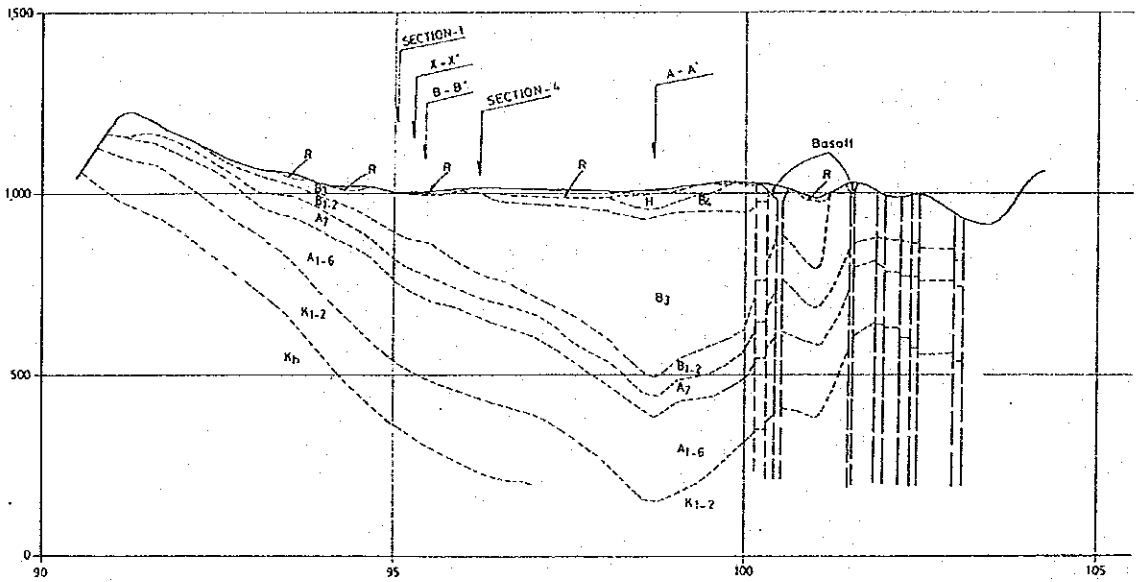

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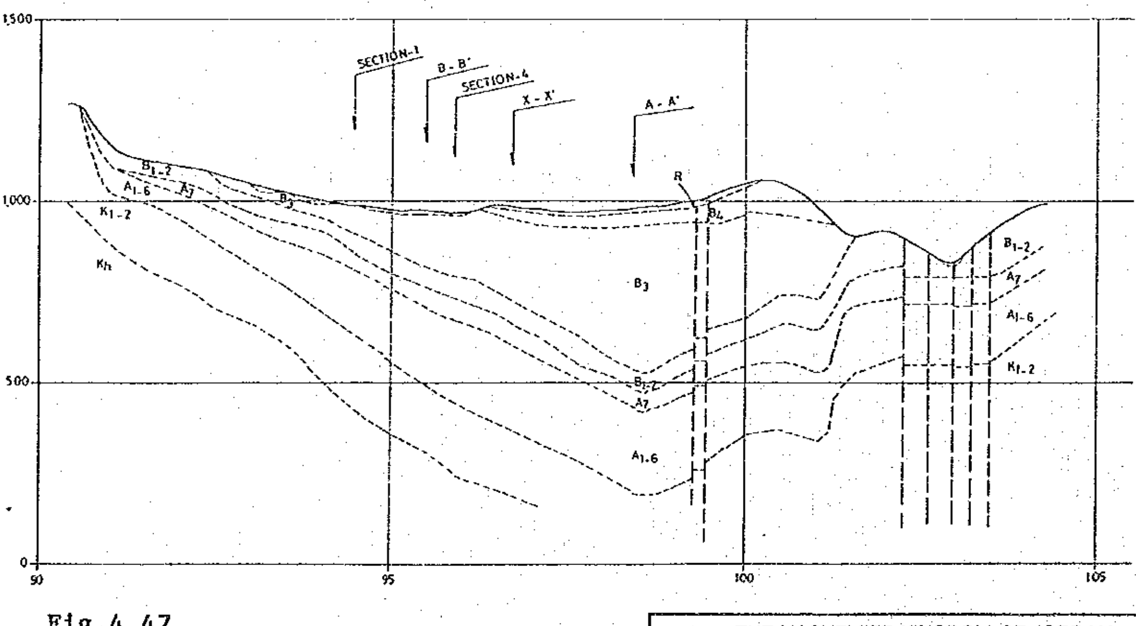


Fig.4.47

Geological Profile 26

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

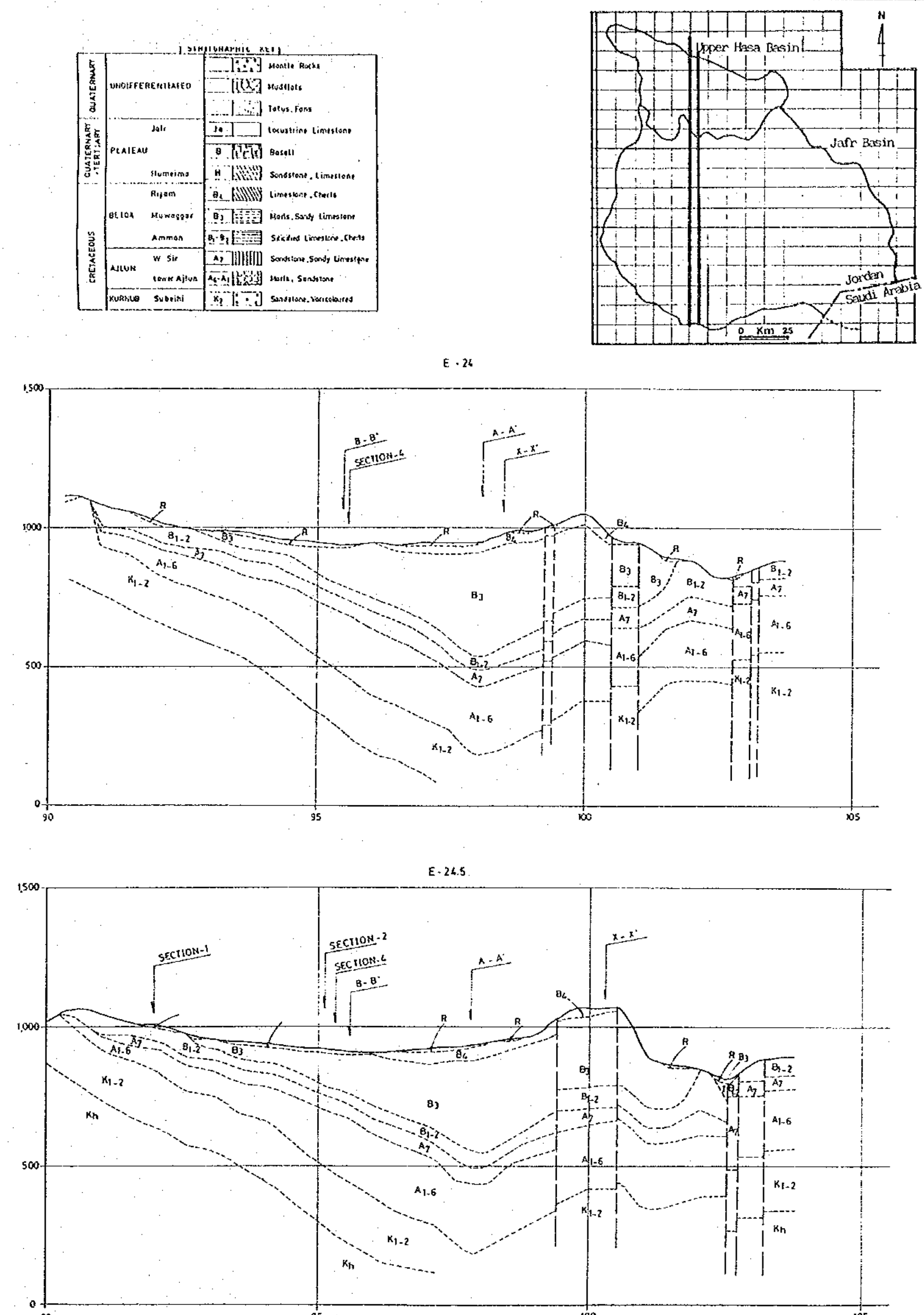


Fig.4.48

Geological Profile 27

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

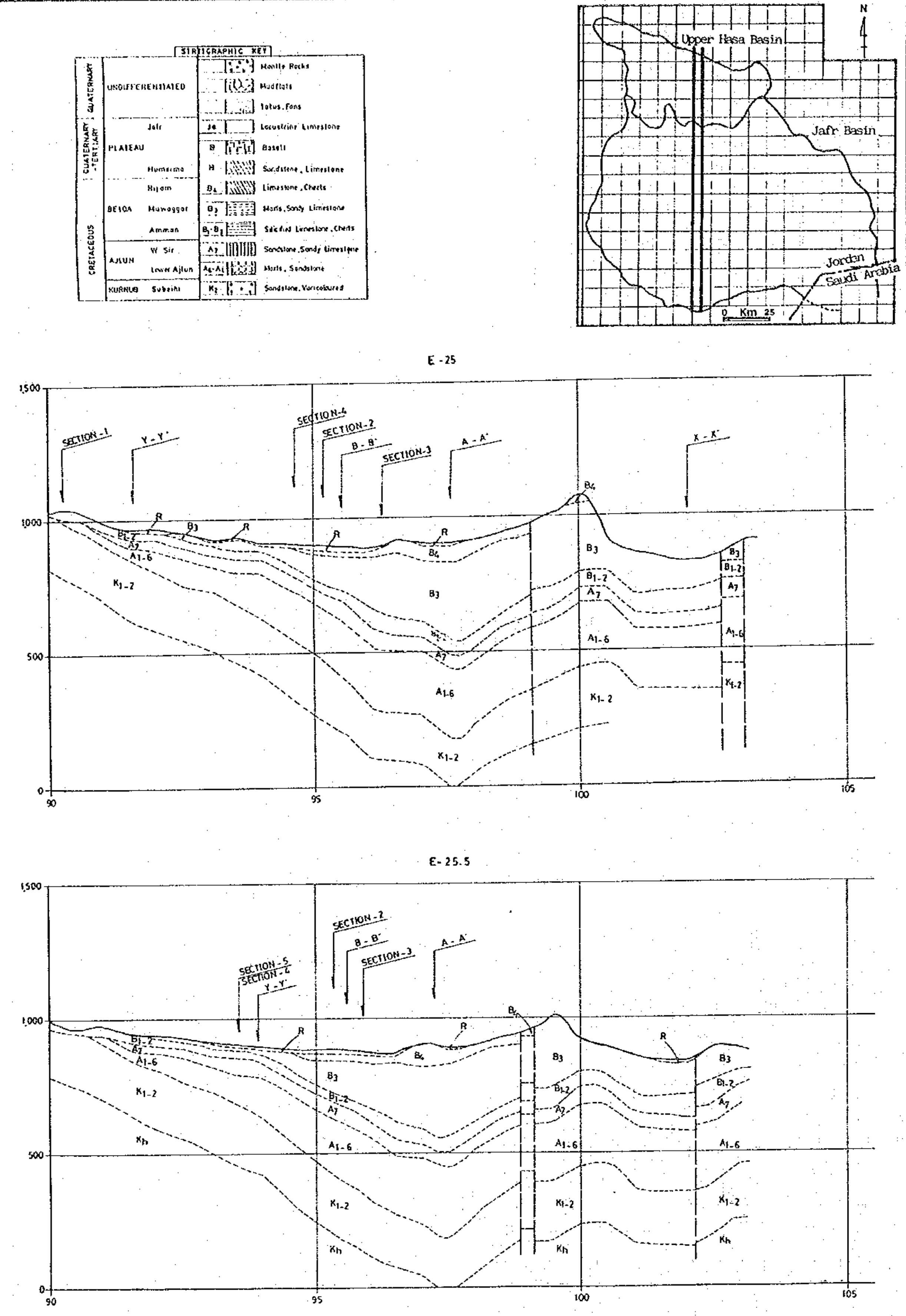


Fig.4.49

Geological Profile 28

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

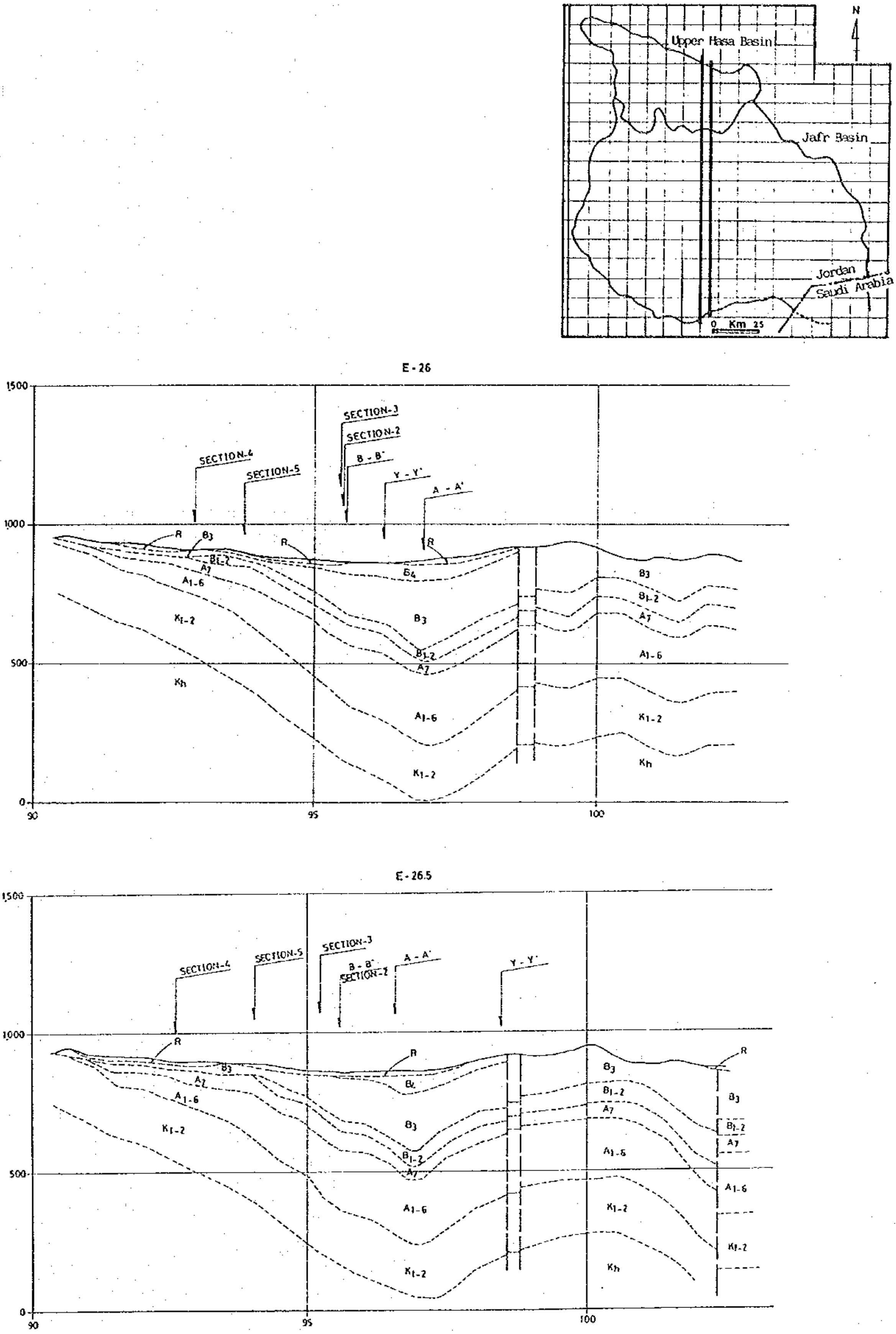


Fig.4.50

Geological Profile 29

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

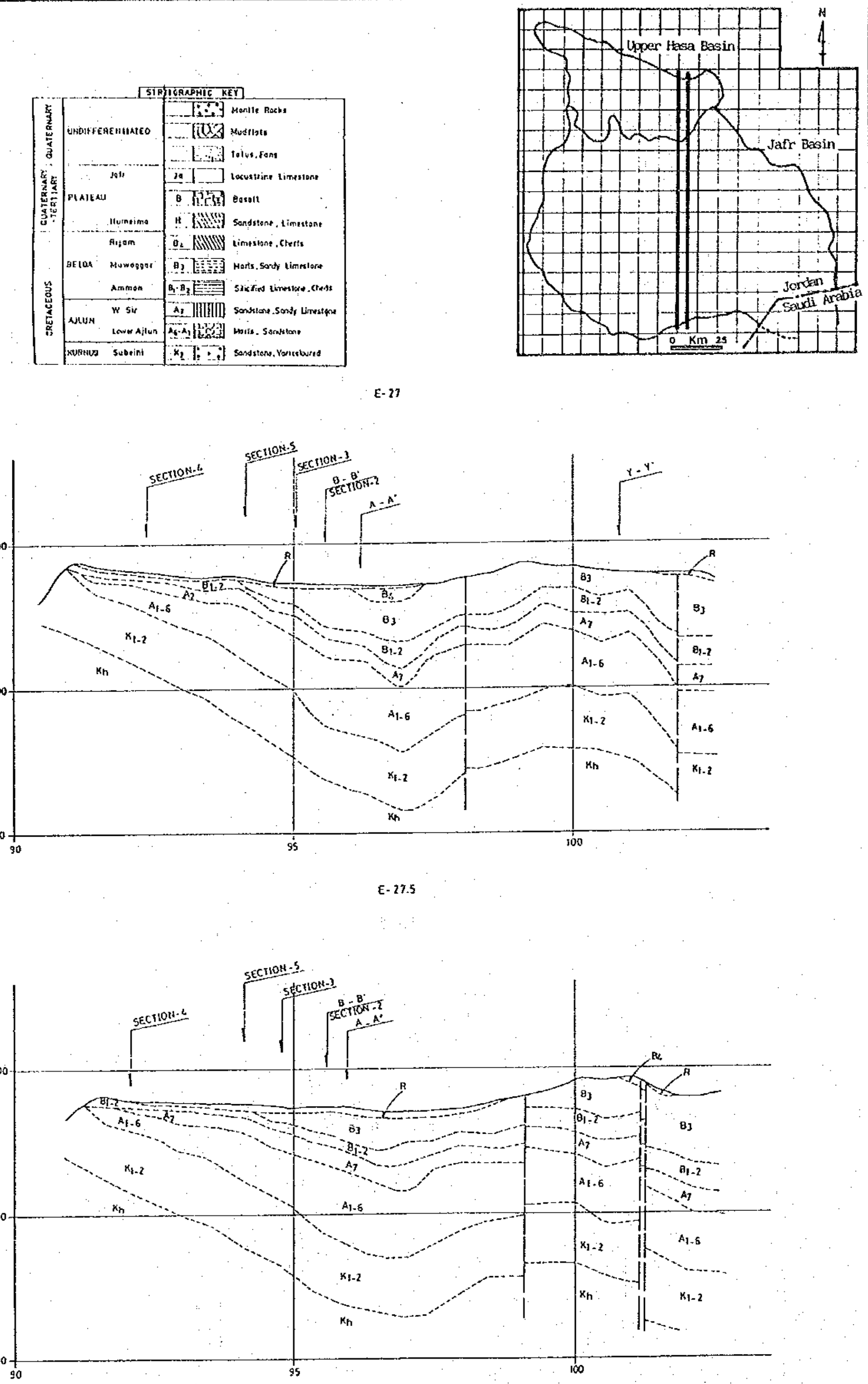


Fig.4.51

Geological Profile 30

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

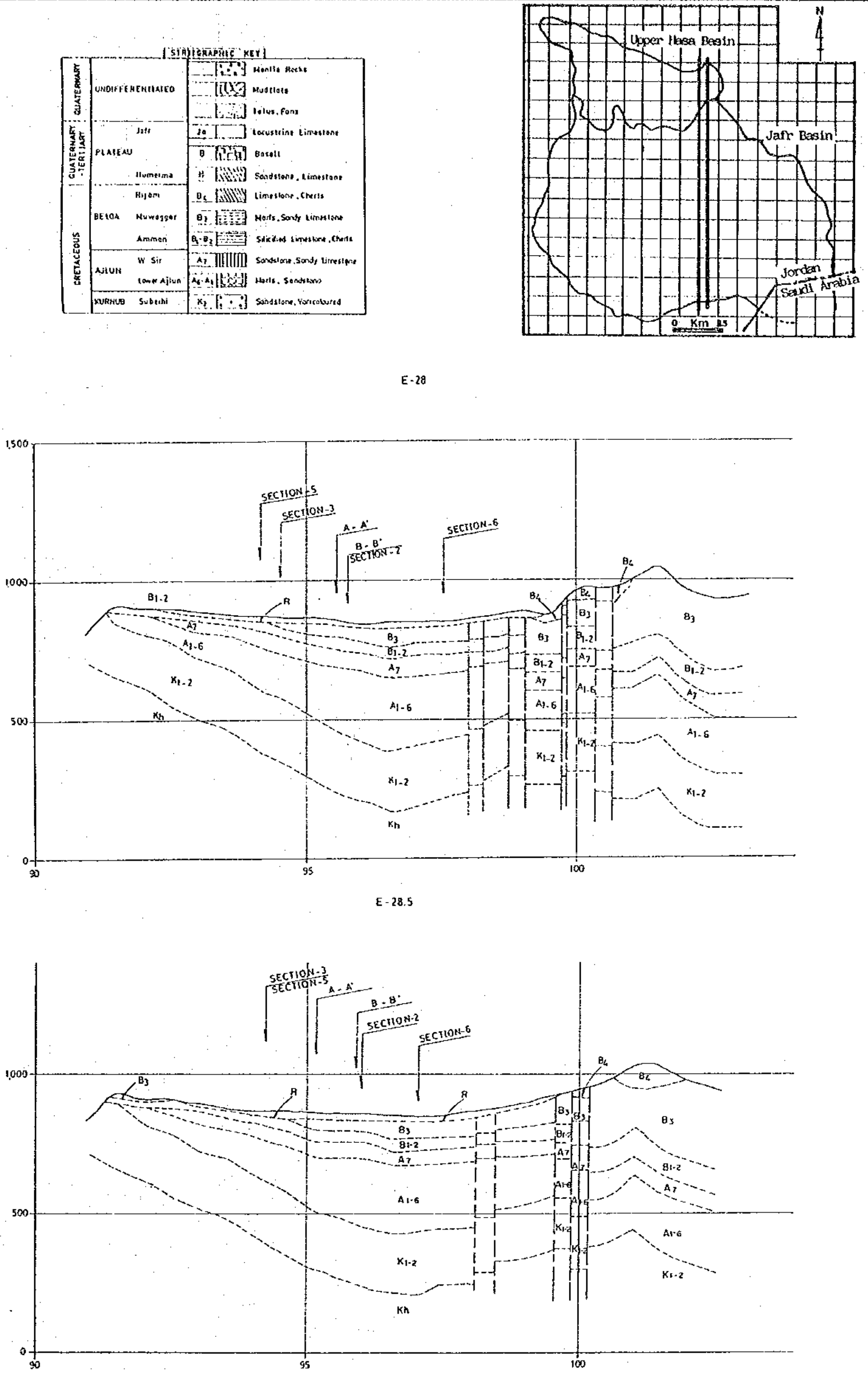


Fig.4.52

Geological Profile 31

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

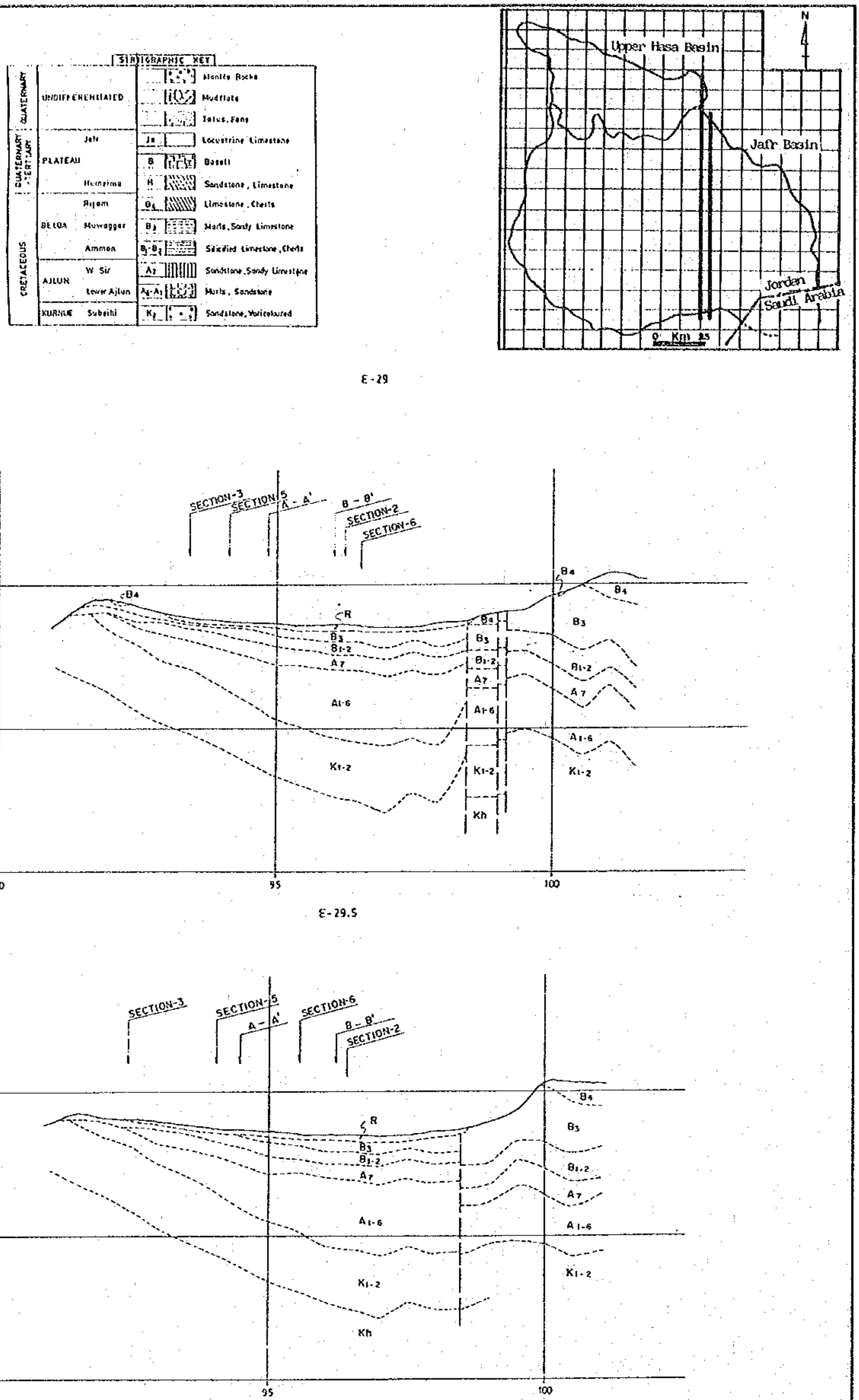


Fig.4.53

Geological Profile 32

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

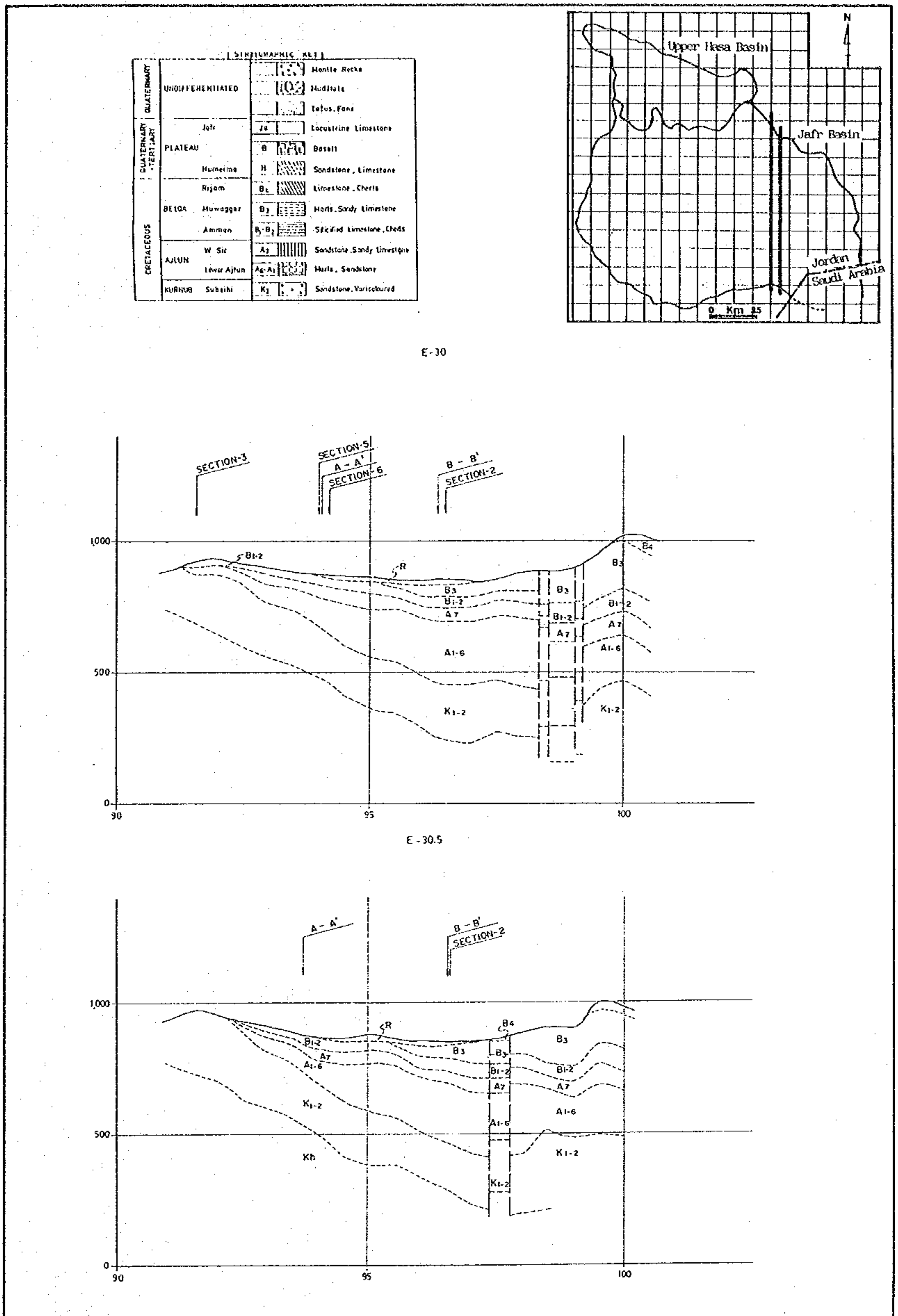


Fig.4.54

Geological Profile 33

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

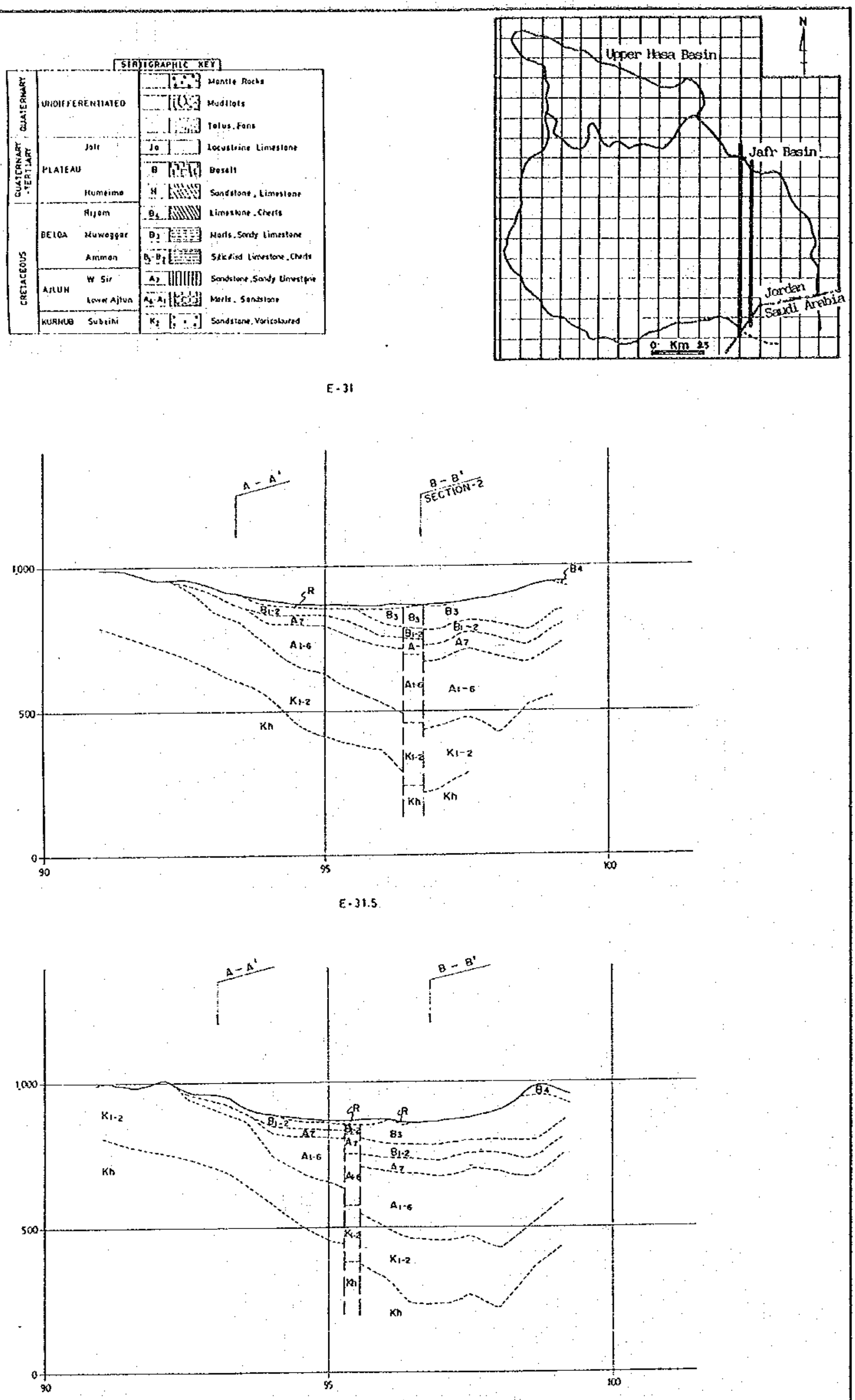


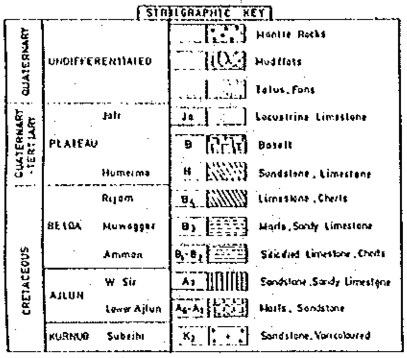
Fig.4.55

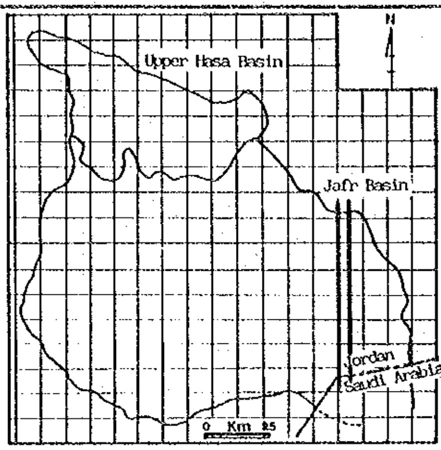
Geological Profile 34

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





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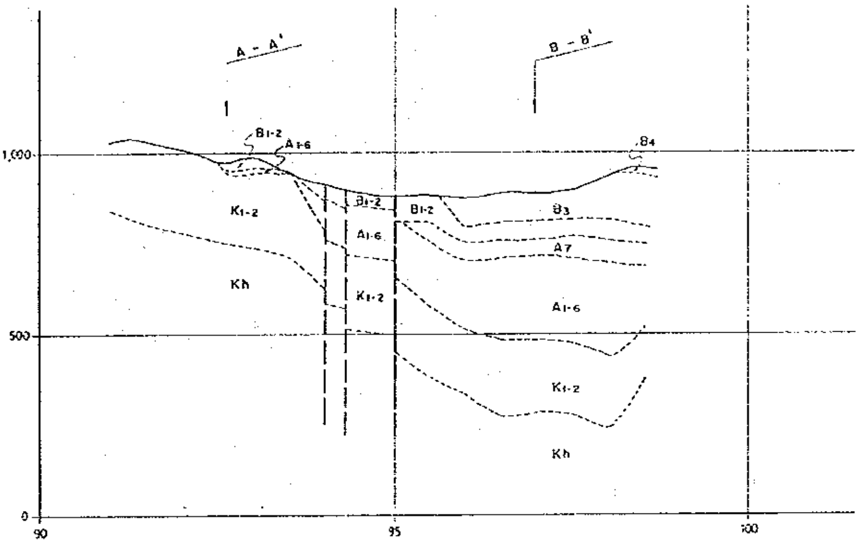

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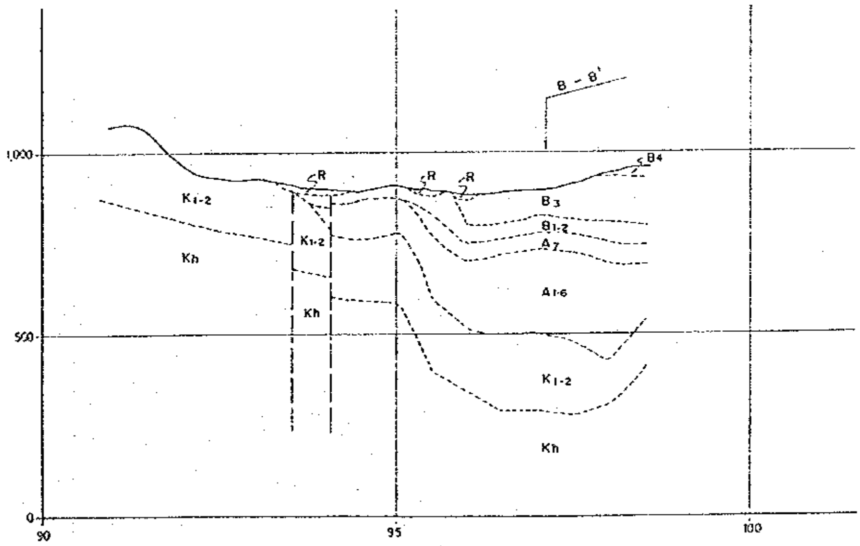


Fig.4.56

Geological Profile 35

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

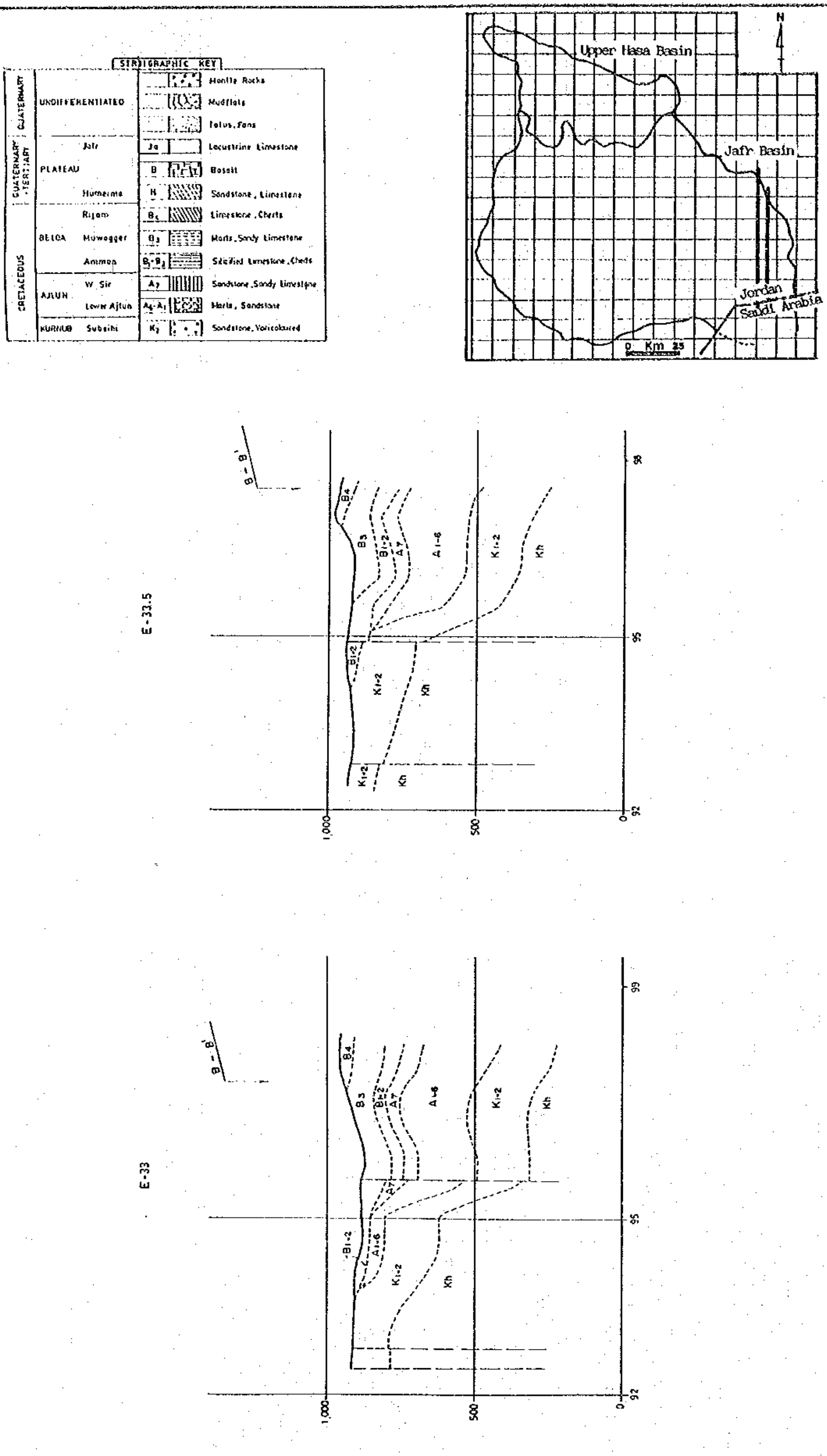


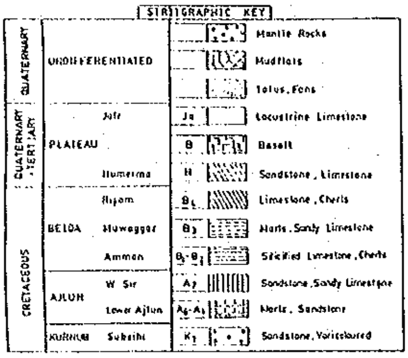
Fig.4.57

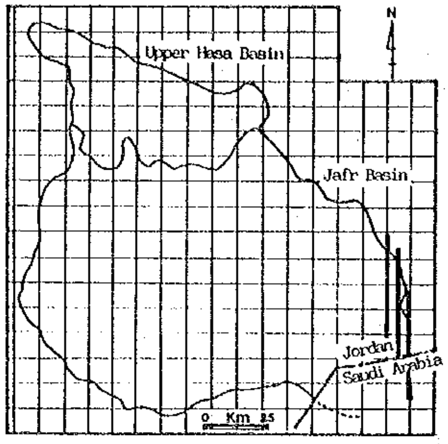
Geological Profile 36

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY





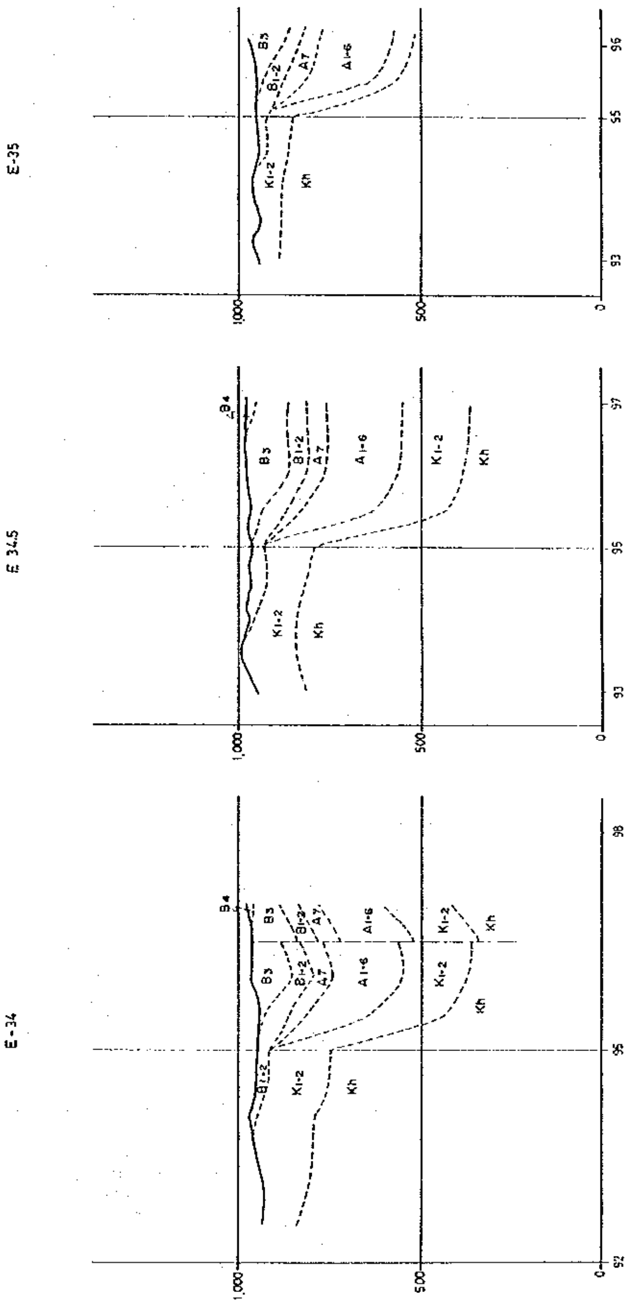


Fig.4.58

Geological Profile 37

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

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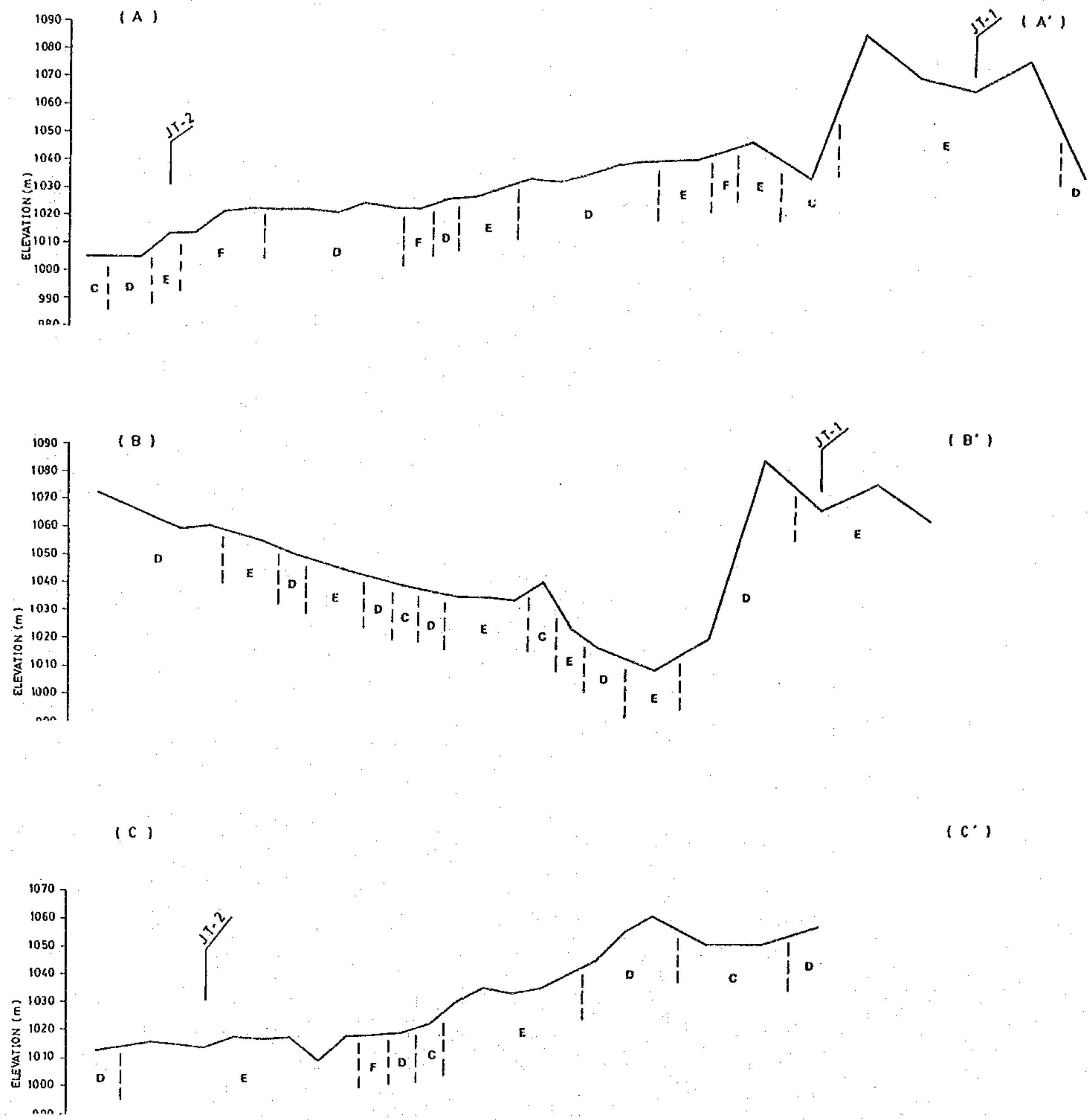

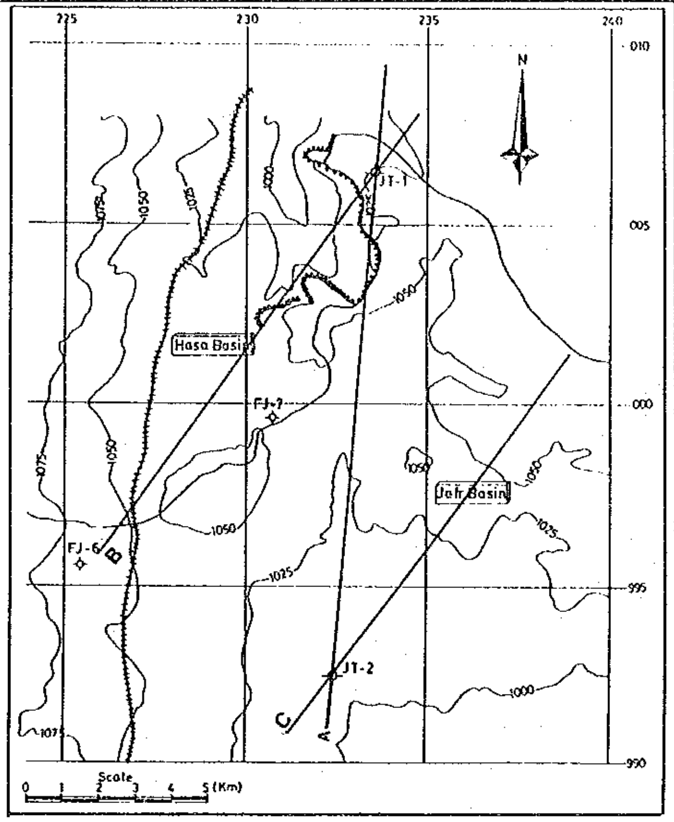

Legend

Resistivity of 2nd Layer

Symbol	:	(Ohm-m)
A	:	- 500
B	:	500 - 300
C	:	300 - 100
D	:	100 - 50
E	:	50 - 30
F	:	30 - 10
G	:	10 - 5
H	:	5 -

Fig.4.59

VLF Profile of Northwest Jafr Basin ;
JT1-JT2

THE HASHEMITE KINGDOM OF JORDAN

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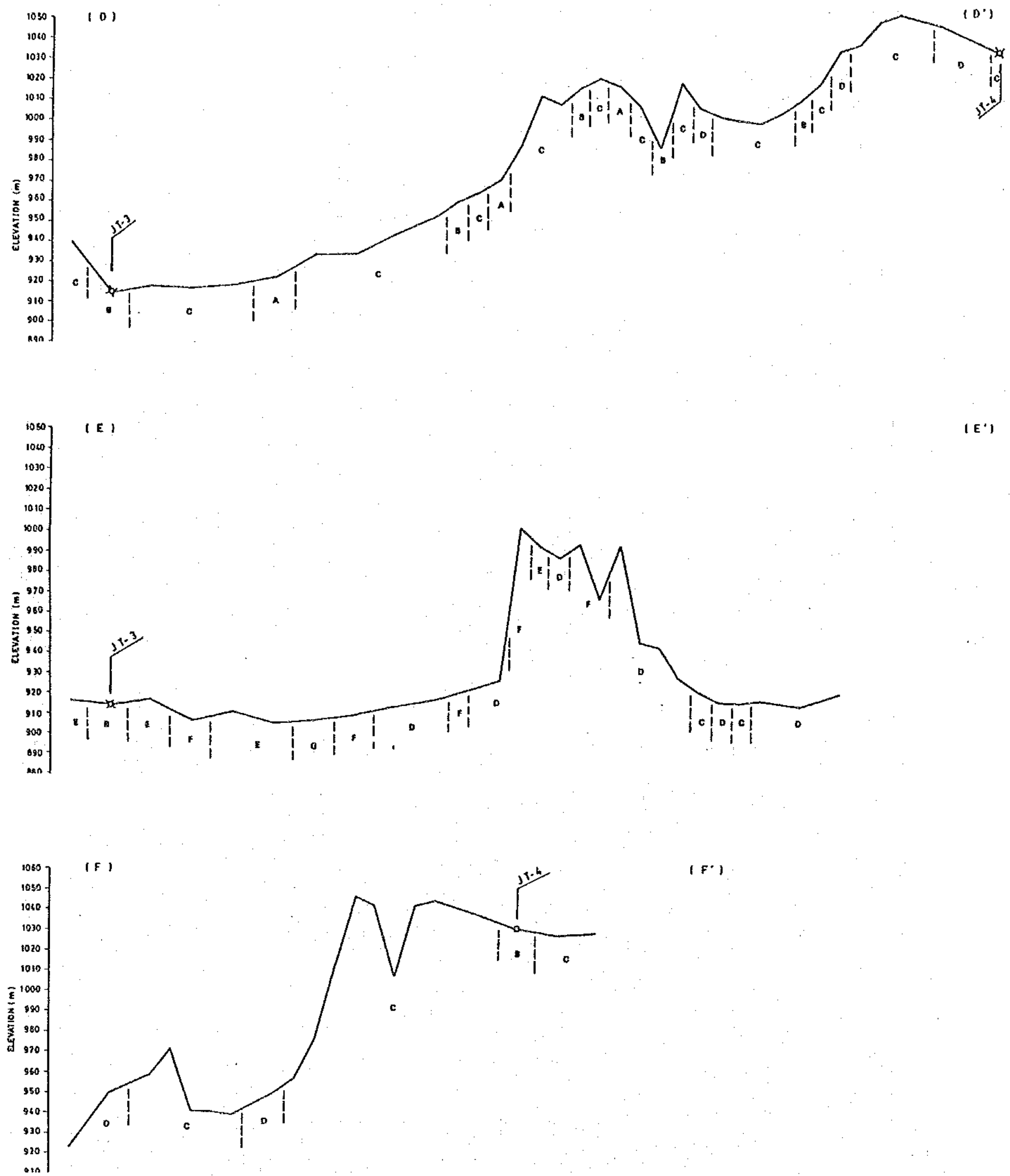

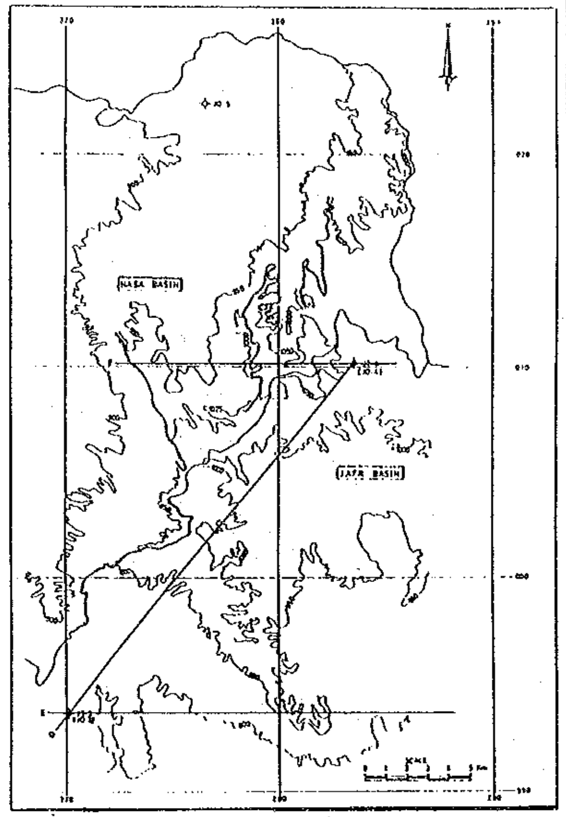

Legend

Resistivity of 2nd Layer

Symbol	:	(Ohm-m)
A	:	- 500
B	:	500 - 300
C	:	300 - 100
D	:	100 - 50
E	:	50 - 30
F	:	30 - 10
G	:	10 - 5
H	:	5 -

Fig.4.60

VLF Profile of Northeast Jafr Basin ; JT3-JT4

THE HASHEMITE KINGDOM OF JORDAN

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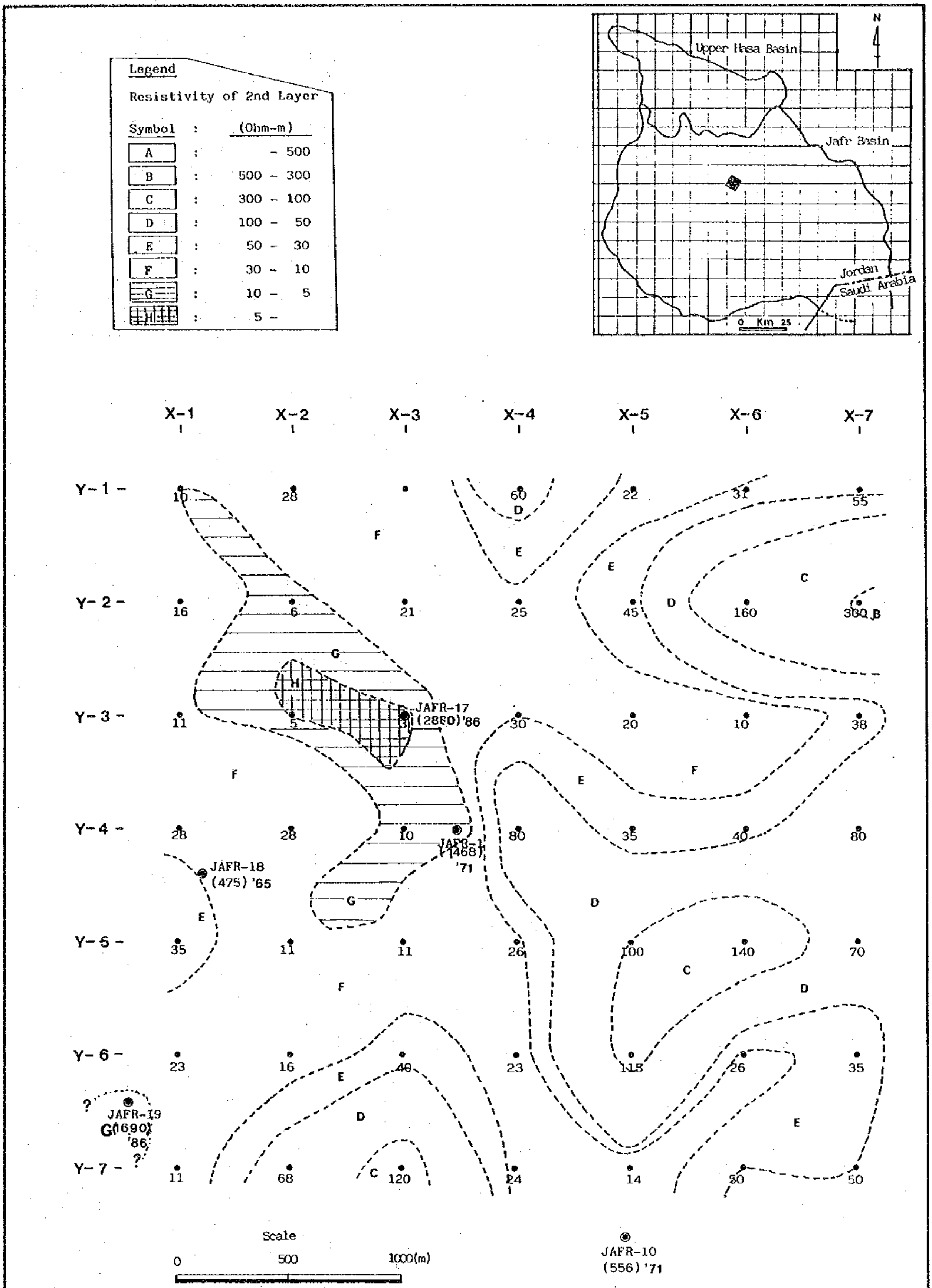

Fig.4.61

Apparent Resistivity (VLF) Contour map in El Jafr Area

THE HASHEMITE KINGDOM OF JORDAN

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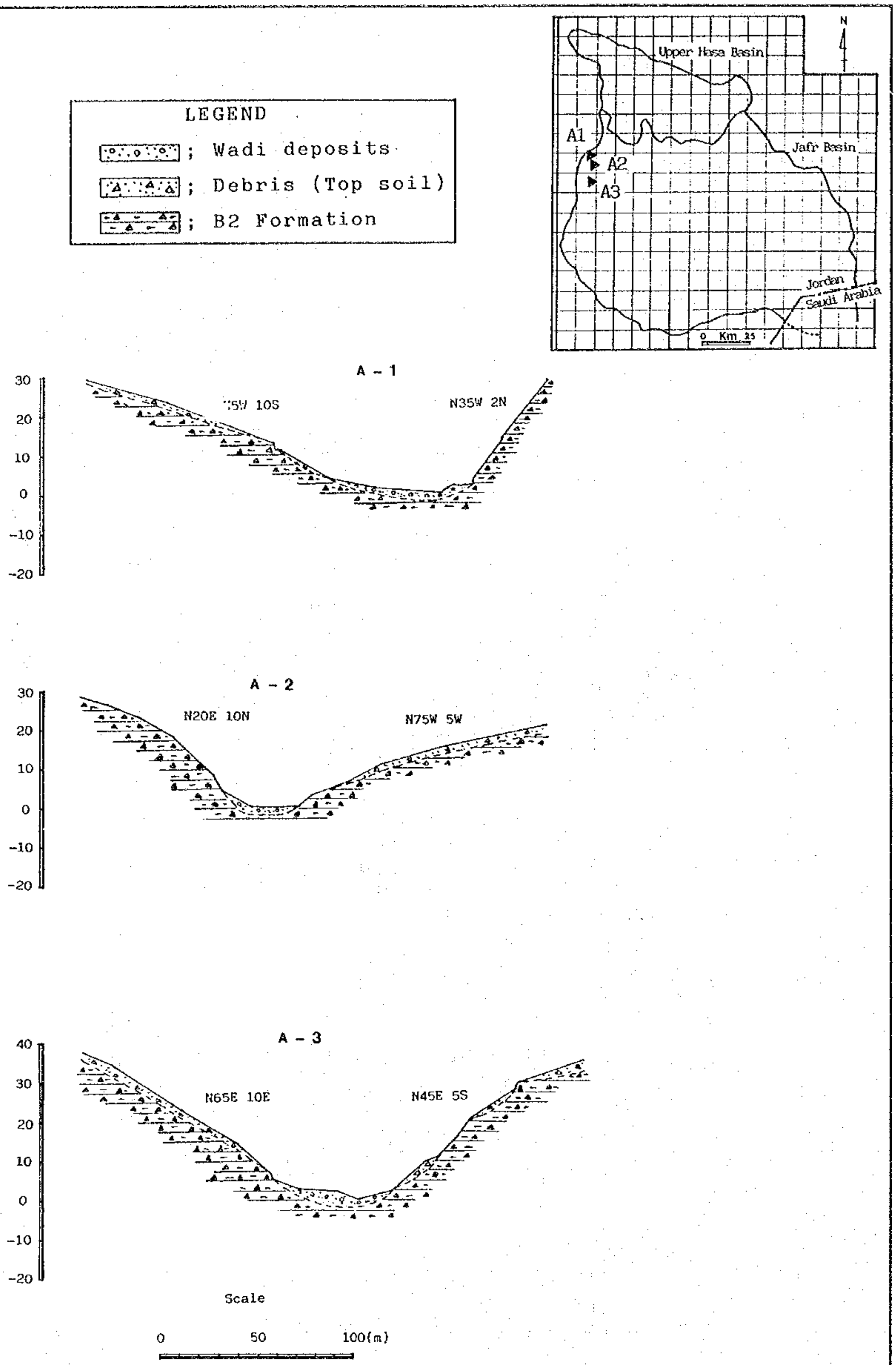

Fig.4.62

Geological Profile Along Dam Axis in Group A

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

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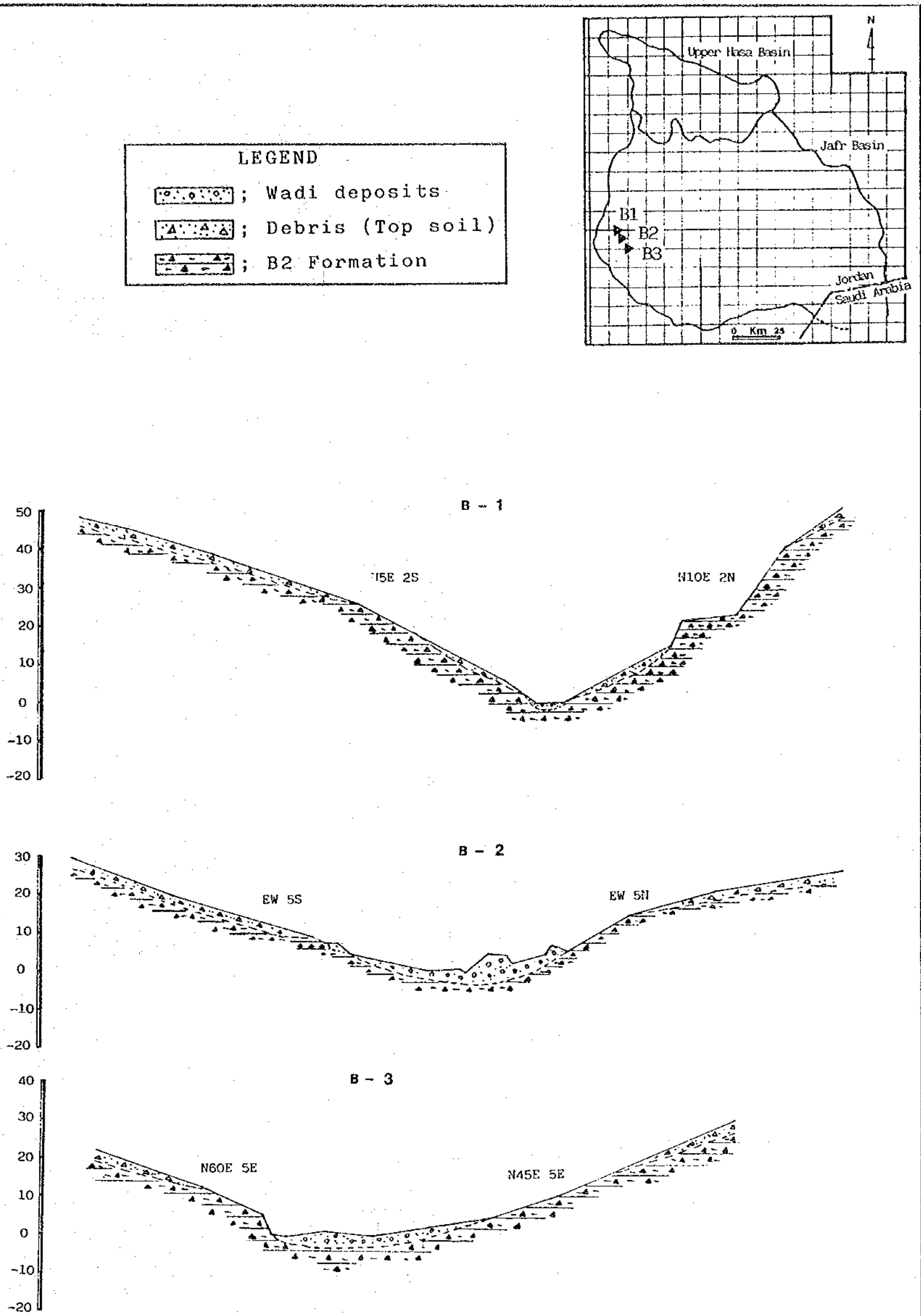

Fig.4.63

Geological Profile Along Dam Axis in Group B

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

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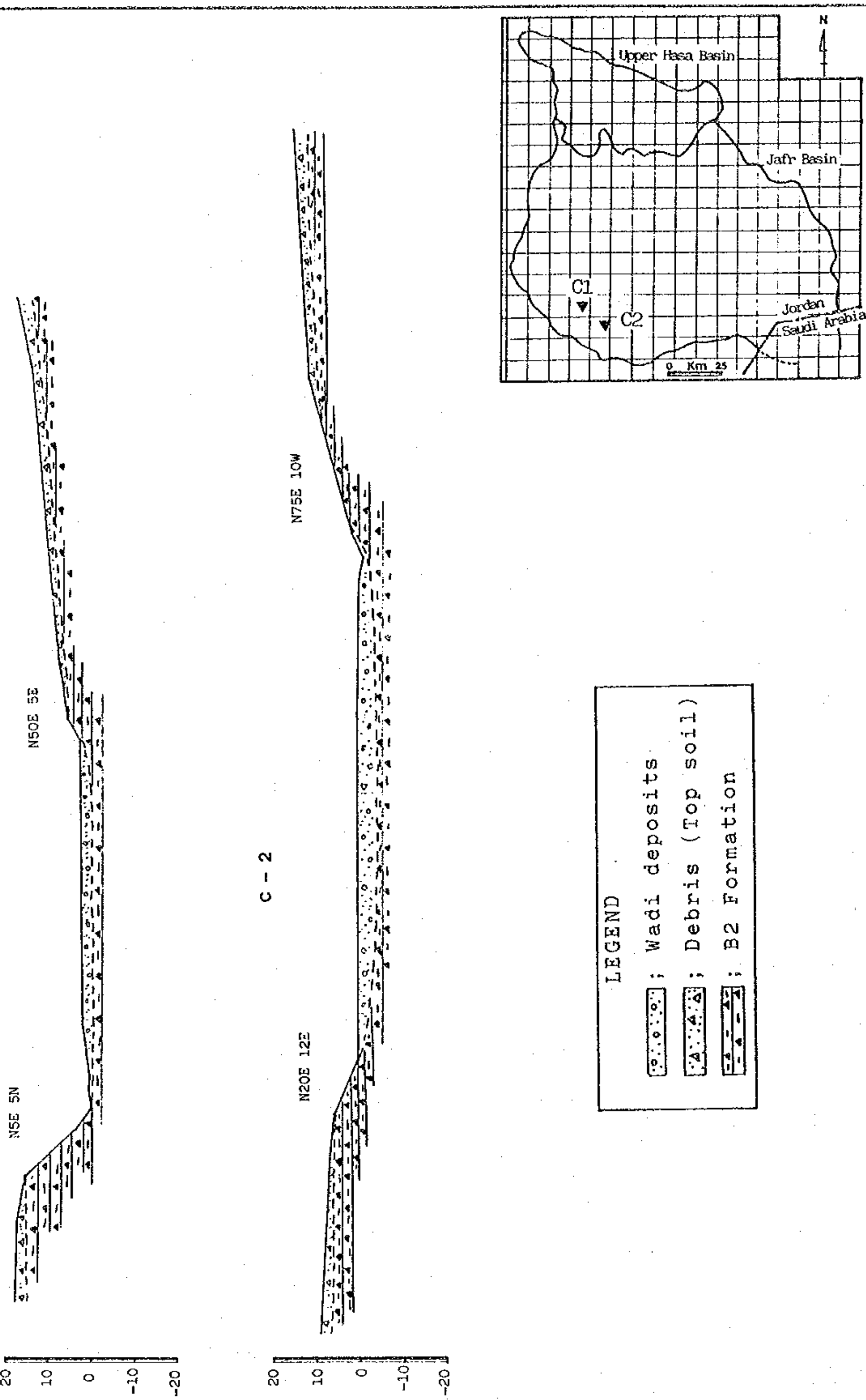

Fig.4.64

Geological Profile Along Dam Axis in Group C

THE HASHEMITE KINGDOM OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

JAPAN INTERNATIONAL COOPERATION AGENCY

V. HYDROGEOLOGY AND GROUNDWATER RESOURCES DEVELOPMENT

V. HYDROGEOLOGY AND GROUNDWATER RESOURCES DEVELOPMENT

5.1 Present Condition

5.1.1 Existing wells

WAJ maintains a series of well data which cover the whole country, including 146 borehole data in the Study area. The wells which have been drilled prior to the Study are prefixed S, PP, W, PHT/PHO, and serially numbered. Among them, the PHT/PHO test/observation wells, which comprise 26 boreholes in total, were drilled in the southern part of the Jafr basin by "Shidiya Groundwater Study Project" in 1985. In addition, 7 boreholes including 4 test wells and 3 observation wells which are drilled during the present investigation, are prefixed "JT" (test well) and "JO" (observation well) respectively.

The well inventory of the 146 boreholes include the basic information of such i) coordinates - Palestine grid, ii) ground surface elevation, iii) total depth, iv) formation unit, v) static water level, vi) yield of pumping test, vii) specific capacity, viii) drawdown, and ix) electric conductivity. Many wells have been drilled in the economic aquifer of the B2/A7. While some deep boreholes such as S-1, S-53, S-57, S-88, S-132, PHO-1, PHO-2, PHO-3, PHO-4, PHO-5, PHO-6, PHO-7, PHO-8, PHO-17 and PHO-18 penetrate the Kurnub group. No deep boreholes which penetrate the bottom boundary of the lower Ajlun (A1-6) formation have been drilled in the area of both northern Jafr basin and upper Hasa basin. Boreholes of 27 in number with serial sub-number of "J1-J27" were drilled in the Al Jafr area, by installing shallow tubewells in the Rijam (B4) formation. Tables 5.1 to 5.6 show the summary of well inventory.

5.1.2 Abstraction and water demand

The B2/A7 aquifer is a major source of the groundwater exploitation in the Study area, while there are no abstractions from the lower Ajlun (A1-6) aquifer. The exploitation of the B2/A7 aquifer is taking place almost exclusively in the Western Highlands and Hasa mining area. The Rijam (B4) aquifer has been exploited locally to irrigate pilot farms such as at west of the Al Jafr town by installing a series of shallow tubewells. Water use of the Jafr irrigation is decreasing, however, by lowering the piezometric surface and increasing the salt contamination in the B4 aquifer. The Shidiya phosphate mine, which is going to be exploited, will require 6 to 20 MCM per annum industrial water supply by the year 1992 to 2000. Present amount of pumped water in the whole basins is preliminary estimated at 18.4 MCM/y in total by WAJ. The inventory of groundwater abstractions for the purpose of i) phosphate mining, ii) water supply and iii) irrigation are shown as below;

<u>Phosphate Mining</u>

Hasa phosphate mine is the biggest consumer of the groundwater resources in the Study area. Groundwater in the B2/A7 aquifer is being exploited by 10 deep wells which have been installed in and around the Hasa mine since 1961. Abstractions are estimated at 7 MCM per annum. The following is a record of annual abstractions from each deep well;

Well No.	1983 (m^3)	1984 (m^3)	1985 (m^3)	1986 (m^3)	1987 (m^3)	1988 (m^3)
Hasa 17	713,520	788,344	551,940	11,760	101,400	450,000
Hasa 19	1,018,910	1,154,419	723,390	1,109,810	1,179,800	1,090,720
Hasa 20	1,257,340	929,323	1,193,370	1,243,600	777,780	927,720
Hasa 14	205,520	270,780	421,824	376,210	87,720	-
Hasa 21	1,008,780	1,301,310	1,561,560	1,421,571	1,407,000	1,406,000
Hasa 13	449,250	512,786	944,470	1,041,430	849,370	140,100
Hasa 6	829,250	515,410	604,345	800,850	281,000	1,122,500
Hasa 11	238,500	305,528	51,600	124,200	468,100	233,300
Hasa 12	56,800	108,200	818,456	792,490	1,352,000	1,282,800
Hasa 23	-	-	-	-	685,350	736,560
Total	5,778,870	5,886,100	6,870,919	6,921,921	7,189,520	7,389,700

Water Supply

Towns and cities are located almost exclusively to the west of the desert Highway where B2/A7 aquifer is a major source of water supply. Abstractions from B2/A7 aquifer are estimated at 4.5 MCM per annum in total in 1987. Shallow aquifer of the B4 is being used for the water supply of the Al Jafr town. However, the water demand is as small as less than 0.037 MCM per annum. Following is the inventory of water supply wells in the study area;

Locality (City/Town)	1986 (m^3)	1987 (m^3)	1988 (m^3)	Remarks
Qa Ma'an	610,900	738,040	850,678	
Tahouneh	695,432	1,275,754	1,346,658	
Arja	734,427	712,860	-	
Shoubak	1,570,611	1,678,737	1,757,485	
Tell Burmah	407,348	759,761		with irrigation
Abour Twaneh			36,500	
Hasa			40,000	
Al Jafr			36,500	B4 aquifer
Shidiya(Mine)			73,000	SH2, SH3

Irrigation

Irrigated lands are located almost exclusively in the Western Highland, where the B2/A7 aquifer is a major source of the groundwater exploitation. Groundwater resources in the northwestern part of the Jafr basin have been exploited by installing 17 wells to irrigate the apples, grapes and almonds in the 14 private firms. The area of irrigated land is estimated at 633 ha in total, which requires 3.27 MCM/y of pumped water by assuming the unit water requirement of 5,160 m^3/ha/y. Abstractions from other private wells are estimated at 2 MCM/y in total. In the Al Jafr area, small scale pilot irrigation (100 to 200 ha) is being practiced by using the shallow tubewells which were penetrated in the Rijam (B4) formation. Abstractions have been decreasing from 2.0 MCM (1970) to 1.1 MCM (1989), corresponding to the gradual increment of water salinity in and around the irrigated land. The following is the inventory of irrigation wells in the Study area;

Locality	1987 (m^3)	1988 (m^3)	Remarks
Wuheida	189,272		
Abu Lissan	529,667		
Mureigha	297,661		
Udruh			0.05 MCM before 1982
IR-3 (west of Ma'an)			0.20 MCM before 1982
Al Jafr	1,316,375	1,139,000	B4 aquifer, 2MCM before 1975

5.1.3 Groundwater monitoring

Systematic groundwater monitoring is being carried out by WAJ monitoring section, that covers the whole country including the measurement of the groundwater level and water quality.

Groundwater Level

In the Study area, five automatic water level recorders have been installed by WAJ in the existing boreholes such as at Hasa (Hasa NO-15, S-121) and Western Highlands (S-111, S-65, S-118). The monitoring well S-121, which was installed in the southwestern part of the upper Hasa basin in 1972, has a longest record since 1972. After 1975, gradual decrease in water table at a rate of 0.57 m/y has been monitored, corresponding to a fall in static water table of 8 m in the last 13 years (1975-1988). The other four monitoring stations with automatic water recorders were installed during 1985 to 1987. Fig.5.1 shows the groundwater hydrograph of the five monitoring wells.

Piezometric levels in the northern part of the Jafr basin and eastern part of the upper Hasa basin have been monitored by this Study, including the dry season from April to October in 1989. The piezometric levels, which are the depth from ground surface to water table in the boreholes of JT-1, JT-2, JT-3, JO-3, JT-4 and JO-5. are shown as below;

Well No.	Ground Elevation (m)	Feb.1989 (m)	4 July,1989 (m)	16 Oct.1989 (m)	Aquifer
JT-1	1,065.03	183.37	183.57	183.97	B2/A7
JT-2	1,013.47	219.00	219.55	219.50	B2/A7
JT-3	914.28	38.27	37.25	37.27	A1-6
JO-3	914.28	123.77	123.94	124.69	B2/A7
JT-4	1,030.17	244.42	244.55	244.92	B2/A7
JO-5	899	174.34	175.06	175.14	B2/A7

The piezometric levels in the Rijam (B4) aquifer have been monitored since 1964, using the boreholes of Jafr No.J-10-12-17-20-23. In those boreholes, the piezometric level were declined at the rates between 0.1 m/y to 0.36 m/y in those 16 to 22 years, corresponding to a fall of the piezometric levels in the 10 to 20 years of 2 to 7 m as shown in the NRA's study report in 1985;

Borehole No.	Decline (m/y)	Period (year)
J-12	0.165	1966 - 1983
J-17	0.195	1962 - 1982
J-23	0.080	1967 - 1983
J-26	0.130	1968 - 1981
J-10	0.360	1966 - 1983

Abu Jamieh and Hirzalla reported that no measurable changes in the piezometric levels in the southern part of the saturated B4 aquifer were measured during and after the largest flood in the wadi Wuheida in 1966 which inundated a large part of the Ma'an city. (Ref.5.1)

Water Quality

Quality of groundwater has been monitored by WAJ to collect the water samples from 14 existing wells which are being used for the water supply and/or irrigation, including the boreholes of Hasa No.13-17-19-21, Tell Burmah No.1, Al Tahouneh No.2, Al Shoubak No.1, Jafr No.2-17-19-20-23-25. The chemical analysis has been carried out by NRA/WAJ since 1960, while systematic monitoring data has been stored in the government files after 1971.

In general, the quality of groundwater in the carbonate rocks and/or sandstones is fair to good. While emphasis is put to the water salinity in the Jafr well fields where a part of the shallow unconfined aquifer in the Rijam (B4) formation has been contaminated by irrigation returns with substantial increase in T.D.S from 500 to 3,500 ppm. The historical changes in water salinity (E.C; Electric Conductivity) after 1965 are shown on Fig.5.2.

5.2 Drilling Exploration

5.2.1 Objective

The objective of test well drilling is to provide the hydrogeological data of constructing groundwater simulation models in the study area. After examining 146 existing wells, the northern part of the Mujib basin where no existing drilling data are available, was selected for constructing of test wells. The drillings were carried out to examine the geological effects of hydrogeology on the major aquifers of "B2-A7" and "A1-6" which have been assumed to be intersected by the two major faults of "Karak - Al Wadi Hifa" and "Salwan". The test well drillings were performed from October 1988 through February 1989, including test wells, 4 in number JT-1,JT-2,JT-3 and JT-4, and observation holes 3 in number JO-3,JO-4 and JO-5, with a total depth of 2,940 m. These wells were drilled with the following four additional objectives;

a) JT-1 & JT-2 : These were drilled in the north-western part of the Jafr basin, to examine the effect of Salwan fault on the hydrogeology of the B2/A7 aquifer system.

b) JT-3 : This was drilled in the north-eastern part of the Jafr basin, to examine the hydrogeology of the lower Ajlun (A1-6) formation.

c) JO-3 & JT-4/JO-4 : These were drilled in the north eastern part of the Jafr basin, to examine the effect of "Karak - Wadi Al Fiha" fault on the hydrogeology of the B2/A7 aquifer system.

d) JO-5 : This was drilled in the north-eastern part of the Upper Hasa basin, to examine the effect of "Karak - Wadi Al Fiha" fault on groundwater flow in the B2/A7 aquifer system.

5.2.2 Method

Drilling

The method was based on drilling with mud, polymer, clear water or foam by using conventional techniques of direct circulation rotary and/or down-the-hole hammer. Taking account of the importance of lithologic samplings in the test well drillings, the rotary technique with direct mud circulation was used except at depths where circulation mud was lost completely without any return. The down-the-hole hammer technique was used only in the borehole JO-3 in a section from 140 to 200 m deep. However, the deep samples are mixed with cuttings from upper layers, which makes it difficult to interpret the formation lithology. The rotary method with chemical foam is used in borehole JT-1 below the depth of 350 m where circulation mud was lost completely without any return.

Three drilling rigs, "GARDEN DENVER-2500", "FALLING-3000" and "FALLING-

2500", were used to carry out the drilling program as shown below;

Drilling Rig	Borehole Number
GARDEN DENVER-2500	JO-3, JT-3
FALLING-3000	JO-4, JT-4, JO-5
FALLING-2500	JT-1, JT-2

Well Grouting

Well grouting was performed in the four test wells to separate the aquifer units of B2/A7 and A1-6 and to support the pump chamber of the blind casing pipe. After constructing observation hole of JO-3, which penetrated the full thickness of the B2/A7 formation up to a depth of 247 m, JT-3 test well was drilled beside JO-3 at a distance of 20 meters.

JT-3, which was designed to examine the hydrogeology of the lower Ajlun (A1-6) formation, was drilled to a depth of 496 m. In the course of the drilling, the borehole was grouted up to a depth of 259 m, to ensure the complete sealing of the B2/A7 aquifer by the cement grouting as shown in Fig.5.3. Other groutings were performed to stabilize the casing pipes in the Muwaqqar (B-3) formation to a depth between 200 and 240 m.

Prior to grouting, the annular space was flushed with clean water to ensure that the space was free from any drilling mud. The annular space between the drilled hole and the casing pipe was then grouted by cement mixture with a specific gravity of 1.6 Kg/cm^3. The double plug method was used to inject the cement in the annular space from the bottom to the top. After 24 to 36 hours waiting, the inside of the casing was flushed out with clean water. No accelerator such as calcium chloride was used.

Well Logging

Owing to mechanical failure of the logging apparatus, well logging could not be performed during drilling.

Casing and Screen

The casing pipes with diameter of 9-5/8 and 7 inch were of a type of carbon steel "ERW" in accordance with API specifications H-40. The casing pipes with diameter of 9-5/8 inch were used to install the pump chamber. Parts of the 7 inch casing pipes were slotted with torch cuts 2 mm wide and 20 cm long, to match the aquifer sections in the observation wells.

Screen pipes with diameter of 7 inch, of a pipe-based type would with stainless wire with a slot opening at 1.0 mm, were installed in the aquifer sections in the test wells.

The screen was placed using a reverse threaded (left-handed thread) coupling affixed to the top of the pipe.

Well Development

After installing the casing and screen, the borehole was cleaned out to remove any drilling fluid and/or debris by circulating clean water. Sodium polyphosphate, which is a mixture of 1.5 kg per meter saturated thickness of aquifer in the well, was pumped into the well to disperse the mud cake, and then left in the well for 24 hours. The borehole was circulated again with clean water until it was confirmed that all tracers of the drilling mud have been removed. The sodium polyphosphate was used in the wells which were drilled by using bentonite mud. The following is the summary of the amount of the sodium polyphosphate which was used during the drilling campaign;

Borehole Number	JT-1	JT-2	JT-3	JT-4	JO-3	JO-4	JO-5

Sodium Polyphosphate (Kg)	-	250	150	150	150	175	175

The boreholes were developed by compressed air and/or pumping. The two pipe system was used to develop the well by the air lift method. This was continued until clear sand-free water was confirmed.

After air lifting, a vertical shaft type pump was installed in the test wells with a static water level of less than 200 m deep. Prior to step drawdown test, the wells were developed by the surging (pump) method for up to 48 hours.

Pumping Test

The pumping test was carried out in the test wells with a static water level of less than 200 deep, such as JT-1 and JT-3. After developing the well by pumping, the pumping unit was removed to install a pressure type of automatic water level recorder. A step drawdown test with five steps was performed in test well JT-3 to estimate the well efficiency, while it was not performed in JT-1 where the static water level was as low as 185 m. After 24 hours of complete recovery of the static water level in the test wells, a continuous pumping test was carried out for 72 hours both in JT-3 and JT-1, to estimate the aquifer parameters. The discharge rates varied depending on the aquifer permeability and the depth to water level. The discharge rate is 28 m^3/h both in JT-1 and JT-3, corresponding to the drawdown of 1.5 and 12 m respectively. The discharge volumes were measured by means of a flow meter.

Pump-in test was performed in the test wells JT-2 and JT-4 where the static water level was deeper than 200 m such as in the range between 219 and 245 m. This method was used to estimate the permeability in the very poor aquifers such as at JT-2 and JT-4. The rate of the constant injection was 36 l/min. with duration time of 2 hours.

Water Sampling and Testing

Water samples were collected from the pumping wells during development and/or pumping. Following is a list of the water samples;

Well No.	Source	Conditions of Sampling
JT-1	Pumping	Representative sample after 72 hours pumping
JT-2	Air lifting	Mixed with injected water during development
JT-3	Pumping	Representative sample after 72 hours pumping
JT-4/JO-4	Air lifting	Mixed with injected water during development
JO-3	Pumping	Representative sample after pumping one week
JO-5	Air lifting	Representative sample after lifting 48 hours

The representative samples were sent to WAJ's laboratory to perform the chemical analysis on the following items;

General : E.C, T.D.S, pH
Cation : Na^{+}, K^{+}, Ca^{++}, Mg^{++}
Anion : Cl^{-}, $HCO3^{-}$, $CO3^{--}$, $SO4^{--}$
Others : $NO3^{-}$

5.2.3 Lithological description

Lithologic samples were taken from each borehole at intervals of one meter in depth. After describing the lithology of each sample, representative samples were taken at each 10 meter in depth. The representative samples near the formation boundaries were used to examine the micro-fossils. (see Figs.4.3 to 4.6) The following is a summary of the stratigraphic analysis of each borehole;

Well No.	A1/Bslt	B4	B3	B1/2	A7	A5/6	A4	A3	A2	A1
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
JT-1	-1	-87	-295	-387	-500	-516	***	***	***	***
JT-2	-12	-40	-413	-497	-610	-616	***	***	***	***
JT-3	-1	***	-19	-115	-232	-330	-352	-444	-458	-495
JT-4	-2	-96	-226	-333	-394	-395	***	***	***	***
JO-3	-1	***	-19	-115	-232	-263	***	***	***	***
JO-4	-2	-96	-226	-333	-394	-408	***	***	***	***
JO-5	-5	***	***	-136	-242	-247	***	***	***	***

Well logs of each borehole are shown on Figs.5.4 to 5.10.

5.2.4 Piezometric head

After developing the wells, static water level in the boreholes was measured by means of an Ohmscope which is a conventional hand leveling equipment. The JT-1 test well, which was drilled with use of chemical foam, jammed at a depth of 358 m. This was due to the substantial water leakage through the fractures and/or caves in the B2 formation. The piezometric head in the section of B2 was lowered to the depth at 200 m or more, and no flow returns were obtained. The piezometric level in borehole JT-1 rose again to a depth of 185 m, just after penetrating into the A7 formation which is highly confined with an aquifer pressure at 20 Kg/cm^2. The following is a summary of the piezometric levels in each borehole;

Well No.	Depth to S.W.L.	Aquifer	Remarks
JT-1	220 m	B2	During drilling by foam
JT-1	185	B2/A7	Automatic water level recorder
JT-2	219	B2/A7	
JT-3	38	A1-6	Automatic water level recorder
JO-3	124	B2/A7	Automatic water level recorder
JT-4	245	B2/A7	
JO-4	245	B2/A7	
JO-5	175	B2/A7	Automatic water level recorder

5.2.5 Aquifer test and parameters

Aquifer tests were performed to estimate the aquifer parameters of "B2/A7" and "A1-6". To assess the storage coefficient, the JO-4 observation hole was installed just beside the JT-4 test well with a distance at 20 m. Since the permeability of the aquifer was too low to carry out a pumping test, a pump-in test was performed in JT-4. However, the observation borehole of JO-4 did not work to detect the very small change in the piezometric head during the injection. This was due to the very low permeability of the B2/A7 aquifer.

Analysis on the aquifer parameters were performed using both modified equilibrium equations and conventional non-equilibrium equations. For the pumping test without observation hole, following modified form of the equilibrium equations were used to estimate the regional transmissivities;

$$T = \frac{Q.In(R/r)}{2x3.14\ (h_2-h_1)} \qquad \ldots\ldots(5.1)$$

$$R = 2(h_2-h_1)(T)^{1/2} \qquad \ldots\ldots(5.2)$$

From (5.1) and (5.2), substituting R by x

$$F(x) = In(x) - \frac{3.14}{\quad} x^2 - In(r) = 0 \qquad \ldots\ldots(5.3)$$

$$2Q(H\text{-}h)$$

$$k = T/b \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.4)$$

For a unconfined (phreatic) aquifer,

$$K = \frac{Q.In(R/r)}{3.14(h_2^{\,2}-h_1^{\,2})} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.5)$$

$$R = 10.2(H\text{-}h)(k)^{1/2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.6)$$

From (5.5) and (5.6), substituting R by x

$$F(x) = In(x) - \frac{3.14(H\ {}^{2}h\ )}{104Q(H\text{-}h)^{2}}\, x^{2} - In(r) = 0 \qquad \ldots\ldots\ldots\ldots(5.7)$$

where, In:	Natural log
k:	coefficient of permeability, L/t (m/d)
T:	Coefficient of transmissivity, L^2/t (m^2/d)
Q:	Pumping discharge, L^3/t (m^3/d)
R:	Radius of influence, L (m)
r:	Radius of the test well, L (m)
b:	Saturated thickness of the aquifer, L (m)
r_1, r_2:	Horizontal distances from centerline of the test well to centerline of observation wells 1 and 2, L (m)
h_1, h_2:	Saturated thicknesses or piezometric heads of the aquifer at distances r_1 and r_2, L (m)
H:	Piezometric head before pumping, L (m)
h:	Piezometric head after pumping, L (m)
L:	Unit length
t:	Unit time
*:	Multiplying

Equations (5.3) and (5.7) are numerically solved by Newton-Raphson iteration method by using three input data such as pumping rate, well drawdown and radius of well. This simple numerical analysis is also used to estimate the regional transmissivities in the Study area by using the data of 146 existing wells. The following is a summary of pumping and/or pump-in tests;

Well No.	Static Water Level	Drawdown	Discharge	Specific Capacity	Transmissivity	
	(m)	(m)	(m^3/h)	($m^3/d/m$)	(m^2/d)	
JT-1	185	1.5	28	448	444	
JT-3	38	12.0	28	45	66	
JT-4	245	(50.0)	(1.75)	nil	nil	(Pump-in)

5.2.6 Water quality

Water samples from the Amman Wadi-Sir (B2/A7) aquifer were collected from the boreholes of JT-1, JT-2, JO-3 (during pumping test) and JO-5 (during by air lifting.) The samples from the lower Ajlun (A1-6) aquifer were taken only from the borehole JT-3 during the pumping test. The field testings such as electric conductivity (E.C), water temperature and pH were performed prior to the laboratory testing. The following is a summary of the field testing;

Well No.	Electric Conductivity (micromho/cm)	Temperature (°C)	pH (-)	Aquifer Unit
JT-1	445	27.0	7.2	B2/A7
JT-3	585	34.0	7.2	A1/6
JO-3	945	27.0	7.2	B2/A7
JO-5	2,000	-	8.0	B2/A7

Water samples were not collected from the JT-2 and JT-4 test wells, where the static water level was deeper than 220 to 245 m and no pumping tests could be carried out. The results of the chemical analysis of the four water samples are shown on a form of Piper's tri-linear diagram. (Fig.5.11) The groundwaters of JT-1 and JT-3 are plotted in a quality type of "carbonate hardness", while JO-3 and JO-5 are on a type of "no one cation-anion pair".

5.3 Aquifer System

5.3.1 Aquifer condition

Aquifers have been recognized in argillaceous, arenaceous and/or carbonate rocks of the Cambrian to Paleogene age such as Disi, Kurnub, lower Ajlun (A1-6), Amman-Wadi-Sir (B2/A7), and Rijam (B4). In the course of the present Study, attention was focused on the aquifers in Ajlun and Belqa group such as A1-6, B2/A7 and B4.

The Study area includes both Jafr basin and upper Hasa basin. In the southern part of the Jafr basin, to the south of the Shidiya phosphate mines, the B2/A7 and A1-6 are both thin and unsaturated. In the central part of the Study area, the B2/A7 is confined by overlying thick impervious argillaceous unit of the Muwaqqar (B3) formation, while the surrounding areas are unconfined. Except the area along the Jafr trough, the confined B2/A7 aquifer is promising to be developed. The A1-6 is highly confined in the area of the north of the Salwan fault, which is conceived to be a promising aquifer. The B4 aquifer exists in an independent regional shallow sedimentary basin which overlies the impervious Muwaqqar (B3) formation. In the central part of the sedimentary basin, the B4 is saturated with water table condition, while it is unsaturated in the surrounding areas. The aquifer receives limited recharge through the wadi beds during the occasional floods, of which potential is evaluated to be limited and small.

5.3.2 Lower Ajlun (A1-6) aquifer

The lower Ajlun (A1-6) underlies the Amman - Wadi Sir (B2/A7) aquifer, which is comprised of multi-layered units of sandstones, marls, clays and shales. The hydrogeology of the lower Ajlun (A1-6), including the southern part of the Jafr basin, was examined by NRA in 1985, by installation of a series of multiple piezometers. In this investigation, the emphasis was put on the northern part of the Jafr basin, north of the "Salwan" fault and west of the "Karak - Wadi Al Fiha" fault, where the aquifer was conceived to be highly confined but neither hydrogeological nor hydrochemical data could be obtained.

In the northern part of the Study area, i.e. north of the "Salwan" fault and the west of the "Karak - Wadi Al Fiha" fault, the lower Ajlun (A1-6) is composed of two lithological units; i) mainly arenaceous facies in the upper part of A4-6 and ii) mainly argillaceous facies in the lower part A1-3. The upper most part of the lower Ajlun formation comprises A5/6, which is composed of alternating marly sandstone, sandy marl and marl with a thickness of about 100 m in total. The A5/6 acts as a capping layer to confine the underlying aquifers such as A4 and A2. The main aquifer is recognized to be A4 formation which consists of an uniform unconsolidated sandstone unit with uniform grain size of medium to coarse. The A4 is only 20 m thick, but it is pervious and highly confined with an aquifer pressure of 30 Kg/cm^2. The A1-3 is an argillaceous unit, which mainly consists of alternating shales and clays, intercalating some impure layers of sandstones and limestones. The variation in lithological facies in the lower section of A1-3 gives complexity to its hydrogeology. No promising aquifers may be distinguished in A1-3.

The regional groundwater flows in A1-6 aquifer are confined by the three major fault systems, the "Arja -Uweina" flexure, "Salwan" fault and "Karak - Wadi Al Fiha" fault. These faults act as impervious barriers, since displacements exceed the total thickness of the A4 formation. (see Fig.5.12) In the Western Highlands, the groundwater flows from southwest to northeast in and along the Arja - Uweina flexure. In the northern part of the Study area, north of the "Salwan" fault and the west of the "Karak - Wadi Al Fiha" fault, the groundwater flows from west to east with a piezometric elevation at 890 m. While south of the Salwan fault, the piezometric elevation is as low as 750 m.

The regional piezometric level is shown in Fig.5.13.

The water salinity is as low as 330 mg/l of T.D.S to the north of the Salwan fault. This may be largely due to the arenaceous character of the hydrogeology in the upper part (A4-6) of the lower Ajlun (A1-6). Where the groundwaters are in a stagnant environment in the confined area east of the "Arja - Uweina" flexure and south of the "Salwan" fault, the water salinity is as high as or more than 1,000 mg/l of T.D.S.

The hydrogeological map of the lower Ajlun (A1-6) is shown in Fig.5.14.

5.3.3 Amman - Wadi Sir (B2/A7) aquifer

The Amman - Wadi Sir (B2/A7) aquifer underlies the Muwaqqar (B3) formation, which is composed of two formations: i) the silicified chert limestone unit of the Amman (B2) and ii) older sandy limestones and calcareous sandstones of the Wadi Sir (A7). The two aquifers are conceived as having hydraulic continuity, and are regarded as a single hydraulic system. The Amman (B2) formation is well jointed and fissured both at outcrops and at depth. The sandy limestones and sandstones in the Wadi Sir (A7) are variable in their texture, well to loosely cemented. The sandstones become friable in their more arenaceous facies. Eastwards, the limestones become more calcareous and/or sandy.

South of the Salwan fault, the B2/A7 aquifer has an average thickness of 100 m, comprising the Amman (B2) 40 m thick, and the Wadi Sir (A7) 60 m thick. Whereas north of the Salwan fault, B2/A7 aquifer is as much as about 200 m thick, comprising the Amman (B2) of 100 m and the Wadi Sir (A7) of 100 m. In general, the B2/A7 thins to the south and thickens to the north.

The piezometric elevations of the groundwater surface in the Western Highlands are as high as 1,200 to 1,500 m, while they are as low as 800 to 900 m immediately east of the "Arja - Uweina" flexure. In the central area of the Jafr basin, the piezometric elevations are in the range of 750 and 800 m with a nearly flat hydraulic gradient on an average of 0.0003. The "Arja - Uweina" flexure acts as a hydraulic barrier to the regional groundwater flows following abrupt drops in the piezometric elevations over a short distance. North of the Salwan fault, the piezometric elevations gradually decrease from west to east and/or northeast. The piezometric elevations are as high as 1,200 to 1,400 m in the Western Highlands, while they are 800 to 1,000 m eastwards from the Husseiniya with an hydraulic gradient on average of 0.005. The measurements of the piezometric heads in and around the "Karak - Wadi Al Fiha" fault using the observation boreholes of JO-3 and JO-4 indicate that the fault is not an impervious barrier with hydraulic discontinuity. The displacement of the fault is about 100 m which is half of the total thickness of the B2/A7 aquifer as shown in Fig.5.12.

The regional groundwater flows in the B2/A7 aquifer are confined by the two major faulting structures "Arja - Uweina" flexure and "Salwan" fault. These faulting structures act as impervious barriers, but they are not continuous barriers because of their complicated structures. In the Western Highland, the groundwater flows from west to east intersecting the "Arja - Uweina" flexure which is composed of a group of discontinuous faults. In the northern part of the Jafr basin, the "Arja - Uweina" flexure acts as an impervious barrier intersecting flows to the east. The flows of groundwater turn from the west to the northwest direction passing through the basin boundary between Jafr and upper Hasa. To the north of the Salwan fault, the groundwater flows from west to northeast and east, and flows out through the "Karak - Wadi Al Fiha" fault which is not a continuous faulting system and acts as a semi-pervious barrier with hydraulic continuity in B2/A7. The regional piezometric level is shown in Fig.5.15.

The Amman - Wadi Sir (B2/A7) aquifer is conceived as a single hydraulic system with hydraulic continuity between the B2 and the A7. In the JT-1 test well which was drilled in the northwestern part of the Jafr basin, however, different piezometric heads were measured in each formation unit of B2 and A7. Drilling with chemical foam jammed at a depth of 358 m which is in the lower part of the B2. No flow return could be obtained due to the substantial circulation losses in the fractured B2 formation. Just after penetrating into the top of the A7 formation at a depth of 387 m, however, the piezometric head in the borehole recovered instantly from 220 to 185 m. Between 380 and 387 m deep, the lithology changed to marls, that were conceived to be part of the B1 formation which confines the underlying A7 aquifer unit. North of the Husseiniya, B2 is slightly confined, while A7 is highly confined with a piezometric pressure of 20 Kg/cm^2 or more.

Due to the variations in lithology, diagenetic and structural phenomena, the transmissivities and/or the permeabilities of the B2/A7 aquifer are extremely variable. The transmissivities vary between less than 1 and more than 10,000 m^2/d depending on the size of fissures and caves in the carbonate rocks. The lower transmissivity zones such as less than 50 m^2/d are regionally mapped in the southern and western parts of the Jafr basin, where the aquifer thickness decreases to less than 50 m. The higher transmissivity zones such as more than 100 to 200 m^2/d which locally includes extremely high values of more than 1,000 m^2/d are regionally mapped in the zones corresponding to the major groundwater flow passes such as passing through "Wuheida" - "Ma'an" - "Al Jafr" and "Husseiniya" - "Jurf ad Darawish" - "Hasa". The regional transmissivities of the B2/A7 are mapped in the Fig.5.16.

The hydrogeological map of the Amman - Wadi Sir (B2/A7) is shown in Fig.5.17.

5.3.4 Rijam (B4) aquifer

The Rijam aquifer has been studied since 1967 as reported by Abu Ajamieh,1967 (Ref.5.1), Parker,1970 (Ref.5.2), AHG,1977 (Ref.5.3) and

NRA,1985 (Ref.5.4). The present report summarizes of these previous studies and includes the result of the VLF survey which was carried out during this investigation.

The Rijam (B4) aquifer comprises crystalline limestone, chalk and chert bands, and is underlain by chalky marls and thick impervious shales of the Muwaqqar (B3) which form the base of this aquifer. It occurs in the center to the northern part of the Jafr basin with elevations of less than 1,200 m. The sequence is thick in and around the Jafr trough with a maximum thickness of about 100 m at the northwestern edge, while it becomes as thin as about 50 m or less in the southeastern part of the Jafr trough. The B4 wedges out eastwards and southwards of the Al Jafr town. The aquifer is saturated only in the central part of the Jafr basin where the ground elevation is less than 930 m as seen in Fig.5.18.

The Rijam (B4) aquifer receives limited recharge by infiltration of the flood runoff through the wadi courses such as in the lower reaches of the wadi Nijl, wadi Arja, wadi Jurdhan, wadi Wuheida, and wadi Husseiniya. The groundwater flows from north east to southeast following the main wadi courses such as shown in Fig.5.19. The hydraulic gradient is as relatively flat as 0.001 in the eastern part of the saturated B4, while it becomes steeper to upstream to the west.

The transmissivities vary between 16 and 10,000 m^2/d, which indicate the karstic nature of the Rijam limestones. The higher transmissivities are mapped locally in the area of 1 to 10 km northwest of the Jafr town where the gradient of the groundwater table flattens to 0.001. Fig.5.20 shows the regional transmissivities of the Rijam (B4) aquifer.

5.4 Hydrochemistry

5.4.1 General

In the course of the study, the hydrochemistry of the following three