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IDENTIFICATION AND ASSESSMENT OF SHARED GROUND-WATER POTENTIAL IN TWO BASINS WITHIN THE ESCWA REGION

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Part One

WADI ES-SIRHAN BASIN

1. Introduction

1.1. General

Proper planning, assessment and development of the total water resource system in any country are key elements in the overall social and economic development of that country.

The water resources in the Arab region (located in arid to semi-arid regions) may be described as scarce.

Improper planning and management of the Water resources, mainly owing to lack of data and adequate and sufficient studies, have resulted in critical water resources situations, and water supply problems in many areas. Moreover, since some important surface and ground-water resources are shared by two or more countries, lack of co-operation, co-ordination and information exchange has been a significant constraint on planning, developing and managing of such shared water resources.

Remote sensing technology has been widely used for exploring and managing the various earth resources of which the water resources constitute a subsystem of the overall system. This remote sensing technology provides a free sky information available for a large number of countries. The Economic and Social Commission for Western Asia (ESCWA) is trying through its programmes to help its member States to benefit from this technology in the studies of these shared water resources and to encourage concerned countries sharing common water resources to establish co-operative programmes to achieve a better and more comprehensive understanding of the total water resource system.

The present report presents its results of a remote sensing analysis of potential surface-water and ground-water resources of Wadi es-Sirhan basin (Figure 1) which is shared by Jordan and Saudi Arabia. Principle contents include a series of maps expressing imagery interpretations of several regional features pertinent to surface and ground-water occurrences including geology and geomorphology. There is also an outline of methodology that illustrates the interpretive approach. Specially produced for this project is a Landsat false color composite at a scale of 1:250,000. This report is anticipated to be of particular value in future programmes.

1.2. Remote sensing: application and benefits

Varying visual aspects cause different factors to become distinguishable at different scales. Owing in part to its resolution and broad perspective, remote sensing imagery expresses important, larger aspects that otherwise may be indiscernible. Consequently, since its inception, remote sensing has become an integral early step to virtually every sort of regional analysis. Normally, precise results are unpredictable but, invariably, analysis provides information that is highly valuable to subsequent interpretation of larger scale data, including a unique means to extrapolate regionally local features and tentatively identify relations that deserve close subsequent study. In this analysis, particularly beneficial initial results have included identification of ground-water aquifers, ground-water discharge and recharge areas, geological and geomorphologic control on ground-water, previously undocumented features which are largely indiscernible from other data sources, and areas of concentration of surface runoff and soil moisture. Finally, the airphoto analysis identified areas recommended for detailed exploration, and those demonstrating a higher ground-water development potential.

Additional benefits from the imagery in its initial analysis will continually provide input for future study and investigation programmes.

Consequently, the findings of this report should be considered preliminary and not simply as an end-product in itself, but rather an initial foundation to supplement more conventional analyses to follow.

1.3. The study area

This study is considered a start for an overall study programme for ESCWA which is planned to study and assess various shared water resources in the member States within the ESCWA region. As instructed by ESCWA, two basins have been selected at this stage: the Wadi es-Sirhan basin shared by Jordan and Saudi Arabia and the Wadi Bana basin shared by the Yemen Arab Republic and Democratic Yemen.

This report presents findings with respect to the Wadi es-Sirhan basin. A separate report has also been prepared for the west Sirhan basin.

Because of the nature of remote sensing, and the regional characteristics of geology, hydrogeology and physiography, the interpretation of certain features had to be extended outside the basin boundaries in order to provide ancillary information on the Wadi es-Sirhan area.

The Wadi es-Sirhan basin is located in the north-eastern corner of Saudi Arabia (see figure 1). A major part of its catchment, however, occurs in the Jordan eastern desert. The basin has an area exceeding 50,000 km^2; it extends from the eastern boundaries of the Azraq basin in Jordan towards the Shaka Al-Jauf are in Saudi Arabia.

1.4. Goals and objectives

This study is a service rendered by ESCWA for the purpose of achieving the objectives of the Arab member States to realize a more comprehensive understanding of their shared water resources, and to be able wisely to plan, develop and manage these resources. The application of remote sensing (RS) in this respect would be most useful in strengthening the hydrological hydrogeological data base, and provide complete and integrated information on the total water resource basin across the political boundaries. This, in turn, will have significant implications on the social and economic development potential for these countries. There is an evident and urgent need in both the Yemen Arab Republic and Democratic Yemen to achieve standardization and homogeneity in interpretation, data handling, monitoring and estimation of the ground-water resources in both countries, particularly for those watersheds shared by the two countries.

1.4.1. Development objectives

The development objectives of the study are as follows:

(a) To help Jordan and Saudi Arabia in assessing, developing, managing and utilizing the water resources of the Wadi es-Sirhan basin, which is shared by the two countries.

(b) To improve communication and technical co-operation between the two countries in the exchange of hydrological and hydrogeological information pertaining to the shared basins in general. This would also help the two countries to acquire information to formulate the needed water strategies and plans of actions at the national and regional levels for water-related projects.

1.4.2. Immediate objectives

The immediate objectives of the study are as follows:

(a) To apply the remote sensing technique in the development, exploration, management and assessment of the water resources in the Wadi es-Sirhan basin shared by Jordan and Saudi Arabia.

(b) To use information obtained from applying such technique to assist the two countries to plan for further detailed investigative programmes needed for various water resources development projects.

(c) To produce hydrological hydrogeological maps on a practical scale.

1.4.3. Specific objectives

In order to achieve the above general objectives, the following specific objectives have to be achieved to the maximum extent possible from interpretation of Landsat images.

A. Ground water

(a) To identify and delineate the potential aquifers in the study area;

(b) To identify qualitatively the ground-water flow systems;

(c) To provide preliminary qualitative analysis of the ground-water recharge-discharge conditions in the area;

(d) To identify and delineate the topographical geologic, and hydrologic control factors on the ground-water systems;

(e) To provide a preliminary assessment of the ground-water potential and locate potential areas for ground-water exploration and possible development;

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(f) To investigate the interrelationship between the ground-water and surface-water resources in the study area;

(g) To identify areas where flood water concentration occurs for possible development;

(h) To identify areas where potential soil moisture storage exists.

B. Surface water

Although repetitive coverage of Landsat imagery is available for various times of the year, it was not possible to obtain the needed time-varying coverage for the study area owing to budget limitations. This situation has limited the scope of investigations with respect to the time variations of rainfall, streamflow, ground-water recharge and soil moisture storage. Moreover, it is not always successful or possible to record and detect the complex sequence of generating sheet-wash and runoff flows. Therefore, the objectives of this study with regard to surface water and other time-dependent parameters will be limited to areas of concentration of flood flows and soil moisture.

2. Investigative procedures

2.1. General

The use of satellite imagery is still a relatively new technique in resource investigations. Although some of the interpretive procedures are similar to those used with conventional aerial photography, the use of satellite imagery provides the interpreter with a much wider range of data from a variety of sensors. For example, a Land Resource Satellite (Landsat 4 or 5) contains a number of sensors which record the electromagnetic energy in wavelength bands 1, 2, 3, 4, 5, 6 and 7.

Five satellites have been launched since 1972. The following tables give some facts about these satellites.

The spectral response for the different bands is as follows:

Spacecraft	Date launched	Date decommissioned	MSS* wavelength bands
1	23 July 1977	6 January 1978	4, 5, 6, 7
2	22 January 1975	25 February 1982	4, 5, 6, 7
3	5 March 1978	31 March 1983	4, 5, 6, 7, 8
4	16 July 1982	______	1, 2, 3, 4
5	1 March 1984	______	1, 2, 3, 4

* Multispectral scanner.

Spacecraft Landsat 4, 5	Band Landsat 1, 2, 3, 4	Spectral response (micro meters)
1	4	0.5 - 0.6
2	5	0.6 - 0.7
3	6	0.7 - 0.8
4	7	0.8 - 1.1
-	8	10.41-12.6

Operating from an orbit of 705 kilometres, the spacecraft of Landsats 4 and 5 can obtain repetitive coverage of the earth's surface every 18 days. The linescan digital data contained in one full scene cover an area on the earth of 185 x 185 kilometres or about 34,000 square kilometres. These digital data are received at earth-based receiving stations and processed onto computer-compatible tape (CCT) so that one full scene can be constructed from one CCT. The CCT covers bands 1, 2, 3 and 4 and is, therefore, termed multispectral (MSS) as it contains a measure of the electromagnetic energy contained in those wavelengths. Because of the repetitive coverage, multitemporal (different seasons of the year) and multispectral image analyses can be applied to problems confronting most types of resource inventory.

Landsat images contain geologic and hydrologic information, but this information must be obtained by analysis and interpretation. Ground-water information can commonly be inferred from geomorphology, surficial geology, drainage, land use patterns, vegetation characteristics, image tones and structural lineaments. In arid environments, some vegetation types may indicate depth to water table or the locations of natural ground-water discharge areas.

2.2. Principles of image analysis

Landsat images represent pictures of the land surface. The images are composed of picture elements or pixels that represent the physical and cultural components of the landscape. As with any classification system, elements which appear similar generally represent similar conditions. Identification, classification and delineation of similar-appearing elements have geologic and hydrologic significance. Thus, the principles of photographic interpretation, such as comparison of tone, colour, shape, relief, size, texture, brightness, location and association, are also relied upon for interpretation of Landsat images. The end-result of a landscape interpretation is an analysis with the following categories:

Drainage and land forms: Watershed size, shape and channel density, geometry of channels;

Vegetation and agriculture: Natural occuring and agricultural and soil characteristics;

Lineaments:	Straight to curved lines formed by a combination of landscape elements, such as fractures, joints, faults, cultural features and vegetation lines;
Lithology and stratigraphy:	Types and sequence of rocks, outcrop areas, etc;
Hydrology and hydrogeology:	Soil moisture, runoff and sheet flows, ground-water recharge and discharge areas, etc.

A detailed review of the interpretation displayed on the figures is presented in subsequent sections of this report.

The foregoing categories are used for a geological and hydrological interpretation. From a geological interpretation, a conceptual geological model was constructed which tied together an interpretation of landforms, lithology, structure and stratigraphy. Interpretation of lithology in Wadi es-Sirhan were based on drainage characteristics, surficial geological features, vegetation patterns and geological structure. The landform interpretation for Wadi es-Sirhan, based on morphology and inferred genetic materials, emphasized the lithology by the density and form of the drainage network. An interpretation of igneous and sedimentary processes, as well as the tectonic, allowed an interpretation of stratigraphy. All of these interpretations were used to construct a 3-dimensional geological model, which formed the basis for ground-water interpretations.

The geologic model, based upon satellite imagery, was then compared with existing geological data to identify areas of correlation and deviation of interpretations. Field-checking will be needed to confirm these features which occasionally identified previously-undetected geological features which may be significant in geohydrologic modelling.

In order to build an interpretative geohydrologic model, several inferences were made. Based on the conceptual geological model, alluvial and bedrock aquifers were identified and depth to the water table postulated in the unconsolidated materials as much as possible. Estimates of ground-water quality, based on infrared radiations and geology, were limited. Locations of ground-water discharge and recharge were postulated as a relationship between topography, vegetation pattern and hydrology. The results of these interpretations yielded conceptual hydrologic models which lent understanding as to the behaviour of the various aquifers, their physical limits and hydrological situations.

2.3. Selection of images

An enlargement of false colour composite images composed of bands 1, 2 and 4 was obtained at a scale of 1:250,000. This colour composite image stresses vegetation, water, agricultural areas, stream channels, structure, lithology and landforms.

This color composite is characterized by an overall red appearance and was used as the basis for interpretation of geology, hydrology and hydrogeology.

The images clearly indicate areas of natural surface vegetation, as compared with dry land irrigation farming; stratigraphic and lithologic boundaries; cultural features and ground-water recharge and discharge areas.

The factor listed below were considered in selecting the Landsat images required for this study. Of course, budget limitations were a major constraint on ordering the various bands and band combinations which would best reflect certain ground features more than others. Moreover, the time-dependent characteristics of stream flow, vegetation, infiltration and ground-water recharge and discharge would require repetitive coverage for different seasons of the year and different climatic cycles. Other factors considered were:

1. Cloud-free images as much as possible.

2. Selection of bands which would best reflect certain geological, hydrological, vegetal and hydrogeological features or properties. For this purpose, colour composites for bands 1, 2 and 4 were selected.

3. Selection of dates in the dry periods of the year to best reflect natural ground-water discharge zones and perennial streams.

4. To have all photos of different sites taken in the same month and same year as much as possible.

The following photos from Landsat "5" (MSS) were selected at a scale 1:250,000 with reference to the computerized photo index received recently from the EROS Data Center in Sioux Falls, South Dakota (United States). The cloud cover for the ordered photos ranged from zero to 5 per cent.

Landsat photos

85131107255 x 0	172	038	10/3/87
85131107262 x 0	172	039	10/3/87
85131807321 x 0	173	038	10/10/87
85016607350 x 0	173	039	8/14/84

3. Hydrological-hydrogeological data base

3.1. Physiography

The Wadi es-Sirhan basin has an area slightly over 50,000 km^2. About 28,000 km^2 of this area are within Saudi Arabia. The Sirhan basin is a tectonic depression extending in a northwest-southeast direction starting from the Damascus basin in the Syrian Arab Republic through the Azraq depression in Jordan and southward till Al-Yaqeen, 40 km south-west of Al-Jauf in Saudi Arabia. The basin may be classified geomorphologically into three areas as follows:

1. The central topographic depression which extends for about 300 km in a northwest-southeast direction along, and slightly east of the eastern borders of Jordan with Saudi Arabia. This wadi depression ranges in elevation from 500 to 600 m above mean sea level (amsl) sloping at an average gradient of 0.28 m/km towards Azraq in Jordan (northwest). The wadi depression is therefore rather flat with an average width of 30 m, thus making the total area about 8,500 km^2.

The Wadi es-Sirhan depression constitutes the main discharge area of a large number of ephemeral streams draining into it from all directions.

2. The Western Drainage Area: This area includes the main tributaries for Wadi es-Sirhan draining from the western Jordanian territory. The most important of these wadis or tributaries are: Wadi Bayer, Wadi Al-Hasida, Wadi Al-Hasat, the lower reaches of Wadi Al-Fakuk, Wadi Al-Ghina and Wadi Hadraj. The wadis are characterized by shallow and wide channels. The total catchment area of these major streams is about 11,780 km^2. The general slope of these streams is about 2-5 m/km towards the northeast. The highest mountains in this area are Jebel Assuwan, Jebel Bayer and Jebel Tbaiq, which has the highest elevation (1,366 m/amsl). This area has a large number of mud flats and salt lakes. The largest of these is Al-Hadhawdhe salt lake which has an area of about 400 km in the central part of Wadi es-Sirhan.

3. The Basalt Plateau: This area constitutes the eastern and north-eastern parts of the Wadi es-Sirhan basin and extends for about 220 km to the south of the borders of the Jordan panhandle into Saudi Arabia. The highest elevation in the basalt plateau within Saudi Arabia is about 1,109 m at Jebel Al-Almoud. The land surface slopes westward towards the main Wadi es-Sirhan depression at rates ranging from 6-12 m/km^2. The basalt plateau is dissected by a number of relatively small streams, the most important of which is Wadi Al-Aily. A relatively large number of salt lakes and mud flats are scattered in this area which are fed by local steams during the rainy season. The most important of these are Khabari Dougrah near Turaif. The basalt plateau area forms a landscape of flows, fissures and fusions, and isolated volcanoes and topographic depressions. The surface of the basalt flows has been cracked, and broken into blocks.

3.1.1. Climate and precipitation

The Sirhan basin is affected by tropical air masses throughout the year. In winter, low pressure areas coming from over the Mediterranean and north Africa meet the colder air fronts coming from the north and result in rainfall between October and May. This effect diminishes southward. In summer, the area is affected by the extension of the Indian thermal depression, giving rise to hot weather conditions.

Information indicates that rain storms in this area are characterized by short duration, low frequency and high variability. The annual total rainfall is highly variable. The annual average over the area ranges from 50-60 mm.

3.2. Water resources and utilization

3.2.1. Surface water resources

The surface water resources of the Sirhan basin constitute the ephemeral stream flood flows caused by local rainfall. There are no perennial streams or springs within this basin. There is only a small amount of data on streamflow measurements on the major streams in this basin. Therefore, indirect estimates are based on analysis of the catchment characteristics and some rainfall properties. The average runoff coefficient was calculated as high as 4 per cent for the western drainage areas, and 2 per cent for the eastern basalt plateau. However, it does not exceed 1 to 1.5 per cent on the basin level (Arab Centre for the Study of Arid Zones and Dry Lands, 1982).

Assuming an average basin rainfall of 50 mm/yr, and using an average runoff coefficient of 1.25 per cent, the average annual precipitation water and runoff volumes are calculated at 2,500 and 32 million cubic metres, respectively.

It can be said that no real development of this resource has taken place in either country. However, floodwater accumulations in the topographic depressions and mud flats constitute temporary water sources for the bedouins and their cattle.

3.2.2. Ground-water resources

Ground water occurs in different parts of the study area at different depths, different water quality and different yields. More details on the ground-water conditions and potentials will be given below.

Significant development of the ground-water resources has taken place in the Sirhan basin in Saudi Arabia, mostly for irrigation purposes. More than 1,000 wells were reported drilled and operational in Saudi Arabia, producing about 100 million cubic metres (MCM) of water per year. Such ground-water development was based on a few studies only, mostly on the reconnaissance level. On the other hand, very little ground-water development has been reported in Jordan within Wadi es-Sirhan basin. A small number of wells have been reported. No specific detailed studies were carried out in this basin in Jordan. However, the Jordanian Government has plans for conducting detailed studies including drilling of test wells, and test holes.

Although, the annual rate of replenishment for the ground-water aquifers seems to be too low, large volumes of water are believed available in underground-water storage.

3.3. Geology

3.3.1. Stratigraphy

The surface of the Sirhan Basin is covered by sediments ranging in age from Eocene/Tertiary to the Quaternary. However, these sediments are covered by different basalt flows and volcanic tuffs in the eastern part of the Sirhan basin. Triassic and Jurassic rocks were only identified in deep wells in the Turaif and Ara'ar areas. They were identified as consisting of dolomites and shale which were uncomformable laid on top of the Paleozoic rocks.

Cretaceous rocks were also encountered in wells, particularly in the eastern and western dips of the Sirhan depression. The lower Cretaceous (rocks) consist of sandstone while the middle Cretaceous rocks (middle and upper Cenomanian and Turonian consist of limestone and marl; the upper Cretaceous rocks consist of carbonate rocks, marls, cherts and phosphorites.

The Tertiary rocks on the other hand cover most of the Sirhan basin, except in the eastern parts where they are overlain by volcanic rocks. The tertiary sediments consist of carbonate rocks: limestones, chalks, marl and marly limestones, with some chert beds.

The Quaternary deposits, which are mainly continental in origin, are of the Pleistocene and Holocene ages. These sediments fill the morphological depressions in the area and consist of conglomerates, gravel, sand, silt, clay and calcareous deposits.

The volcanic rocks cover a large area in the eastern and northeastern side of the Sirhan basin. They range in age from Neogene to the Quaternary. The volcanic eruptions took place through deep-seated faults which appeared on the surface as volcanic necks scattered all over the area. The volcanic necks are sometimes shown aligned along some southeast-northwest faults. The thickness of the basalt flows range from a few tens of metres to more than 200 m in the study area.

The Palaeozoic sandstone outcrop is in the Al-Jauf area south of the Sirhan basin. It was encountered in the Ara'ar area east of West Sirhan at depths between 1,300 to 1,500 m below ground surface.

Table 1 gives a stratigraphic column for the study area.

3.3.2. <u>Structure</u>

The Sirhan basin is a northwestward-trending topographic and structural depression positioned between the Jordan Arch-Central plateau region on the west, and the basalt plateau-Risha uplift on the east. The basin represents a zone of subsidence as a result of subsurface faults with large vertical displacement (50-1,500 m) which affected the upper cretaceous sediments during its deposition, particularly during the maastrichtian and also due to the subsequent faults of smaller displacements during the Cainozoic. This tectonic movement and subsidence resulted in thick deposits in this basin particularly for the sediments of these ages. The Sirhan depression rises gradually southward towards the Arabian Shield.

The shape and the configuration of the Sirhan depression is outlined by Tertiary and Quaternary deposits in its central part.

Stratigraphic column in Wadi es-Sirhan basin

Age				Symbols	Sedimentary rocks	Volcanic rocks
Quaternary				Q V	Gravel, sand, silt and clay	Different basalt flows and volcanic tuff
Tertiary		Pliocene-Miocene		T_e	Sand, marl, limestone (50-160 m)	
TERTIARY		Eocene	Upper	T_d	Chalk, mud and limestone (57 m)	
			Middle	T_c	Chalky marl and marly limestone (57 m)	
			Middle-Lower	T_b	Chert, marl, limestone, partly covered with aeolian sand	
		Palaeocene	Lower Eocene and Upper Paleocene and Danian	T_aC_d	Marl, limestone, marly limestone, silicified limestone (together with Tb 80-150 m)	
CRETACEOUS	UPPER	Maastrichtian, Campanian, Santonian		C_c	Marly limestone and chert in Jordan side, changes to chalky marl in western Sirhan (53-350 m)	
		Turonian		C_b-C_c	Limestone, dolomites, marl and marly limestone	
		Cenomanian	Upper and Middle			
			Lower	C_b	Limestone, marl and sand intercalations (20-90 m)	
	Lower			C_a	Sandstone	
Jurassic				J	Calcareous, argellaceous and evaporitic deposits	
Triassic				T_r	Sandy limestone, marl and dolomite	
Palaeozoic				P_z	Sandstone	

4. Landsat photo interpretation and water resources of the Wadi es-Sirhan basin

4.1. General

Because of the nature of remote sensing investigations, the interpretation of bedrock areas, outside the Wadi es-Sirhan catchment area was used to provide ancillary information for the Wadi es-Sirhan area.

The following pages briefly describe the interpreted features. The examination of each feature or set of features mentions various regional characteristics which illustrate the overall interpretative processes from which the maps are derived.

The initial step in this preliminary investigation of water resources in Jordan was the preparation of a small-scale topographic map at a scale of 1:25,000 which could serve as a base map on which the boundaries of catchment areas and drainage basins, precipitation and geologic data could be overlain. The divide surrounding the drainage basins was delineated on false-colour Landsat images. Where regional relief was low and did not allow visual identification of divides on the photos, boundary lines were transferred to the drainage basin map from topographic maps. A small-scale map of the drainage network was also prepared in the same manner. The resulting drainage basin map was then reduced and overlaid on the topographic base map. The isohyetal map of the study basin was also superimposed on the other parameter maps. All these maps are at the same scale and may be readily compared in order to bring out such relationships as may exist between location, altitude, shape and size of watershed on one hand, and precipitation and rock types on the other hand.

The next step was to identify, locate and describe those drainage channels where streamflow could be observed. Lastly, areas supporting vegetation were also identified as a basis for inferring other hydrological conditions.

The areas with vegetation of the study location are also important to such a report devoted to water resources because plants are an excellent indicator of water availability during their growing season. However, seasonal variations of plant growth could not be studied at this stage because of inavailability of repetitive photos for the different months and different seasons of the year.

Seasonal plant growth in alluvial valley floors takes on different meanings depending on site location, which in turn may reflect one of the many cultural, ecological or economic patterns of human activities. In the valleys, relatively low elevations near the drainage basin divide the catchment areas (where precipitation is relatively low because of altitude, and population density is also low). Seasonal variations in plant growth do not imply varieties in agricultural crops.

4.2. Results of Landsat image interpretation of the Wadi es-Sirhan basin

4.2.1. Introduction

Four Landsat images have been studied to determine the capability of remote sensing techniques as a support for water resource evaluation of the Wadi es-Sirhan basin and Landsat images have been interpreted for hydrogeological purposes, closely defining the objectives of the study.

1. Geographical setting of Wadi es-Sirhan.
2. Geomorphological setting.
3. Geological setting.
4. Structural setting.
5. Tectonic setting.

Once a framework is settled to answer the above questions, the interpreter's mind is set to investigate the Landsat images, knowing that the ultimate objective is the evaluation of the water resources of the Wadi es-Sirhan basin.

Wadi es-Sirhan is a prominent geomorphic feature in the south and southwest of Jordan, and northern Saudi Arabia, representing a structurally controlled depression. The wadi runs for about 100 kilometres in a northwestern direction, and ranges in width from 25-40 kilometres. The catchment area of the Wadi es-Sirhan basin is bounded by latitudes 29^{o} 30'-32^{o} 15' north and longitude 36^{o} 40' east, occupying an area exceeding 50,000 km^2.

Wadi es-Sirhan is a structurally controlled depression formed as a result of Neogene faulting that dominated and shaped the present layout of all Arabia and the effect thereof is very clear in south and southwestern Jordan and northern and northwestern Saudi Arabia.

The morphostructural setting of Wadi es-Sirhan is a feature of the tectonic setting of the Arabian plate bounded westward by the Dead Sea-Gulf of Aqaba shear (transform fault plate margin) and to the southwest by the Red Sea rift structure. Accordingly, the structural setting of the Wadi es-Sirhan basin is mainly controlled and shaped by various Neogene faults associated with the above described tectonic setting. The wadi itself forms a relatively pronounced downfaulted block, being one of a series of faults that caused on one hand the rise of the Pre-Cambrian Basement Complex (rocks along with Pre-Neogene formation) that form the western highland and Red Sea hills physiographic provinces in Jordan and Saudi Arabia respectively. On the other hand, these faults brought down the Phanerozoic sedimentary cover over a series of step faults giving rise to a series of structural depressions like Wadi es-Sirhan separated by zones of local uplift and doming caused in places by the associated volcanicity during the Neogene time.

The Wadi As-Sirhan basin lies over formations that range in age from the uppermost Cretaceous, Paleogene, Neogene, and Quaternary eras with the exception of Tertiary-Quaternary basalt. The formations underlying the basin are all made of sediment rocks.

The lithologies are characterized by carbonate sequence formed of limestone and chalk (Paleocene and Eocene), overlain by sandstone and marl with subordinate limestone (Miocene-Pliocene), overlain at the upper part with gravel, sand and clay of Quaternary age. Prior to the Quaternary fill, basalt was extruded above the early Tertiary carbonates, and chalk as well as Miocene and Pliocene sandstone and marls.

All formations that preceded the Quaternary sediment were affected by faulting to some extent. Faults associated with the Red Sea rift and Dead Sea transform are known to have been activated (rejuvenated) during the Neogene era and possibly rejuvenated in the Quaternary era.

With the above described data, three significant aspects emerged to be considered in the analysis and interpretation of the Landsat images covering the Wadi es-Sirhan basin.

1. As the Wadi es-Sirhan basin is underlain by sedimentary formations, and their lithologies indicate their suitability as an aquifer formation, the hydrogeological evaluation requires a subsurface geological and hydrogeological input. Such input includes variation of rocks at depth, their thickness, hydrogeological properties (as aquifer and aquitard) as well as data on ground-water level, flow and quality.

Therefore, the data on the Wadi es-Sirhan basin obtained by remote sensing need subsurface input, and cannot be used as the only criterion in a water resource evaluation process. Such subsurface geological and hydrological input has been included elsewhere in this report.

According to Landsat images, interpretation should be thought of as supporting input for water resource evaluation. However, if the matter is further extended to include Water Resource Management and environmental planning, then its value substantially increases as a source of data and powerful tool in management. As a support, remote sensing products should be analysed to provide the following data:

(a) A reliable geographic data base, using Landsat images, to plot hydrological, hydrogeological, geomorphological, geological, structural and land-use data;

(b) Drainage network, drainage density, and delineation of catchment area;

(c) Major geomorphic features;

(d) Major formation boundaries;

(e) Lineament maps, particularly for regions like the Wadi es-Sirhan basin, located in a tectonically significant area, closely affected by plate movement.

2. From the structural and tectonic setting, it is obvious that the area was continuously stressed during the Neogene time. As a result, various sets of faults disrupted the area, influencing the distribution of rocks and their depth and characteristics, and controlled the drainage, the location of volcanic field and thicknesses of Quaternary cover. All of the above aspects are required for hydrological and hydrogeological analysis. The Wadi es-Sirhan basin may well be described as a monostructural feature, greatly controlled and shaped by faults. Faults show up very well in Landsat as lineaments, which in fact can be better delineated by Landsat image analysis than by any other method, namely aerial photography or field mapping, particularly for hydrogeological purposes.

3. For trans-country studies, Landsat images are an ideal geographic data base, particularly for hydrological, geological and environmental purposes. The frontier areas represent zones where variable nomenclatures, definitions, styles and kinds of data occur; therefore, Landsat provides an ideal base for compilation and homogenization of data across the frontier. The value of using Landsat images increases with the size of the area to be investigated, and with difficulties in accessibility, and shortage of time.

4.2.2. Present input from Landsat images of the Wadi es-Sirhan basin

Taking into account the aspects described above, deciding on the input required using Landsat images, two main maps were produced:

1. Broadly, a geographic data base plate (see plate 1) showing drainage network, catchment area, significant geomorphic features and land use, all directed to serve the purpose of water resource evaluation.

2. A fault lineament plate (plate 2) over broad lithological contact to show zones of intensive fracturing and to provide a base to understand faults. This is crushed in the process of subsurface construction of formations and structures.

A. Geomorphic interpretation (plate 1)

The Wadi es-Sirhan basin is made up of a catchment area that passes through the volcanic plateau to the east and northeast and turns westwards near the Al-Azraq basin. Structurally, the Wadi es-Sirhan basin extends in a northwestern direction and should include the Al-Azraq basin as a morphostructural feature. However, owing to structural and subsurface configuration reasons, the two basins become hydrogeologically separate.

On the western side, the catchment is defined by the water divide that separates the Wadi es-Sirhan basin from the Al-Jafar basin.

Drainage flows into the Wadi es-Sirhan basin from almost all directions. The drainage network at the western side is controlled mostly by structure and to a lesser extent by lithology. Streams move from one set of a fracture or fault and course into another, forming a rectangular set. In fact, the landforms themselves are shaped by faulting, and most of the basins are bounded by sets of faults creating depressions toward the basin and escarpments binding them.

Drainage densities, closely related to intensity of faulting and fracturing of the original rocks, differ with the age of rocks. A noticeable contrast is, however, observed between drainage density in the sediments and those over the volcanics. Owing to lithological and local geomorphologic aspects (presence of radial drainage around volcanoes), the microrelief of the volcanic rocks does not enhance surface flow and thereby promote internal drainage. As a result, few streams originating in the volcanic terrains reach Wadi es-Sirhan. Drainage density also noticeably decreases in dunes and sandsheet covered areas, and in recent rocks in general. In contrast, over older sedimentary lithologies (Pre-Pliocene) which represent formations affected by intense Neogene faulting, drainage becomes a conspicuous feature.

Recent reshaping of the drainage occurred in areas with some contrasted physiography, i.e., at the foot of escarpments, resulting in higher reflectance observed in the Landsat images. The intensive drainage system flowing from the west into Wadi es-Sirhan is abruptly terminated along the margin of Wadi es-Sirhan, giving rise to noticeable tonal differences and often marking a lineament. Such features indicate the fault-controlled nature of the wadi, which continuously influenced its evolution relative to surrounding terrain, and also caused preferential deposition of recent deposits along the wadi. As a result, even modern flow coming over relatively solid, well-drained land will be thinly distributed, infiltrated and evaporated over the Wadi es-Sirhan fill deposits. Volcanic rocks in the north and northeastern part of the area form a dark tonal raised land over which the water divide of Wadi es-Sirhan passes. The volcanic bile is well differentiated into at least three or four phases of volcanic flow. The earliest lava flows form a subdued topography, intensely weathered, and in parts fractured and characterized by variable microrelief, internal drainage and several playa deposits. The youngest phase of volcanic flow shows clearly the modern form of the volcanic cones, and characteristic radial drainage with lava flowing, following pre-existing topographic depressions characterized by their shape and tone. Some of the young volcanics flowing over the Wadi es-Sirhan depression, create a localized change in the direction of surface water flow, separating topographically the Wadi es-Sirhan basin from the Al-Azraq basin. However, as a structural feature, these two basins may be considered continuous, as mentioned above. Farms, villages and roads located at Wadi es-Sirhan can be easily delineated. Furthermore, the pattern of agriculture and even vegetation health can be observed. So far, the land use in the wadi has not yet caused any significant changes in the image reflectance that could be taken as an indication of land deterioration and degradation.

B. Lineament map (plate 2)

Three sets of major lineaments were delineated in the area, ranging from a few kilometres to a few hundreds of kilometres. Most of the lineaments mapped represent high angle faults commonly inherited by drainage, or forming straight fault escarpments readily differentiated in Landsat images. Playas and mudflats, often of linear or triangular shape, are characteristically developed over fault zones, and may well be used as criteria for recognition of fault lineaments.

Plate 1. <u>Geomorphic map of Wadi es-Sirhan basin</u>

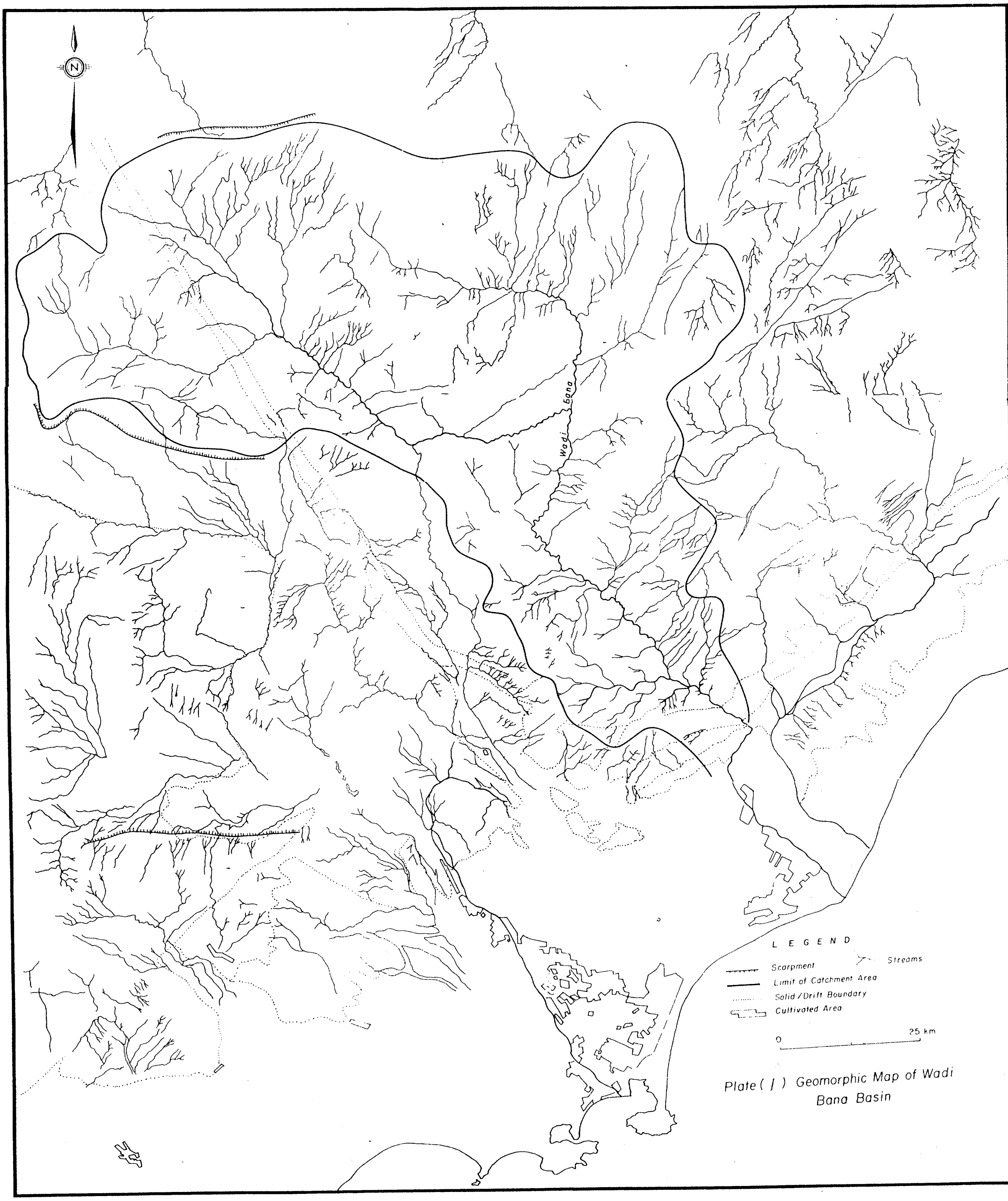
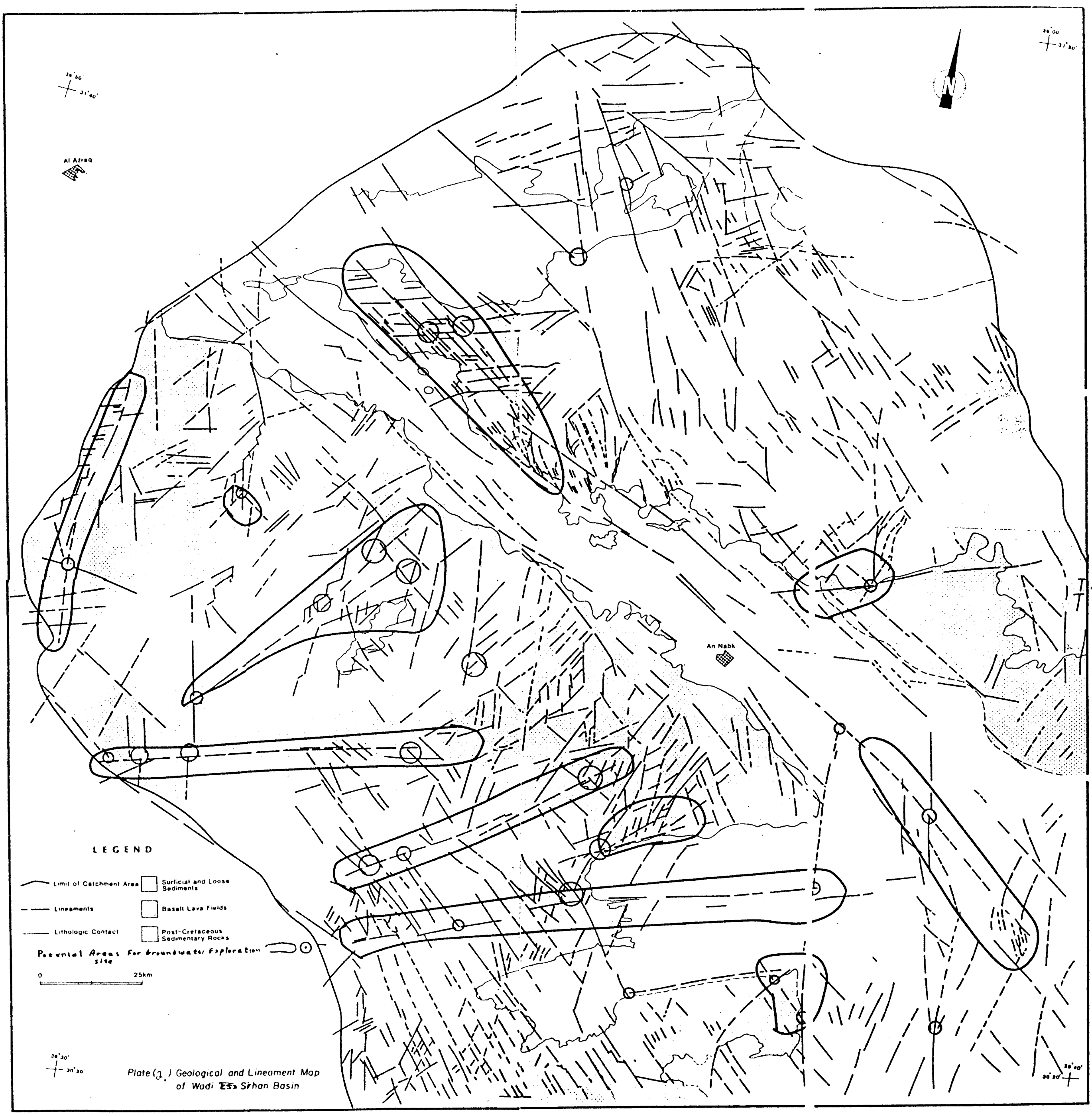


Plate 2. <u>Geological and lineament map of Wadi es-Sirhan basin</u>



The three major sets of fault lineaments may be distinguished by their orientation as follows:

1. The Red Sea trend fault lineament constitutes a major lineament trending in northwest-southeast parallel to the Red Sea Rift trends. Fault lineaments defining Wadi es-Sirhan belong to this category as well as two major fault lineaments to the west separating Wadi es-Sirhan from the Gafar basin and two other major fault lineaments binding the volcanic from the east. Lineaments with the Red Sea trends are conspicuous to the east of the areas affected by the Dead Sea Shear structures. The first significant set of northwest trending faults to the west is represented by the Ras-en-Naqub fault bringing older rocks (Pre-Cambrian and Paleozoic) in front of Cretaceous formations, forming a major escarpment considered one of the most prominent geomorphic features of Jordan.

2. The Dead Sea trend lineament is represented by major lineaments trending parallel to the Dead Sea fault zone, i.e., north-northeast directions. Such fault lineaments become more intense westward towards the Red Sea, and decrease eastward where the Red Sea fault lineament becomes dominant. Generally, such lineaments represent disrupting faults of the Red Sea trend. However, the age relationship between faults is a complex subject that will be touched upon later.

C. Mediterranean trend lineaments

Mediterranean trend lineaments represent east-west trending lineaments that become more frequent to the north and northeastern portion of the area. The lineaments are commonly displaced and terminated by the northwest (Red Sea trend) fault lineaments. In the northeastern portion, they run for a considerable distance (> 100 kilometres). The age and origin of these fault lineaments is a complex subject. Such lineaments in southwest Jordan are considered to represent dragged segments of older faults due to the shear effect of the Dead Sea transform. In south and southcentral Jordan, these faults were considered to represent Pre-Neogene structures developed since the Cretaceous time and rejuvenated during the Paleocene time owing to the motion of Africa and Arabia relative to Europe along the Mediterranean plate margin, prior to the Red Sea rifting.

The most characteristic feature about these lineaments is that they represent faults associated with major crustal movement, and hence represent deep and significant fracturing of the earth's crust.

Faults represented by lineaments parallel to the Red Sea rift and the Dead Sea Shear are structures that originally initiated in the Miocene era and regenerated during the Pliocene-Pleistocene and even in the Holocene time. As a result, age relationship appears complex, using the simple criteria of cross-cutting relationship. As a result, in places the northwest-trending faults appear to displace the north-northeast trends, and in other places the opposite occurs. Both structures and in particular those associated with the Dead Sea Shear show smaller faults (second order) faults oriented obliquely to the main trend, thus giving rise to smaller lineaments trending in other directions (northeast direction is noticeable). The Mediterranean (east-west) fault trends are mostly displaced by the previously mentioned Neogene faults;

however, in places there is evidence of renewed movement along these faults, which again give rise to conflicting criteria regarding the relative age of the east-west set of faults.

Evidence of rejuvenation of faults is well recognized in relationship to the volcanic sequence underlying the eastern and northeastern portion of the Wadi es-Sirhan catchment area. The volcanic sequence is well differentiated into at least four episodes of volcanic flows. Each phase of volcanic flows is now well characterized by tonal, textural and reflectance characteristics in the Landsat images. Reflectance increases with the age of these volcanic sequences, owing to erosion, fracturing and deposition of recent sediments and formation of playa deposits over older lava. Such lava is characterized by subdued topography overlying the Paleogene sediments and often remains in patches. The microrelief of these old lavas is variable, with depression receiving recent sediments or becoming sites of playas formed by the capillary rise of ground water. Wherever this old sequence of the volcanic series is recognized (best from Landsat), the underlying sediments (mostly representing aquifers) can be reached at relatively shallow depth, under the volcanic rocks. The youngest volcanic flow, with craters well preserved, can be clearly distinguished by thin low reflectance in Landsat (owing to original colour) and by well developed localized radial drainage. Delineating various volcanic flows using Landsat enables hydrogeologists to estimate drilling thicknesses in the sedimentary aquifers below. Furthermore, the distinction of the various flows enables the construction of age relationships between different phases of lava flow and rejuvenation of movement along faults. The Wadi es-Sirhan fault system (including Wadi es-Sirhan faults and associated parallel faults) provided adequate channels for lava extrusion, and directed their flow according to the fault-controlled immature topographic forms. As a result, the volcanic flow may be observed covering the disrupted ground by these northwest-trending faults. Latter rejuvenation of movement caused the faulting and fracturing of these early extrusions, but again the fault is covered by younger volcanic flow.

Such relationships constitute reliable and direct evidence of fault rejuvenation. These lava flows (commonly older phases) were themselves disrupted by renewed faulting and developed a noticeable fracturing system. Over such fractured and faulted lava, the ground water preferentially rises into the volcanic pile, forming a series of linear playa deposits characterized by extreme reflectance aligned along the fault. Such a feature is indicative of the shallowness of the ground water under these fractured areas and also points to the possible existence of ground water in the fractured vesicular lava.

A point of special interest in lineament interpretation is related to the intensive east-west faulting in the northern and northeastern portion of Wadi es-Sirhan. East-west faulting is well recognized in northwestern Jordan represented by the Sevegah fault zone. As mentioned above, these faults are considered be originally of Pre-Neogene age. The occurrence and by turn the geological and structural effect of these faults may have well caused the displacement of the formations in such a way to bring two different lithostructural domains adjacent to each other (strike-slip faults) over the zone separating Wadi es-Sirhan from Al-Azraq basin. Such configurations have existed prior to the Neogene northwest-northnortheast faulting mentioned above to follow the Red Sea Rift and Dead Sea Shear, respectively. As that time, the geology (now the subsurface geology) was different from the north and south on both sides of a major northwest-trending normal fault and the Wadi es-Sirhan faults were superimposed over previous east-west faults, producing the structural depression of Wadi es-Sirhan but keeping lithostructural differences caused by east-west faults. As a result, Wadi es-Sirhan continues northwestward as a morphostructural feature, but in the subsurface the lithostructural domain keeps enough differences to separate hydrogeologically this monostructural zone into two ground-water basins.

As mentioned above, volcanic flow directed by fissures, faults and controlled topography promoted a westward flow into Wadi es-Sirhan, creating some topographic barriers, thus including more reasons to separate the es-Sirhan from the Al-Azraq basin.

When larger areas surrounding Wadi es-Sirhan were investigated for regional purposes, it was found that, over southern and northern Saudi Arabia, cases of morphostructurally controlled basins were repeated to the west and east of Wadi es-Sirhan. Such morphostructural basins are bounded by escarpments or raised land resulting from the intersection of the three sets of faults reviewed in the present study. The original shape of the basin is thought to be triangular, with arms trending north-northeast - south-southwest - northwest-southeast and east-west i.e., controlled by the Dead Sea Shear, the Rea Sea Rift and earlier Mediterranean east-west trends. The present practice therefore is to demonstrate significant examples of the role of understanding tectonics and structures in the process of regional evaluation of water resources, an oft-neglected subject.

Indeed, the whole region adjacent to the Red Sea Rift or affected by Red Sea Neogene faulting is affected by the Dead Sea Aqaba Shear extending into the Syrian Arab Republic and Lebanon. Turkey has exceptionally good targets for remote sensing studies covering water (and soil) resource evaluation. As an example, the Sinai and Wadi Araba Rifts structures between the two Yemens and the Nuba area between the Sudan and Egypt, Somalia and Djibouti are excellent examples that demonstrate the role of Neogene and Neo-tectonics in water resource evaluation as rifted and seismically active zones.

4.2.3. Hydrogeology

The hydrogeological conditions of the Sirhan basin are controlled by a number of factors, namely: climatic, topographic, geomorphologic, hydrologic and geologic.

The arid climatic conditions presently prevailing over the study area would have significant effects on the ground-water régime. The scarcity of rainfall and the high potential evapotranspiration would limit the annual replenishment to a very small fraction of the total annual rainfall. However, the paleoclimatic conditions which prevailed 10,000 to 40,000 years ago, and which were characterized by high rainfall periods, are more important in the formation of the present ground-water reservoirs.

The topographic and geomorphological factors would control the rates and areas of concentration of flood flows, which contribute some recharge to the ground-water reservoirs. The present topographic and geomorphic conditions give rise to great dependence on indirect recharge from surface runoff along the stream channels, alluvial fans and from the topographic depressions where flood water accumulations take place in winter.

The geological factors that mostly control ground-water conditions include the lithology, stratigraphy and the structure.

Significant vertical variations in lithology exists in a vertical direction as well as horizontally. Variations in the depositional environment have given rise to lithofacies changes in these directions. The result of vertical variations would create confinement of the ground-water horizons and variations in their hydrostatic (piezometric) pressures. On the other hand, lateral lithofacies variations would result in vertical boundary conditions with regard to the ground-water flow and possibly to termination of some aquifers.

The alluvial deposits, the volcanic rocks, the carbonate rocks and the sandstone rocks existing in the Sirhan basin all form potential water-bearing rocks. These positions relative to the saturated zone and degree of fracturing, jointing and stratification control their actual status as good, moderate or poor aquifers.

On the other hand, the geological structure, both on the regional and local level, would have significant control over the ground-water movement, both vertically between different aquifers by leakage and/or fault planes, or horizontally by forming conduits or barriers to the ground-water flow.

The Sirhan basin, being a tectonic depression, where subsidence and step faulting have taken place, and the consequent thickening and lithofacies changes of sediments towards its centre, have significant effects on the thickness and horizontal extent of the water-bearing rock formations. Depth of aquifers would be highest along the central northeast-trending depression. On the other hand, depth of water level or piezometric surface is expected to be highest along this same centre line. Confined conditions would be more dominant towards the central parts of the basin.

The water-bearing formations in the Sirhan basin may be grouped or classified into five main ground-water systems (aquifer systems); each system may consist of more than one aquifer (subsystem). Geologic formations which seem to have similar hydrogeologic properties, with regard to storage and transmitting properties, have been grouped together in one system. However, head variations with depth are still expected to occur within the same aquifer and aquifer system.

The lower aquifer system is divided into two subsystems: the Paleozoic sandstone (A), and the Triassic-Jurassic subsystem. The Lower Paleozoic sandstone aquifer sub-system consists of the Cambro-Ordovician Disi Group. Four formations have been recognized within the Disi Group on the basis of lithology. These formations are the Saleb, the Ishrin, the Disi and the Sahm. The hydraulic characteristics of these four formations are different, but they are hydraulically connected and comprise one aquifer system. However, this aquifer is expected to be at excessive depths over most of the Sirhan basin. The depth of this aquifer decreases towards the south.

The Triassic and Jurassic sandstone aquifer subsystem consists of coarse to fine grained sandstone with interbedded shale and calcareous sequences. The thickness and the hydraulic properties of this aquifer are not known in the west Sirhan basin. The lower Cretaceous sandstone aquifer may be hydraulically connected to the overlying Cenomanian and Turanian carbonate aquifer system towards the central part of the basin. The water quality of this aquifer is expected to be the worst among all aquifer systems.

The middle aquifer system includes Cretaceous rock sequence. The Cenomanian and Turonian limestones may form relatively good to moderate aquifers in the study area. The primary permeability of these formations is very low. However, where secondary permeability has been developed by fracturing or karst solution cavities, they have high permeability and form good aquifers. This is one case where remote sensing information on tectonic structure would be most useful for siting exploratory and production wells.

The Campanian and Maastrichtian of the Eocene intercalated limestone, silicified limestone, chert and phosphorite form the upper aquifer system. This system is expected to be good in the Jordanian side of the west Sirhan basin. However, the lithofacies changes which occur towards the east, where this formation becomes chalky marl in the central part of the basin, make this of more importance. In much of west and central Jordan, they underlie a cover of younger sediments at depths that can be economically drilled. Ground-water movement generally follows the regional dip which is eastward and northeastward in the Jordan side of the basin, while it is westward and southwestward in the basalt plateau area. In the central part of the basin there is a gentle hydraulic gradient towards the northwest, indicating also the direction of movement. However, ground water in the Tertiary and Cretaceous formations is also expected to flow from the northwest, the Azraq basin in Jordan, towards the west Sirhan basin in the southeast.

The Lower Tertiary-Eocene formations are also part of the aquifer system. They form a good aquifer in the Sirhan basin. However, it will be at greater depths towards the centre of the depression. This formation is composed of chert, limestone, marl and chalk. The water-bearing properties of the aquifer vary from poor to excellent. The quantity of water available from this aquifer depends on the extent of jointing and solution cavities in the limestones and chalks. This aquifer may be hydraulically connected with the overlying aquifer in the Neogene sandstone and sandy marl and limestone. In some places, recharge from the land surface or the overlying basalt may occur depending on the degree of fracturing and jointing of the surface rocks, the permeability of the top soil and the overlying unindurated sediments, as well as the occurrence of major stream channels and surface depressions which form points of concentration of surface runoff.

Upper Neogene syntectonic conglomerates, Early Pleistocene sands, and clastics and more recent alluvial clastic deposits form the shallow aquifer system extending mostly in the topographic lows. This aquifer would be under water table conditions, and might have some hydraulic connections with the underlying bedrock aquifers.

A. Aquifer recharge

Direct infiltration of rainfall is an important source of ground-water recharge in humid and sub-humid climatic zones. However, recharge by direct infiltration is significantly diminished in arid climatic zones. Except for sandy soils and outcrops of permeable rocks such as gravelly deposits, sandstones and fractured limestone or basalt, the land surface in such regions has a low infiltration capacity. In the western Sirhan basin, direct infiltration of rainfall occurs primarily in the major drainage channels and forms infiltration of floodwater accumulations in the surface depressions scattered in the central and basalt plateau and from infiltration of floodwater accumulations in the surface depressions scattered in the central and basalt plateau areas. The initial filling of these depressions when the mud cracks are not yet fully closed is expected to contribute some discharge to the shallow ground water.

Subsurface recharge occurs locally in some aquifers by inter-aquifer flow along joints, faults, and karst solution channels. This type of recharge occurs in the subsurface and its occurrence and distribution is mainly controlled by faults and fractures as well as the hydraulic gradient between aquifers. As a result of the detailed photogeologic study, important structures and fault/fracture zones have been mapped which will likely prove to be major traps or conduits for increased ground-water flow.

These systems are separated from each other by less pervious rock formations which may act as aquitards.

B. Potential areas for ground-water exploration

Based on the results of the interpretation of the topography, drainage, geomorphology, geology, hydrology and hydrogeology, the most promising areas for ground-water exploration have been determined (plate 2). Pilot drilling sites within each of these areas have also been selected. The delineated exploration areas and the selected drilling sites apply to all the potential aquifers existing at each specific site as inferred from the local geology. The well depths would depend on the target aquifers intended to be explored.

Because of thickening in the sedimentary formations, depth of any target aquifer within the Wadi es-Sirhan basin generally increases from the east and west towards the central part of the Sirhan depression. The depth of any target aquifer within the depression areas increases from southeast towards the northwest.

4.2.4. Summary

1. Analysis and interpretation of Landsat images covering Wadi es-Sirhan and adjacent areas made possible the establishment of a reliable geographic data base for the purpose of water resource evaluation.

2. Such a data base, if extended to include more data on land use, soil and natural vegetation, would demonstrate the ability of remote sensing techniques in natural resource planning and management.

3. From the Landsat images of Wadi es-Sirhan, it was possible to delineate its catchment area, drainage network, drainage density, type and pattern of drainage and to establish geomorphic and morphostructural relationships.

4. Major lithological types were differentiated, and their boundaries were delineated. Volcanic rocks were further differentiated and characterized and their relationship with faults established.

5. Fault lineaments were mapped, classified in accordance with their trend, and the faults and fractures producing the lineament were structurally analysed. Their relative age, depth, behaviour, and effect on disrupted rocks were described. Furthermore, the wider tectonic relationship between the faults and major crustal features, i.e. Red Sea Rift and Dead Sea Shear, were reviewed and their bearing on regional hydrogeological investigations mentioned.

6. Special geological and hydrogeological relationships were noted such as the separation of the Wadi es-Sirhan and Al-Azraq basins, and the reasons for these were taken from data collected from Landsat.

7. The Wadi es-Sirhan basin analysis and interpretation from Landsat images provided an excellent example of how to use remote sensing techniques for water resource evaluation in regions characterized by special tectonic settings. Future examples were proposed.

8. The potential ground-water areas and exploratory drilling sites are shown on plate 2.

Figure 1. Location of the study area

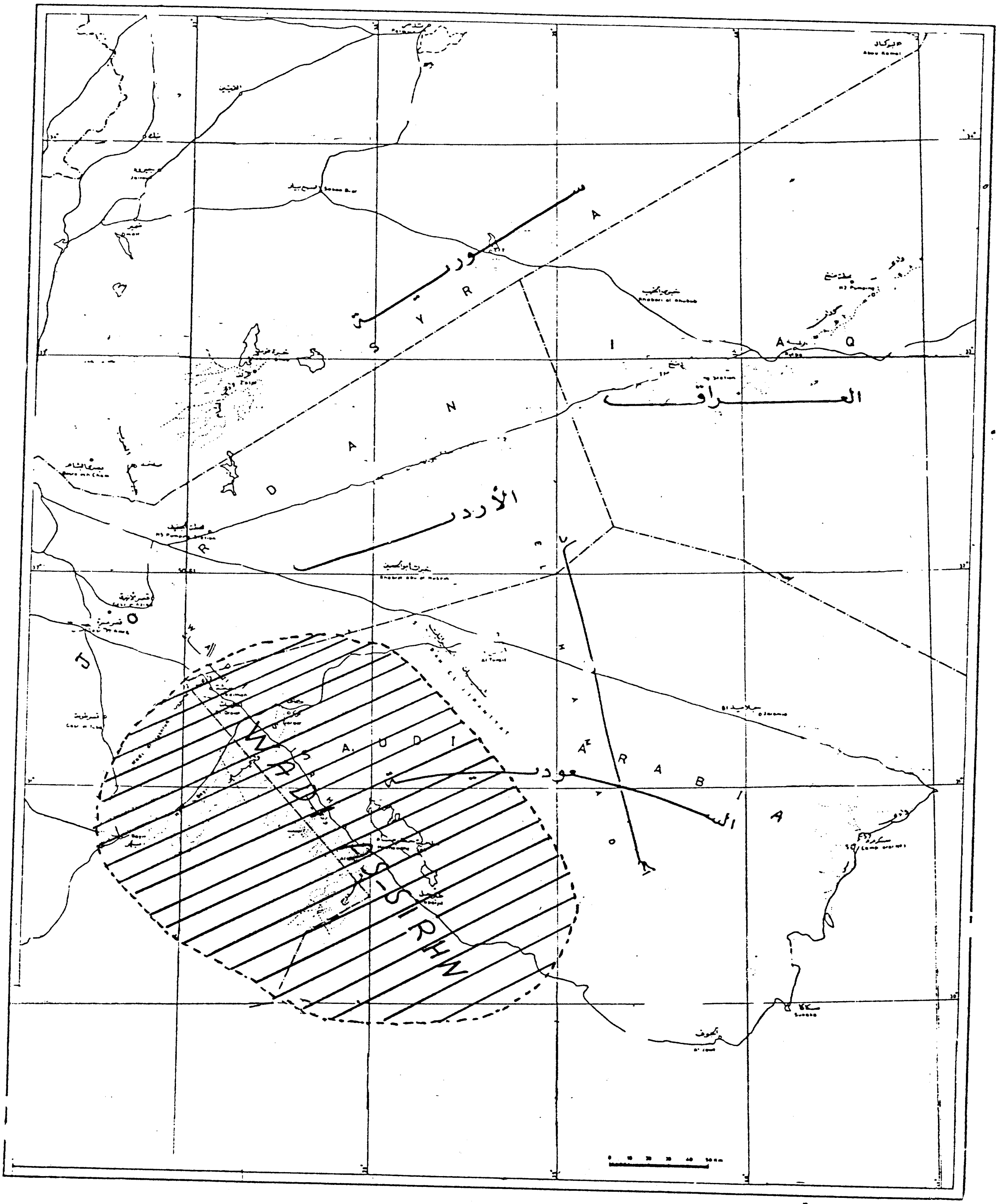
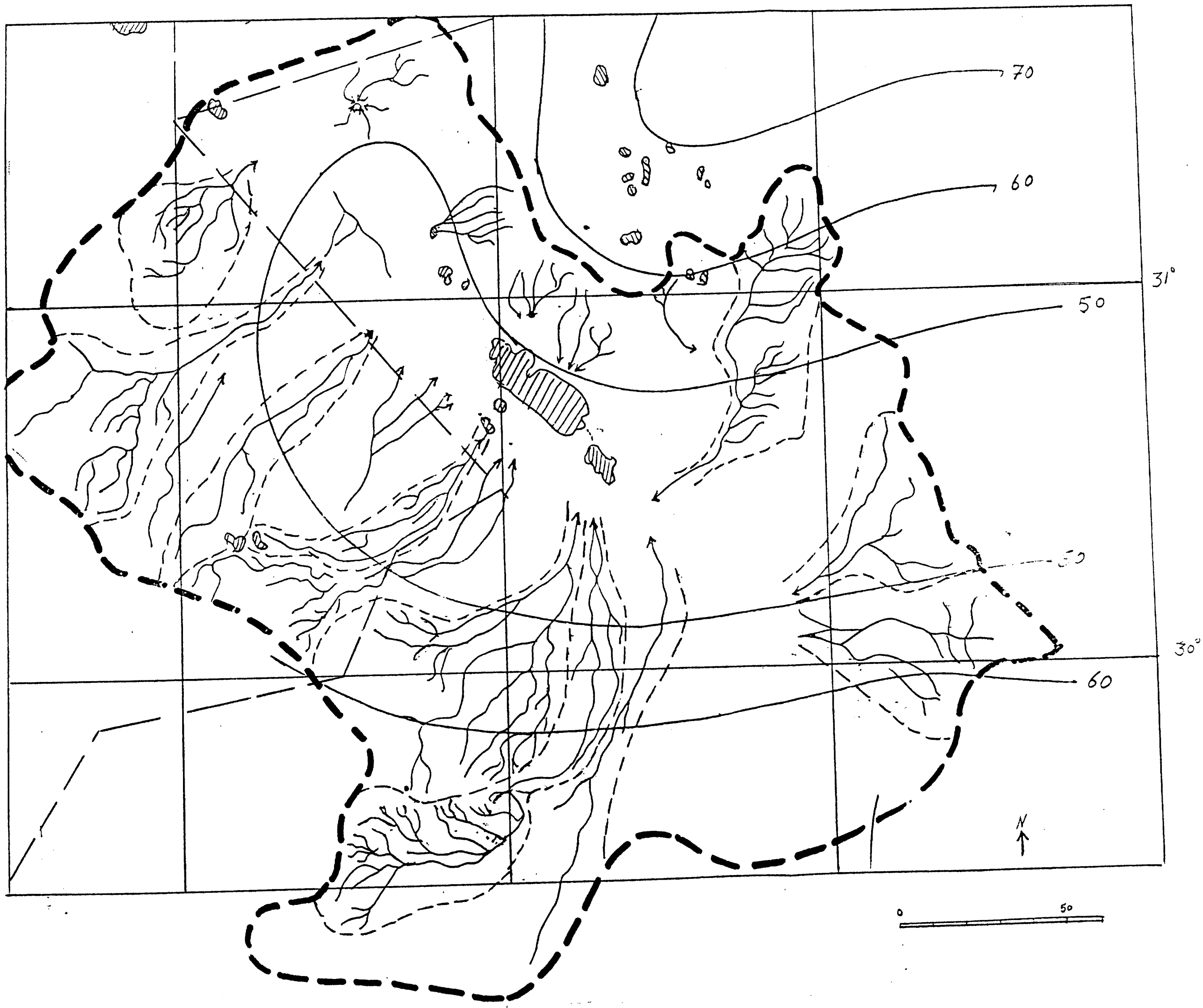


Figure 2. Drainage and hydrographic basins



Main surface water divide

Secondary water divide

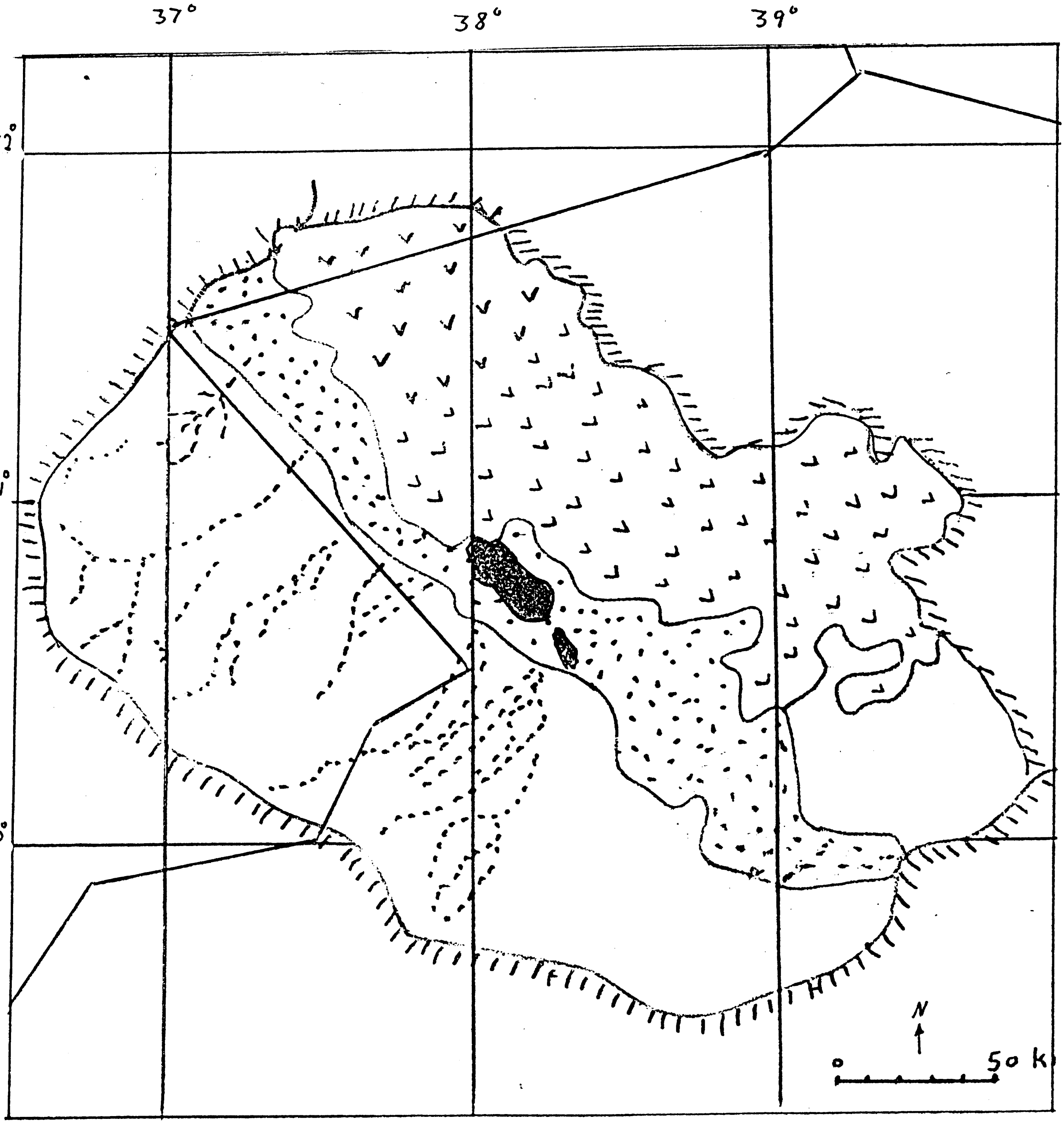
Sabka, Kabra or ground-water discharge area

Isohyet (mm)

Drainage line

International boundary

Figure 3. Geomorphic areas of the Wadi es-Sirhan basin



Stream channel

International boundary

Basalt Plateau

Sabkha

Boundary

Sarhan Depression

The western drainage area

Figure 4. Geological map of Wadi es-Sirhan basin

(Explanation of symbols is given in table 1)

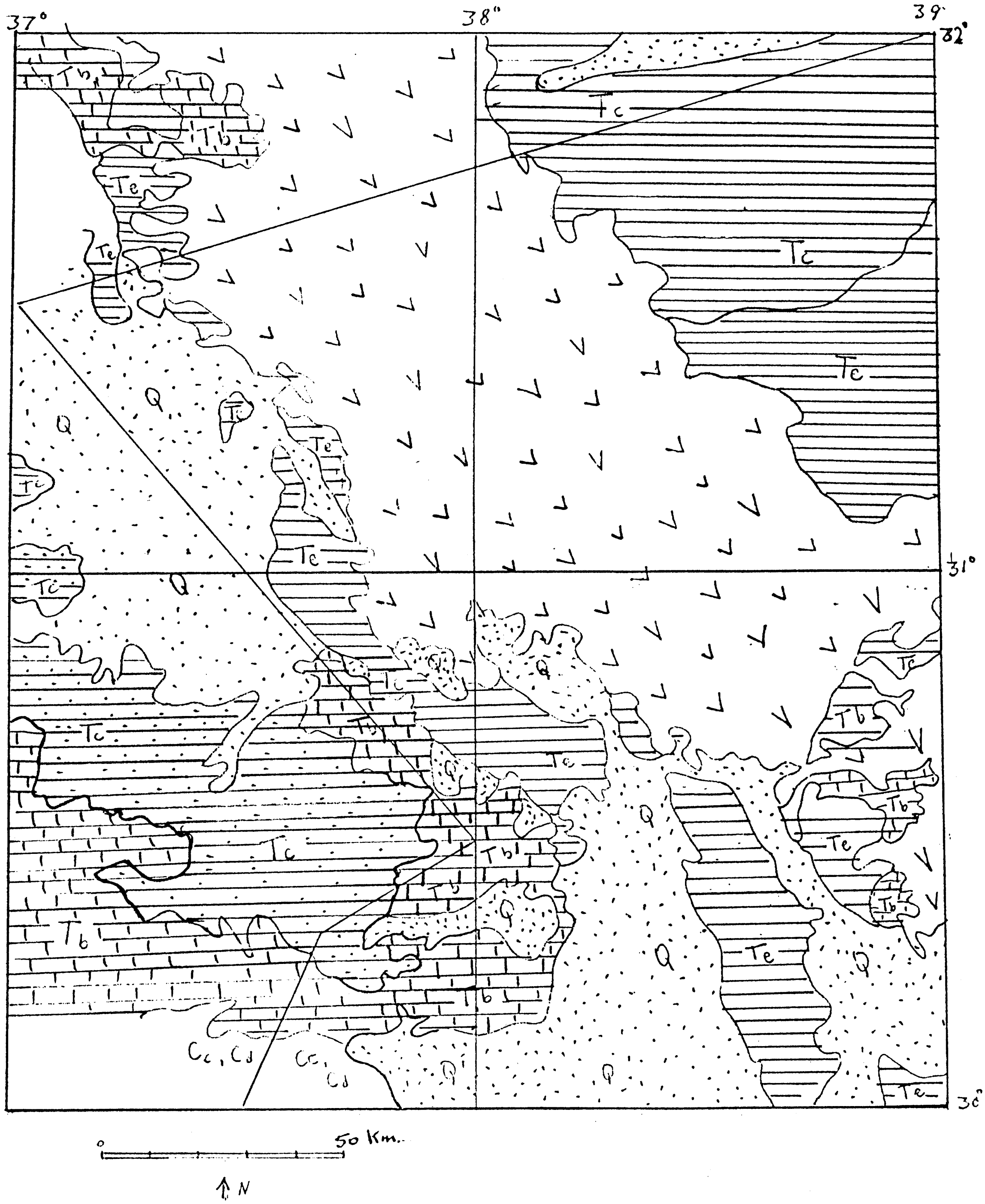
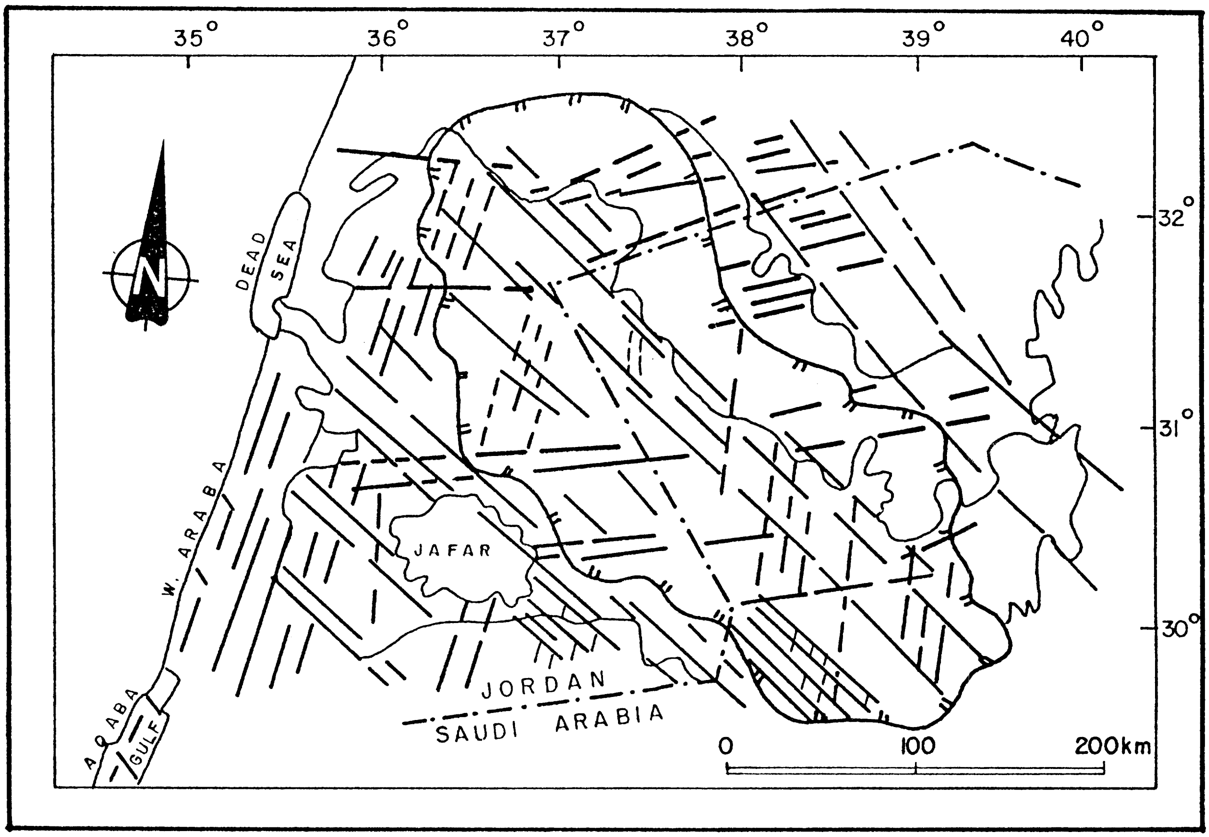


Figure 5. Structural setting of Wadi es-Sirhan basin



—— Major fault lineaments

Figure 6. Schematic geological cross-section through al-Gafar and Wadi es-Sirhan basins

(With centres of uplift and volcanic doming indicated)

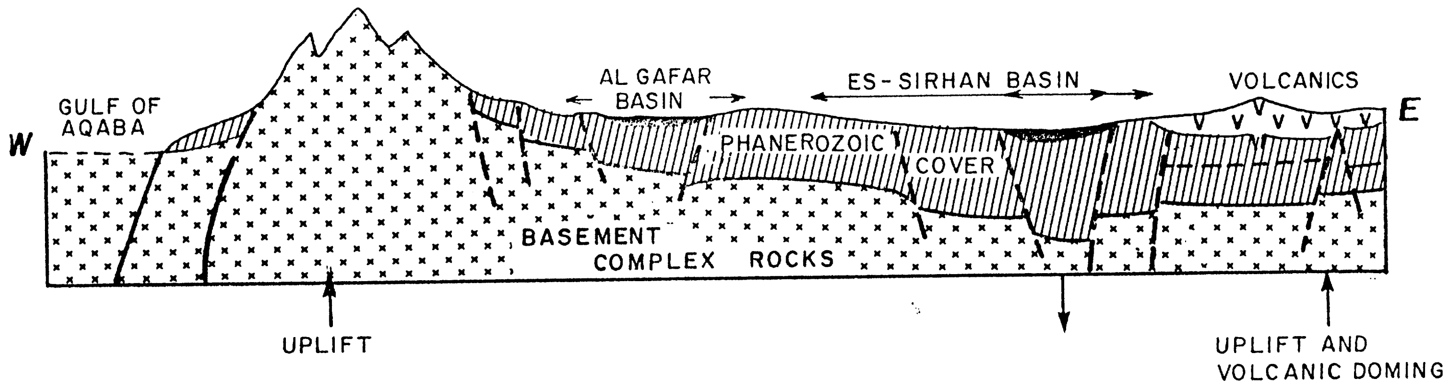


Figure 7. Schema showing the interference of Wadi es-Sirhan fault zone and early E-W faults separating al-Azraq from Wadi es-Sirhan basin

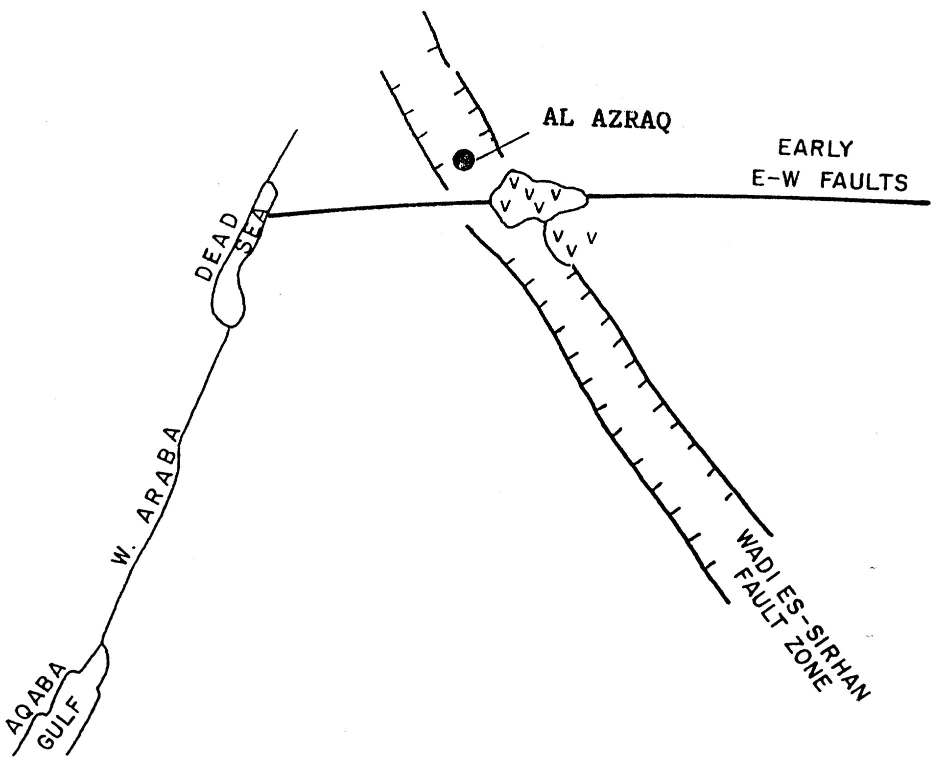
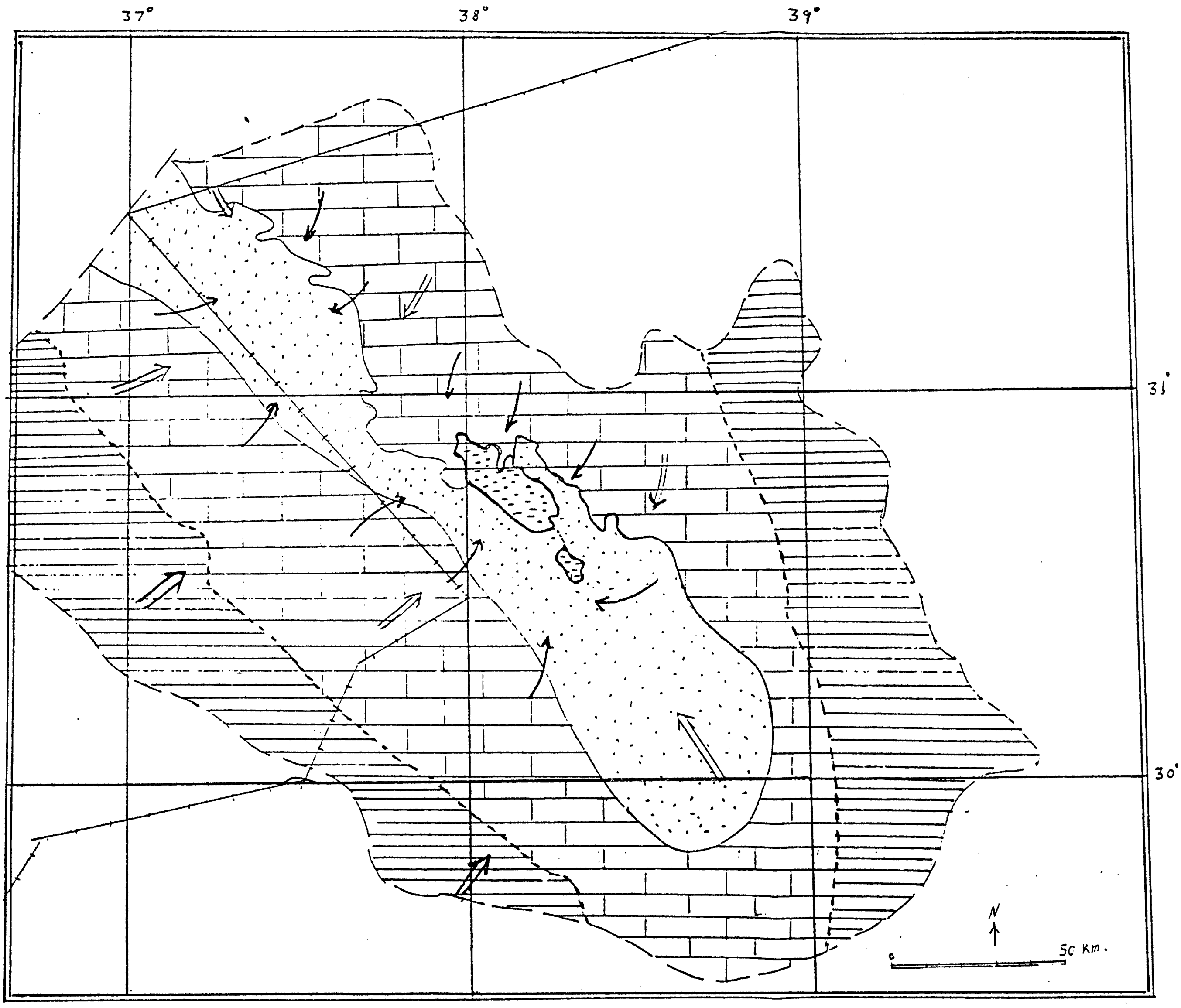


Figure 8. Ground-water flow direction in the Wadi es-Sirhan basin



Shallow, Quaternary, Neogene, Paleocene and Miocene aquifers

Eocene and Paleocene aquifers

Cretaceous aquifers

References

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Part Two

WADI BANA BASIN

1. Introduction

1.1. General

Proper planning, assessment and development of the total water resource system in any country are key elements in the overall social and economic development of that country.

The water resources in the Arab region, which can be categorized as arid to semi-arid, may be described as scarce.

Improper planning and management of the water resources, mainly owing to lack of data and adequate and sufficient studies, have resulted in critical water resources situations, and water supply problems in many areas. Moreover, some important surface and ground-water resources are shared by two or more countries. Lack of co-operation, co-ordination and exchange of information has been a significant constraint on planning, developing and managing of such shared water resources.

Remote sensing technology has been widely used for exploring and managing the various resources of the earth, of which water constitutes a subsystem of the overall system. This remote sensing technology provides a free sky information available for a large number of countries. The Economic and Social Commission for Western Asia is trying, through its programmes, to help its member States to benefit from this technology in the studies of these shared water resources and to encourage concerned countries sharing common water resources to establish co-operative programmes to achieve a better and more comprehensive understanding of the total water resource system.

This report presents the results of a remote sensing analysis of potential surface and ground-water resources of the Wadi Bana catchment area (figure 1) which is shared by the Yemen Arab Republic and Democratic Yemen. Principal contents include a series of maps expressing imagery interpretations of several regional aspects pertinent to surface and ground-water occurrence such as geology and geomorphology. It also includes an outline of methodology that illustrates the interpretative approach. Specially produced for this project is a Landsat false colour composite at a scale of 1:250,000. The outcome of this report is anticipated to be of particular value in future programmes.

1.2. Remote sensing: application and benefits

Varying visual aspects cause different factors to become distinguishable at different scales. Owing in part to its resolution and broad perspective, remote sensing imagery expresses important and larger aspects that otherwise may be indiscernible. Consequently, since its inception, remote sensing has become an integral early step to virtually every sort of regional analysis. Normally, precise results are unpredictable, but invariably, analysis provides information that is highly valuable to subsequent interpretation of larger scale data, including a unique means of regionally extrapolating local features and tentatively identifying relations that deserve close subsequent study. In this analysis, particularly beneficial initial results have included identification of ground-water aquifers, ground-water discharge and recharge areas, geological and geomorphologic controls on ground-water, previously undocumented lineaments which are largely indiscernible from other data sources, and areas of concentration of surface runoff and soil moisture. Finally, the airphoto analysis identified areas recommended for detailed exploration, and those demonstrating a high ground-water development potential.

Additional benefits from the imagery and its initial analysis will continually provide input for future study and investigation programmes.

Consequently, the findings of this report should be considered preliminary and of the first approximation, applicable not simply as an end-product in itself, but as an initial foundation to supplement more conventional analyses to follow.

1.3. The study area

This study is considered a start for an overall study programme for ESCWA which is planned to study and assess various shared water resources in the member States within the ESCWA region. Two basins were selected: the Wadi es-Sirhan basin shared by Jordan and Saudi Arabia (see part one of the present study) and the Wadi Bana basin shared by Yemen and Democratic Yemen.

Part two of this study presents the findings with respect to the Wadi Bana basin (figure 9). Part one covered the West Sirhan basin.

Because of the nature of remote sensing, and the regional characteristics of geology, hydrogeology and physiography, the interpretation of certain features had to be extended outside the basin boundaries in order to provide ancillary information for the Wadi Bana area.

Wadi Bana is one of three wadis draining into the Abyan delta on the southern coast of Democratic Yemen. The other two are Wadi Hassan and Wadi Suhaybiyah. Wadi Bana begins on the high plateau in the Yemen Arab Republic which is highly developed for terrace cultivation from rainwater and ends in the Abyan delta of Democratic Yemen which is highly developed for irrigated agriculture, and finally discharges into the Arabian Sea about 60 km northeast of the capital city of Aden.

1.4. Goals and objectives

The present study was carried out by ESCWA to assist its member States to achieve a more comprehensive understanding of their shared water resources, and to be able to optimize the development and management of these resources. The application of remote sensing (RS) in this respect would be most useful in strengthening the hydrological and hydrogeological data base, and provide complete and integrated information on the total water resource basin across the political boundaries. This, in turn, will have significant implications for the social and economic development potential for these countries.

There is an evident and urgent need in both the Yemen Arab Republic and Democratic Yemen to achieve standardization and homogeneity in interpretation, data handling, monitoring and estimation of the ground-water resources in both countries, particularly for those watersheds shared by the two countries.

1.4.1. Development objectives

The development objectives of the study are as follows:

1. To help the Yemen Arab Republic and Democratic Yemen in assessing, developing, managing and utilizing the water resources of the Wadi Bana basin which is shared by the two countries;

2. To improve communication and technical co-operation between the two countries in the exchange of hydrological and hydrogeological information pertaining to the shared basins in general. This would also help the two countries acquire information to formulate the needed water strategies and plans of actions at the national and regional levels for water-related projects.

1.4.2. Immediate objectives

The immediate objectives of the study are as follows:

1. To apply remote sensing technique in the development, exploration, management and assessment of the water resources in the Wadi Bana basin shared by Yemen Arab Republic and Democratic Yemen;

2. To use the information obtained from applying such techniques to further assist the two countries to plan for further detailed investigation programmes needed for various water resources development projects;

3. To produce hydrological-hydrogeological maps on a practical scale.

1.4.3. Specific objectives

In order to achieve the above general objectives, the following specific objectives have to be achieved to the maximum extent possible from interpretation of Landsat images.

A. Ground water

1. To identify and delineate the potential aquifers in the study area;

2. To identify qualitatively the ground-water flow systems;

3. To provide preliminary qualitative analysis of the ground-water recharge-discharge conditions in the area;

4. To identify and delineate the topographic, geologic, and hydrologic control factors with regard to the ground-water systems;

5. To provide a preliminary assessment of the ground-water potential and locate potential areas for ground-water exploration and possible development;

6. To investigate the interrelationship between the ground-water and surface water resources in the study area;

7. To identify areas where flood-water concentration occurs for possible development;

8. To identify areas where potential soil moisture storage exists.

B. Surface water

Although repetitive coverage of Landsat imagery is available for various times of the year, it was not possible to obtain the needed time-varying coverage for the study area, owing to budgetary limitations. This situation has limited the scope of investigations with respect to the time variations of rainfall, streamflow, ground-water recharge and soil moisture storage. Moreover, it is not always successful or possible to record and detect the complex sequence of generating sheet-wash and runoff flows. Therefore, the objectives of this study with regard to surface water and other time-dependent parameters will be limited to areas of concentration of flood flows and soil moisture.

2. Investigative procedures

2.1. General

The use of satellite imagery is still a relatively new technique in resource investigations. Although some of the interpretive procedures are similar to those used with conventional aerial photography, the use of satellite imagery provides the interpreter with a much wider range of data from a variety of sensors. For example, a Land Resource Satellite (Landsat 4 or 5) contains a number of sensors which record the electromagnetic energy in wavelength bands 1, 2, 3, 4, 5, 6 and 7.

Five satellites have been launched since 1972. The following tables give some facts about these satellites:

Spacecraft	Date launched	Date decommissioned	MSS* Wavelength bands
1	23 July 1977	6 January 1978	4, 5, 6, 7
2	22 January 1975	25 February 1982	4, 5, 6, 7
3	5 March 1978	31 March 1983	4, 5, 6, 7, 8
4	16 July 1982	---	1, 2, 3, 4
5	1 March 1984	---	1, 2, 3, 4

* Multispectral scanner.

The spectral response for the different bands is as follows:

Spacecraft Landsat 4,5	Band Landsat 1,2,3,4	Spectral response (micrometres)
1	4	0.5-0.6
2	5	0.6-0.7
3	6	0.7-0.8
4	7	0.8-1.1
-	8	10.41-12.6

Operating from an orbit of 705 kilometres, the spacecraft of Landsats 4 and 5 can obtain repetitive coverage of the earth's surface every 18 days. The linescan digital data contained in one full scene cover an area on the earth 185 x 185 kilometres or about 34,000 square kilometres. These digital data are received at earth-based receiving stations and processed onto computer-compatible tape (CCT) so that one full scene can be constructed from one CCT. The CCT covers bands 1, 2, 3, and 4 and is therefore termed multispectral (MSS) as it contains a measure of the electromagnetic energy contained in those wavelengths. Because of the repetitive coverage, multitemporal (different seasons of the year) and multispectral image analyses can be applied to problems confronting most types of resource inventories.

Landsat images contain geologic and hydrologic information, but this information must be obtained by analysis and interpretation. Ground-water information can commonly be inferred from geomorphology, surficial geology, drainage, land use patterns, vegetation characteristics, image tones and structural lineaments. In arid environments, some vegetation types may indicate depth of water table or the locations of natural ground-water discharge areas.

2.2. Principles of image analysis

Landsat images represent pictures of the land surface. The images are composed of picture elements or pixels that represent the physical and cultural components of the landscape. As with any classification system, elements which appear similar generally represent similar conditions. Identification, classification and delineation of similar-appearing elements have geologic and hydrologic significance. Thus, the principles of photographic interpretation, such as comparison of tone, colour, shape, relief, size, texture, brightness, location and association, are also relied upon for interpretation of Landsat images. The end-result of a landscape interpretation is an analysis with the following categories:

Drainage and land forms:	Watershed size, shape and channel density, geometry of channels.
Vegetation and agriculture:	Natural occuring and agricultural and soil characteristics.
Lineaments:	Straight to curved lines formed by a combination of landscape elements, such as fractures, joints, faults, cultural features and vegetation lines.

Lithology and stratigraphy: Types and sequence of rocks, outcrop areas, etc.

Hydrology and hydrogeology: Soil moisture, runoff and sheet flows, ground-water recharge and discharge areas, etc.

A detailed review of the interpretation displayed on the figures is presented in subsequent sections of this report.

The above categories are used for a geological and hydrological interpretation. From a geological interpretation, a conceptual geological model was constructed which tied together an interpretation of landforms, lithology, structure and stratigraphy. Interpretation of lithology in Wadi Bana was based on drainage characteristics, surficial geological features, vegetation patterns and geological structure. The landform interpretation for Wadi Bana, based on morphology and inferred genetic materials, emphasized the lithology by the density and form of the drainage network. An interpretation of igneous and sedimentary processes, as well as tectonic, allowed an interpretation of stratigraphy. All of these interpretations were used to construct a three-dimensional geological model, which formed the basis for ground-water interpretations.

The geologic model, based upon satellite imagery, was then compared with existing geologic data to identify areas of correlation and deviation of interpretations. Field-checking will be needed to confirm these features which occasionally identified previously-undetected geologic features which may be significant in geohydrologic modelling.

In order to build an interpretative geohydrologic model, several inferences were made. Based on the conceptual geological model, alluvial and bedrock aquifers were identified and depth of the water table postulated in the unconsolidated materials as much as possible. Estimates of ground-water quality, based on infrared radiations and geology, were limited. Locations of ground-water discharge and recharge were postulated as a relationship between topography, vegetation pattern and hydrology. The results of these interpretations yielded conceptual hydrologic models which yielded an understanding of the various aquifers, their physical limits and hydrologic situations.

2.3. Selection of images

An enlargement of false colour composite image composed of bands 1, 2 and 4 was obtained at a scale of 1:250,000. This colour composite image stresses vegetation, water, agricultural areas, stream channels, structure, lithology and landforms. It is characterized by an overall red appearance and was used as the basis for interpretation of geology, hydrology and hydrogeology.

The images clearly indicate areas of natural surface vegetation, as compared with dry land irrigation farming; stratigraphic and lithologic boundaries; cultural features and ground-water recharge and discharge areas.

The following aspects were considered in selecting the Landsat images required for this study. Of course, budget limitations were a major constraint on ordering the various bands and band combinations which would best reflect certain ground features more than others. Moreover, the time-dependent characteristics of stream flow, vegetation, infiltration and ground-water recharge and discharge would require repetitive coverage for different seasons of the year and different climatic cycles. Other aspects considered for this study are:

1. Obtaining images as cloud-free as possible.

2. Selecting bands which would best reflect certain geological, hydrological, vegetal and hydrogeological features or properties. For this purpose, colour composites for bands 1, 2 and 4 were selected.

3. Selecting dry periods of the year to best reflect natural ground-water discharge zones and perennial streams.

4. Having all photos for the same month and same year as much as possible according to the availability of coverage.

The following photos from Landsat "5" (MSS) were selected at a scale of 1:250,000 with reference to the computerized photo index received recently from the EROS Data Center in Sioux Falls, South Dakota. The cloud cover for the ordered photos ranged from zero to 5 per cent.

Landsat photos

Scene identification number	Patch	Row	Date
85035006504 x 0	165	050	2/14/1985
85027006503 x 0	165	051	11/26/1984

3. Physiographic, geologic and hydrogeologic data base

3.1. Physiography

The Yemen Arab Republic has an area of 195,000 km^2 and Democratic Yemen an area of 337,000 km^2. The resources of water in Democratic Yemen and the Yemen Arab Republic are not abundant.

There are three main drainage basins in Democratic Yemen and the Yemen Arab Republic: the Red Sea drainage basin draining to the west, the Gulf of Aden drainage basin draining to the south, and the eastern drainage basin draining to the Empty Quarter (figure 9). The drainage basin divides between these three basins are created by the two main mountain chains trending in south-north and east-west.

The Wadi Bana, the subject area of this study, is located in the Gulf of Aden drainage basin. The altitude in this basin ranges from sea level to about 3,000 m above mean sea level near the upper part of Wadi Bana. This area is highly developed for terrace cultivation because it receives high rainfall. The Wadi Bana has a total stream length of 240 km and a catchment area of 7,260 km^3 downstream until Batars (figure 10).

The climate in both Yemens is classified as tropical to subtropical over most of the year. However, there is large variety in climatic conditions in this area, particularly along the Red Sea, the Gulf of Aden, the mountain area and the desert area. The mean annual temperature ranges from about 30°C in the coastal plains to about 18°C in the highlands. The frost line is at an approximate altitude of 2,250 m amsl.

The distribution pattern and the amount of precipitation in the Yemen Arab Republic and Democratic Yemen vary with altitude (figure 10), latitude, and distance from the Red Sea and Gulf of Aden coasts. In the Yemen Arab Republic rainfall ranges from less than 75 mm/yr in the Tihama plains to more than 800 mm/yr on the highlands. In Democratic Yemen, rainfall ranges from 50 mm/yr on the coastal areas to about 750 mm/yr on the highlands. The Yemen highland is characterized by two rainy seasons: (1) spring, from April to May or June, and (2) summer, the more important of the two, from July through September. Much of the rain falls in torrential showers. Rainfall in the Yemen highlands gradually decreases eastward and northeastward where arid conditions prevail in the Empty Quarter and Ramlat and Sabatayn.

3.2. Water sources and utilization

There are no perennial rivers in Democratic Yemen. Most of the streams are ephemeral with short-life flood flow during the rainy seasons. The flood water in the major deltas is extensively diverted for irrigation. Some streams have perennial flows in some of their reaches, particularly in the high rainfall areas. Such streams are usually fed by ground-water discharges.

Ground water constitutes the main reliable source of water for domestic, agricultural and city supply. The rural water supply is also based on ground water. Since 1970 the areas under ground-water irrigation have been expanded throughout the country.

The rainfed crops in the Yemen Arab Republic are limited predominantly to the areas between 400 and 2,000 m altitude. Surface water is available only from a number of springs, from transient floods in the wadis and from very limited base flows. For irrigated agriculture, water supplies to the main cities and rural water supply, the Yemen Arab Republic must rely heavily on ground-water resources.

Irrigated agriculture seems to be in an advanced state in the Yemen Arab Republic, as evidenced by irrigation canals, streams, flow diversions, and the large number of wells. This is particularly true in the Tihama coastal plain and in some interior valleys.

The area of highest importance in Democratic Yemen, from the agricultural development point of view and owing to hydrogeological conditions resulting in a significant potential ground-water reservoir, is the Abyan delta of which the Wadi Bana is the largest stream discharging flood water into it.

3.3. Geology

3.1.1. Stratigraphy

The geologic formations of the Yemen Arab Republic and Democratic Yemen range from the Pre-Cambrian to the Quaternary age. They include metavolcanic, metasedimentary, granitic and volcanic rocks, limestone, sandstone, evaporites and unconsolidated colluvial, alluvial and eolian deposits. A simplified geological map of the southern Yemen Arab Republic and Democratic Yemen is shown in figure 11.

Pre-Cambrian rocks are exposed along the outer fringe of the country, mainly in erosional windows in the Red Sea and Gulf of Aden escarpment, and in broad belts in the northern and southeastern regions. Metasedimentary rocks are common in the north, granitic rocks in the northeast and southeast, and metavolcanics in the south. Generally, the Pre-Cambrian rocks of the Yemen Arab Republic and Democratic Yemen form a southern extension of the Arabian Shield of the Kingdom of Saudi Arabia.

Northwest of the Wadi Jawf, the Wajid Sandstone, a cross-bedded sugary sandstone of Ordovician age, unconformably lies above Pre-Cambrian rocks.

Conglomerate, shale and sandstone of the Kohlan Series unconformably overlie the Wajid Sandstone. The Kohlan Series of Early Jurassic age is best exposed around the outer edge of the Yemen highlands in the predominantly calcareous Amran Series of late Jurassic age.

Sandstone of the late Cretaceous-early Tertiary Tawilah Group is exposed north of Sana'a along the outer border of the Yemen highlands and also in the mountains southwest of Ta'iz.

Volcanic rocks were extruded during much of the Cenozoic era. The Yemen Volcanics Series of Tertiary age cover about two thirds of the country. This unit consists predominantly of felsitic tuffs, interspersed with basalt layers, and is several thousand metres thick. Several granite plutons, which intrude the Tertiary volcanics, are slightly younger. Lava flows of Quaternary age are exposed in four distinct lava fields: (1) northwest of Sana'a; (2) north and west of Ma'rib; (3) around Rida; and (4) in the southern part of the Tihama, inland from Mocha (Al-Mukha).

Late Quaternary gravel deposits are common near the drainage divide close to the western edge of the Yemen highlands. Late Pleistocene loess also mantles the highest exposure of volcanic rocks in the southern part of the country.

As in the Yemen Arab Republic, the stratigraphy of Democratic Yemen generally shows a great affinity to the rest of the Arabian Peninsula. Rock units from the Jurassic to recent geologic ages form outcrops in the subsurface of Democratic Yemen. There is a basement complex of Pre-Cambrian age consisting of igneous and metamorphic rock outcrops in the south and southwestern part of the country.

Sandstone formations of Cambrian age, locally called the Wajid formation (350 m thickness) occur in the country and overlie the basement complex. Red shales interbedded with limestone represent the Permian age (150-200 m thickness). This means that Ordovician, Silurian, Devonian and Carboniferous geologic time scales are missing in Democratic Yemen.

The rest of the stratigraphic column in Democratic Yemen can be summarized in an ascending age as follows:

Geologic time scale	Brief description
Jurassic, Lower	Missing
Middle	Coarse-grained sandstone interbedded with conglomerate, limestones and marls (80-180 m thickness, Kohlan Series)
Upper	Limestone, marls, dolomites and shale with evaporites (up to 1,000 m thickness, Amran Series)
Cretaceous, Lower	Limestones and sandstones (Mukalla type, reaching 1,000 m in thickness)
Upper	Basaltoid sedimentary rock units, volcanic and lava with shale and limestone ranging in thickness from 1,500-1,800 m (Wasia and Aruma groups)
Tertiary	Um-er-Radhuma limestone and dolomite
Eocene	Limestone, evaporites and topped with marl
Oligocene-Miocene	Conglomerates, sandstones interbedded with limestones. Tertiary deposits thickness is about 1,000 m.
Quaternary Plicene to Recent	Occur in the coastal plain of the Gulf of Aden, in Ramlat Sabatayn sand plain, the northern slopes of Hadramout and the valley fills consist predominantly of alluvium and eolian deposits of variable thickness.

3.3.2. Geologic structure

Pre-Cambrian metamorphic rocks in the Yemen Arab Republic have been folded and faulted more intensely than younger rocks, and probably more than once. Basement rocks were faulted prior to the deposition of Jurassic rocks, but several large regional faults affected both the basement and the younger overlying rocks.

One of the most prominent faults is the Wadi Jawf fault along the northern edge of the Wadi Jawf valley. The southern fault block of basement rocks moved downward with respect to the northern one, forming a structural basin in which deposition of Jurassic marine sedimentary rocks took place. Later reactivation of the fault resulted in vertical movement in the opposite direction. In the southern part of the Yemen Arab Republic, the fault that controls the trend of the valley of Wadi Kaleyba, about 20 km southwest to Ta'iz is another example of a fault which affects both basement, and overlying sediments and volcanic rocks.

Aside from the many basaltic and granitic plugs in the northern part of the country, very few vents, which were the sites of Tertiary volcanic activity, have yet been identified. The gentle regional southerly and westerly dips of mid-Tertiary volcanic rocks in the central and southern parts of the Yemen highlands may reflect not only accumulation in tectonic basins, but also post-depositional tilting.

Monoclinal folding of the Amran Series is common south of Sa'dah and west of Ma'rib. Piercement domes have brought Miocene-Pliocene evaporites to the surface in the coastal Tihama between Al-Hudaydah and Al-Luhayyah, and Jurassic evaporites near Safir (950^{+}m), in Ramlat and Sabatayn.

Structurally, Democratic Yemen lies in the southern part of the Arabian Megablock of the Afro-Arabian platform. The country can be divided into: (1) Hadramout Arch which is a sedimentary plateau encompassing the eastern region; (2) the uplifted main basement block of the western region; and (3) the depressed area covered by volcanic rocks of the Aden Trap Series in the south-west.

To the west of longitude 50^{o} east, the regional structure is trending north-south approximately parallel to the Arabian Shield trend and is represented by the Mukalla Arch and Mafidh High with the Madbi depression in between. To the east of this longitude, the trend is northeast, southwest and almost parallel to the Gulf of Aden and is represented by the north Hadramout Arch where the Jeza'a Depression lies in between. To the north of the north Hadramout Arch lies the interior homocline of the Empty Quarter basin.

3.4. Hydrogeology

Several hydrogeologic investigations have been carried out in Democratic Yemen by different consulting firms under the auspices of the Food and Agriculture Organization of the United Nations (FAO), Arab Funds and other technical assistance from some donating countries. These studies were mainly carried out in the wadis of: Hadramout, the Tuban watershed area, the Abyan delta and the Wadi Meefa'h area.

The main and most important water-bearing formation in Democratic Yemen is the quaternary alluvial deposits in the main wadis and deltas as well as the coastal plains. Ground-water conditions vary from free water table to semi-confined. The thickness and well yield of this aquifer is from flood-water infiltration. Extensive development of this aquifer is undertaken. The water levels in wells tapping this aquifer are subject to seasonal fluctuations in response to flood flows and other climatic cycles.

This aquifer occurs in the Hadramout basin, Tuban delta, Abyan delta and Wadi Meefa'h. Other aquifers in Democratic Yemen include Rus Jeza eocene limestone and chalk, Um-er-Radhuma limestone (Paleocene), Mukulla sandstone (Cretaceous), all mostly occurring in the Hadramout basin.

The following table summarizes the ground-water conditions and properties of each of these aquifers:

In the Yemen Arab Republic, the general hydrogeologic characteristics were described widely by Ali Ozkan in a report for the Ministry of Agriculture and Water Resources Development Department of Saudi Arabia.

The principal water-bearing formations in the Yemen Arab Republic are the alluvial deposits, quaternary and tertiary volcanics, the Tawilah Group, the Amran and Kohlan Series and Wajid sandstone. Volcanic series and alluvial deposits have extended aquifers with a higher potential for domestic water supply and also for irrigation in certain areas of the country.

Aquifer	Aquifer thickness (m)	Well yield (m^3/hr)	Depth to water level (m)	Salinity (ppm)
Alluvial	Up to 500		5-30	650-9,000
Rus-Jeza limestone and chalk	45-60	<5	60-120	1,400-3,700
Um-er-Radhuma limestone	-	Low	-	-
Mukalla sandstone	200-300	30-60	50-100	440-1,000

The alluvial deposits in the Tihama Plain and in some mountainous plains form the principal aquifers in those areas where thick sand and gravel sediments store the ground water in quantities sufficient for domestic and for irrigation supplies. Some high-capacity wells within these aquifers produce the water for the above-mentioned purposes.

Along the valley floors, or on the flat lands, thickness of alluvium is usually low and these layers produce only a limited quantity of water (dug wells ranging from 5 to 20 m in depth). Ground water in the alluvial deposits occurs under water table conditions in the main wadis and in the upper parts of the deltas, and under confined to semi-confined conditions in the lower parts of the deltas.

The water quality in the alluvial aquifer is generally good and suitable for most purposes, with a total of dissolved solids ranging from 2,000-3,000 ppm.

Quaternary basalts composed of fractured, fissured and porous zones of basalt flows as well as poorly consolidated or unconsolidated pyroclastic material are usually the reservoirs of water, especially in the lowlands of the Yemen Arab Republic. The quaternary basalts provide the source of ground water to a large number of dug and drilled wells as well as for some springs.

Despite the high capacity of the wells producing water from the basalts, this formation does not have a high ground-water potential in the Yemen Arab Republic because of their limited outcrops and consequently limited recharge. Water quality in Quaternary basalts is generally good. The total dissolved solids in water does not exceed 400-500 ppm. H_2S and iron water sometimes exist but within the acceptable limits.

In general, the aquifers in Yemen volcanics are artesian aquifers with certain hydrostatic pressure. There might be several aquifers in different units of this formation. At shallow depths, there is usually water with water-table conditions.

Tawilah sandstone occurs predominantly within the Sana'a Basin, covered by alluvial deposits, and northeast as well as east from the Sana'a Basin. They are porous and permeable, creating a generally good reservoir for ground water. Sana'a and surrounding villages obtain water for their domestic water supply from this formation through a number of drilled wells. Some springs in the Shibam and Kawkaban areas are discharging from these sandstones with capacities varying from 30 gallons per minute (GPM) up to 300 GPM. Water quality of the Tawilah aquifer is suitable for domestic use and other purposes. TDS in the wells is around 500-600 ppm. The present withdrawal of water from this aquifer within the Sana'a Plain is causing a continuous decline of water level in the range of 2.0 to 2.5 m annually .

Amran limestone crops out in the mountainous areas of the central and northern parts of the Yemen Arab Republic. The Amran series has a considerably high sequence (approximately over 600 m). The depths of the wells there are between 150 to 350 m. Productivity of the wells varies from 30 to 100 GPM but sometimes it exceeds 200 GPM.

The upper fractured zones contain limited amount of water under water-table conditions. In the lower part of the formation, there are several water-bearing zones, separated from each other by shale and marl layers. Ground water in this zone occurs under artesian conditions with different hydrostatic pressures and slight changes in water quality.

The ground-water production from the Amran limestones aquifer has been increased within the last years, causing some decline in water levels.

The Kohlan formation of Lower Jurassic age underlies the Amran limestone in most areas between Sana'a and Sa'adah in the north, and overlies the Wajid sandstone or the Basement Complex in the central-northern and north-western parts of the Yemen Arab Republic. The thickness of this formation was reported as 100 to 300 m. The sandstone units and conglomeratic layers of the Kohlan Series yield water to some dug wells and springs in the outcrop area. Some springs are discharging with a capacity of 500-600 GPM from the Kohlan

Series. Sandstone and conglomeratic layers in this formation are porous and highly permeable and therefore they are creating good water reservoirs, as proved by the high capacity springs.

Wajid sandstone of Ordovician age is known as the oldest sedimentary formation in the Yemen Arab Republic. It unconformably overlies the Basement Complex, with a basal conglomerate at the bottom. The main outcrops of Wajid sandstone are in the northern and north-western parts of the country.

This formation is of deltic and eolian origin and mainly consists of cross-bedded, white quartz sandstone, conglomeratic sandstone and conglomerates. The thickness of this formation may exceed 250 m, but in places may form only a thin cover of sandstone over the basement.

Well depths in this aquifer range from 100-150 m, and their yield ranges from 20-50 m^3/hr.

4. Landsat image interpretation: investigating the water resources of the Wadi Bana basin

4.1. General

Because of the nature of remote sensing investigations, the interpretation of bedrock areas outside the Wadi Bana catchment area was used to provide ancillary information for the Wadi Bana area.

The following pages briefly describe several interpreted features. The discussion of each feature or set of features mentions various regional characteristics which illustrate the overall interpretative processes applied to derive the maps.

The initial step in this preliminary investigation of water resources in the Yemen Arab Republic was the preparation of a small-scale topographic map at a scale of 1.25,000 which could serve as a base map on which the boundaries of catchment areas and drainage basins, precipitation and geologic data could be overlain. The divides surrounding the drainage basins were delineated on false-colour Landsat images. Where regional relief was low and did not allow visual identification of divides on the photos, boundary lines were transferred to the drainage basin map from topographic maps. A small-scale map of the drainage network was also prepared in the same manner. The resulting drainage basin map was then reduced and overlain on the topographic base map. The isohyetal map of the study basin was also superimposed on the other parameter maps. All these maps are at the same scale and may be readily compared with one another in order to bring out such relationships as may exist between location, altitude, shape and size of watershed on one hand, and precipitation and rock types on the other hand.

The next step was to identify, locate and describe those drainage channels where streamflow could be observed. Lastly, areas supporting vegetation were also identified as a basis for inferring other hydrological conditions.

The vegetated areas of the study area are also important to such a report devoted to water resources because plants are an excellent indicator of water availability during their growing season. However, seasonal variations of plant growth could not be studied at this stage because of unavailability of repetitive photos for the different months and different seasons of the year.

Seasonal plant growth in alluvial valley floors takes on different meanings depending on site location, which in turn may reflect one of the many cultural, ecological, or economic patterns of human activities. In the valleys, high near the drainage basin divides between catchment areas (where precipitation is relatively high because of altitude, and population density is also high), the seasonal variation in plant growth implies agricultural crops. At lower altitudes in the Yemen highlands, particularly in the basins of wadis draining Pre-Cambrian crystalline rocks, where aridity is greater than in the higher mountains and population density may be low, seasonal plant growth, particularly spot vegetation at times of low flow, may imply that phreatophytes are growing in alluvium, drawing water from shallow ground water, or that plants are thriving on seeps and springs.

As mentioned above, Landsat image analysis and interpretation proved to be a powerful tool in water resource studies and evaluation. Using only Landsat images without the aid of any additional input, it was possible to identify and characterize the following features over the Wadi Bana basin.

1. Drainage network, drainage density and type;

2. Regional direction of landslope and water divides;

3. Calculation of catchment area and delineation of the drainage basin;

4. Major geomorphological forms, i.e. escarpments, depressions, coastal plain, etc;

5. Solid/drift boundary;

6. Delineation of major lithological boundaries;

7. Distinction of major lithological types and at least their classification into metamorphic, magmatic and sedimentary types, furthermore, volcanic rock and superficial deposits;

8. Lineaments representing faults and fractures indicative of deformed rocks were readily delineated;

9. Natural vegetation, density and frequency can be readily located and mapped, and distinguished from cultivation;

10. Major landuse forms, pattern and type were identified.

The above practice shows beyond doubt the capability of the technique.

4.2. Recent study

Using MSS Landsat in the form of a false colour composite, the previously described features were first delineated. Making use of available data, and data deduced from the geographic setting of the Wadi Bana basin as additional inputs, further steps in the interpretation process were achieved. Additional data input include:

1. Hydrometeorological data;

2. Physiographic and topographic data;

3. Geological data.

The source of these data includes commonly published maps and known records, as well as data collected from the field. New products emerging from the use of the above inputs include:

(a) Geological map showing main lithologies, from which potential aquifer formations were determined;

(b) Calculation of some significant hydrological parameters using data on annual precipitation, evapotranspiration, catchment area, drainage density, and slope gradient. Potential infiltration, and site of recharge may be tentatively recognized judging from ground surface cover, type of rocks, soil, relief, vegetation cover, etc.;

(c) Lineament mapping when used along with other data (rock type, vegetation density, land use) may well represent additional criteria to deduce zones of active infiltration.

Consequently, as a result of the above combination of geomorphic, geologic, hydrologic, soil, land use and structure, the emerging data should considerably help planners concerned with water resource development to take a wise decision. Such a decision in necessary for planning study projects for the exploitation and management of both surface and ground-water resources. In some circumstances the level of data obtained by combined remote sensing techniques and analysis of existing inputs is even sufficient to make an exploration decision. For hydrogeological purposes, the above described state of the acquired data will be noticeably promoted by the addition of subsurface hydrogeological information such as depth of water table, thickness of aquifers and aquitards rock properties, flow direction, water quality, boundary condition, etc. If such knowledge is available together with that obtained from Landsat, then the emerging data is good enough to formulate an exploration, exploitation and management plan for the ground water.

There are conditions under which data obtained by remote sensing combined with inputs on the natural environment, become the backbone of hydrologic and hydrogeologic decision. Such conditions may be well exemplified as follows:

(i) Areas underlain by crystalline rocks (rocks of insignificant primary porosities and permeabilities) in regions with low rainfall (often termed difficult areas). In such areas there is no role played by the original lithology, such as aquifers or aquitards. Aspects of ground-water flow are not directly applicable in such circumstances, and the subsurface data does not play a significant role as is the case in sedimentary basins.

(ii) In areas underlain by crystalline rocks, secondary porosities and permeabilities, often due to erosion along fractures, constitute the determining factor for ground-water exploration in such areas. Reasons promoting secondary permeabilities are mainly structural and morphostructural and to a lesser extent lithologic. Structural and morphostructural controls no doubt are best detected from Landsat images, commonly as structural and geomorphological lineaments.

(iii) Regions with a deep water-table are sometimes considered as uneconomical for exploitation and require alternative shallow sources such as wadi fill, buried channels, and weathered zones, which receive temporary or seasonal recharge. Such features are typically delineated and interpreted from Landsat images, through direct and indirect criteria. The indirect criteria in particular are those of dynamic character, which can be only recognized and monitored through remote sensing techniques. Such features include the state of vegetation cover, its growth, density, health, occurrence of water bands, delineation of wildife tracks and changes in land use.

Keeping in mind the special conditions described above, it is obvious that the Wadi Bana basin may be considered as the classical example where remote sensing techniques would be the superior tool for hydrological and hydrogeological evaluation.

The above conclusion is based on the following reasons:

(a) The hydrologic environment of Wadi Bana crosses the political frontiers of different countries.

(b) Many sectors of the catchment area of the Wadi Bana basin are not easily accessible even inside the territories of a single country.

(c) The existing data on the physical environmental components are either incomplete or oversimplified.

(d) Data on the ground water over most of the basin are not assessed and in some cases are not available or are unpublished, particularly away from the known major water-field in the Abyan delta.

(e) Wadi Bana crosses contrasted terraces of variable soil, physiography, lithology, geomorphology and land use.

(f) Most significant, however, is the fact that the largest portion of the Wadi Bana basin is underlain by crystalline rocks (Pre-Cambrian basement complex and Cenozoic volcanics), and therefore represents a hydrogeologically difficult area. As mentioned above under such conditions, a study based on the use of remote sensing techniques is the unique tool for hydrological and hydrogeological exploration.

(g) Specially significant also is the fact that the Wadi Bana basin lies within a famous tectonic setting in Arabia, bounded to the west by the Red Sea plate margin, and to the south by the Gulf of Aden plate margin. Such a unique structural setting results in the development of structural features having a direct bearing on the hydrogeology of the basin. Unquestionably, structural features are best observed, delineated and correlated over large areas by the use of Landsat images. Structures related to plate margin should be investigated and interpreted over a small scale map. Therefore, the Landsat image scale became the ideal geographic data base for the study of these structures.

As a conclusion, one may say that the study of Wadi Bana drainage basin is the ideal target for remote sensing techniques.

4.3. Hydrogeological interpretation

The following conclusions have been mainly determined from the interpretation of Landsat data combined with available geological inputs.

Water-bearing formations

Water bearing formations in Wadi Bana basin include Jurassic limestone, Cretaceous sandstone and Quaternary alluvial deposits and less significant, however, weathered basement complex rocks and Yemen volcanic series. Each of the above formations are separated from others by a major unconformity surface.

The Jurassic limestone

The Jurassic limestone include the Kohlan and Shugra formation and lies unconformably over crystalline basement complex rocks. The limestone occurs as gently dipping beds occupying the flanks of major domal structures with basement rocks forming the core. It occurs as a linear belt trending northeast-southwest to east-west extending for more than 50 km crossing Wadi Bana near Batais village in Democratic Yemen. The limestone is terminated westward by a major fault generally known as the Ad-Dhala' fault zone running from Aden at the south northward into the Yemen Arab Republic.

A buried Jurrassic limestone formation was encountered in a well drilled for the Aden water supply. Such limestone is generally hard with occasional vugs, but often is severely fractured. Major fractures can be observed in Landsat images, producing a triangular pattern of exposures. East of Logimah more than 115 m of limestone is drilled. Secondary porosity and permeability are expected in the limestone due to doming, fracturing and faulting that enhanced the dissolution of the rock. Ground water occurs in fractures, cavities, voids and porous vuggy layers in the limestone; hence, this formation is considered water bearing.

Cretaceous sandstone formation

This formation in the Yemen Arab Republic was originally named the Taovilah Series by Lamare and others (1930), Lamare (1936) and Beydoun (1960) renamed it the Tawilah Group. It is composed of Cretaceous sandstone, predominantly of continental origin, often exposed in low terrains (e.g. troughs) and mostly cored by quaternary alluvium deposits or volcanics. It is often exposed as low-lying, hilly detached outcrops several metres in height, showing the effect of faulting and fracturing. The sandstone overlies unconformably the Jurassic limestone. It occurs as a varicoloured, ferrigenous succession of repeated cyclic sandstone, siltstone and conglomerate, alternating occasionally with thin bands and lenses of shale, marl and limestone. The degree of consolidation of the sandstone varies, greatly controlled by fracturing, faulting and cementation. In Landsat images, the sandstone may well be distinguished by its patchy tone and relatively light reflectance, commonly associated with nearby white highly reflective Jurassic limestone.

Quaternary deposit aquifers

Quaternary deposits over small patches of extreme reflectance in Landsat images in most of the Wadi Bana basin up to Batais village in Democratic Yemen (latitude 13° 21' N and longitude 45° 19' E), southward towards Al-Husn village (latitude 13° 15' N and longitude 45° 21' E). Quaternary sediments made of sand, gravel and silt occupy the Delta Abyan plain separated by weathered inselbergs made of basement rocks, and Jurassic limestone and often completely cover the subdued topography of the Cretaceous sandstone.

At the foot of the mountainous region in Democratic Yemen, south of Batais village, pediment covered with aeolian sand occurs. Quaternary deposits form wadi-filling, terraces, flood plain deposits and eolian deposits. Quaternary sediments in the upper Abyan delta may reach an average thickness of more than 80 metres, while the maximum drilled thickness at the upper Abyan delta reaches 176 metres. In such occurrences they form buried intermountain valley with major fault zones. Such buried channels may well be delineated from Landsat images as lineament extension from older rocks into Quaternary deposits, often controlling recent stream courses (lower Wadi Bana and Wadi Hassan) in southern Yemen. Such channels may directly create the basement complex rock, thus providing a valuable aquifer in areas otherwise often considered dry or unproductive.

Weathered basement

Among the different pre-Cambrian lithologies occurring over the Wadi Bana basin, intensely foliated and fractured acid gneiss may be considered as the most liable rock for weathering. Second to it are coarse granitic rocks. Generally, the active and repeated pre-Cambrian tectonic history has resulted in the development of well foliated, fractured, and faulted rocks. On such structures are further superimposed Tertiary faulting and fracturing.

In appropriate structural and morphological settings (i.e. intersected faults superimposed by drainage), coarse-grained foliated rocks are easily eroded to a considerable depth. As a result, secondary porosities and permeabilities are enhanced, and the basement rocks may carry an appreciable amount of ground water in areas lacking other types of aquifers.

Weathered basement rocks developing an internal drainage pattern controlled by fold fractures and faults were delineated from Landsat imageries by their characteristic photo texture and light reflectance along drainage lines.

Yemen volcanic series

Yemen volcanic series may be differentiated into several flows. Vesicular lava and pyroclasts, producing irregular relief, act as localized catchment areas characterized by internal drainage networks. Horizons of vericular lava and pyroclasts characteristic of the more basic phases of volcanicity may be separated by more dense and compact volcanic rocks, producing confined aquifers. Silts of volcanic rocks flowing in between the layers of Cretaceous sandstone constitute aquitards. The whole of the Yemen volcanic series may form an overall impervious layer above the Cretaceous sandstone in the Yemen Arab Republic, creating artesian conditions in the tilted sandstone aquifer.

4.3.2. Geological and structural setting

Using tonal differences, reflectance, drainage pattern texture and relationship of shape, size and relative distribution, the following major lithologies were distinguished in crystalline basement complex rocks (of pre-Cambrian age). These may be broadly differentiated into deformed and undeformed rocks according to their distribution behaviour, trends, formation of oriented ridges and valleys representing structural domains and shapes.

Deformed rocks comprise different metamorphical and deformed lithologies constituting a pronounced structural domain trending in a northeast-southwest direction easily delineated in Landsat images. Those metamorphosed and deformed rocks showing major folds and conspicuous shear zones may be further classified according to their texture, reflectance and drainage into the following:

1. Genesis, occupying relatively low land, intensely weathered, giving high reflectance, and characterized by internal drainage;

2. Dominantly metavolcanic sequence and subordinate metasediments often forming high oriented ridges producing contrasted topographic and structural lineaments following the structural domain. These lithologies are of darker tone than the gneiss, hetrogeneous and of relatively low reflectance, and less drained.

Undeformed basement rocks are mainly plutonic masses, unoriented, of light reflectance, rugged relief and have radial drainage. They are all categorized as granite granodiorite intrusions. Deeply weathered pediment around these intrusions characterized by lighter tone and higher reflectance from the granite may occasionally form an aquifer. The deformed rocks show evidence of repeated deformation, producing complex fold patterns complicating the stratigraphy of these rocks. Gneiss often occupies cores of major antiformal structures in lowland. The contact between the gneiss and the metavolcanic and the metasediments is often major shear zones that extend for a few hundred kilometres, many of them ending at the desert of the Empty Quarter in the Yemen Arab Republic and Democratic Yemen. Such shear zones, which represent a zone of a few kilometres in width, superimposed by major straight drainage, are a mighty conduit of water both at the surface and in the subsurface into the eastern desert land of Yemen.

Among such major shear zones, particularly at places of intersection with secondary shear or later Tertiary faults, weathering and erosion become active, and the site may represent a valuable occurrence of ground water at places where no other aquifers exist.

Lineaments delineated from Landsat photos from the pre-Cambrian period thus represent major shear zones, and topographic lineaments resulting from folded ridge patterns.

Smaller lineaments, perpendicular to the fold trend and main structural domain, also occur, representing A-C fractures and faults resulting from tension at the late stage of folding. Both major lineaments representing structural domain < shear zone, as well as small cross lineaments, when resulting from drainage, form a feather pattern characteristic of folded terraces rather than faulted terrain. Such lineaments, though representing fractures, shears and faults, are relatively less attractive for ground water prospecting as the fracturing is often accompanied by mylonitization and recrystallization from the pre-Cambrian time. Nevertheless, these lineaments still represent significant factors in promoting secondary permeabilities, weathering and erosion, and their value for ground water occurrence cannot be overlooked.

4.3.3. <u>Phanerozoic cover rocks</u>

Wajid sandstone, Kohlan and Amran limestone and Tawilah sandstone are all significant aquifer rocks. The Wajid sandstone occurs in the north away from the Wadi Bana basin. The Jurassic limestone and Cretaceous sandstone are the main rock formations that overlay the crystalline basement rocks in the Wadi Bana basin. These formations were deposited unconformably over a periplaned basement surface. Both formations were deformed along with the basement complex in post-Cretaceous time.

Broad domal and synformal structures have affected the Jurassic and Cretaceous rock better displayed (in the photos) at the upper Abyan delta in Democratic Yemen. A broad flexure at An Nadirah in the Yemen Arab Republic trending east-west to northwest-west - southeast-east also affects the early phases of the Yemen volcanic series.

Such broad warping and flexuring caused the tilting of the limestone and, to a lesser extent, the sandstone, which instead displayed more fracturing. The core of the domal structure is occupied by basement rocks, while in the synformal depression Cretaceous sandstone occurs covered by an early volcanic series in northern Yemen. This structural configuration is easily detectable from Landsat images on inspections of the well-recognized Jurassic limestone (highest reflectance) at stream junctions. The effect of tilting and dipping becomes obvious, producing an undulatory contact with the basement over stream courses. Such structural configuration is extremely important for ground water prospecting in the area. Two conspicuous examples may be sited to show such a relationship. In both Yemens, at the eastern boundary of Wadi Bana, all the way northward up to the eastern part of the Syrian Arab Republic, the Cretaceous sandstone is underlain by the Jurassic limestone and/or the basement rocks. In those occurrences in the Yemen Arab Republic, the Yemen volcanic series overlies the sandstone. The geological and hydrological relationship is expressed in figure 13.

The other example is from the upper Abyan delta, near Batais village, and north of Giar where the Jurassic limestone and Cretaceous sandstone occupy the flank of an antiform with the basement complex rocks at the core.

Late Neogene and Quaternary sediments play an important role as aquifers, especially in south Yemen. Everywhere such deposits may include agricultural soil and form small aquifers recharged from seasonal flood flows. At the lower reaches of Wadi Bana over the upper Abyan delta those Quaternary deposits fill eroded zones along many faults, i.e. buried channels made up of fault zones. Under such conditions, thick alluvial deposits may occur, providing extensive aquifers like those at upper Abyan delta which supply Aden with potable water. Landsat images may be considered the best criteria to delineate the possible occurrence of such zones. This is simply achieved by extending well-recognized lineaments over exposed rock below the superficial cover. A geophysical survey of such delineated zones would immediately and economically confirm their existence. Such structural depressions filled with alluvial deposits range from small to huge depending on the intensity of fracture and faulting and the degree of weathering of the disrupted rocks. However, in most cases they form sites where ground water accumulations may occur, particularly after recharge seasons. Such sites, even when small in area, may provide a valuable supply for small villages or for domestic annual supply, particularly over basement terrains where no major aquifers are expected to exist. Judging from the state of vegetation and agriculture over many wadi fill areas, the soil moisture remains high for a considerable period after the rainy season. The Quaternary sediments extend into the coastal plain of the Gulf of Aden at the Abyan delta and should be interlayered with littoral sediments providing an adequate condition for major aquifers, though the salinity of water may be relatively high.

At the eastern boundary of the basement outcrops in north and south Yemen, however, the role of such buried channels over the extension of major pre-Cambrian shear zone would be enormous under the Quaternary aeolian cover.

4.3.4. Neogene evolution of the Wadi Bana basin

The Neogene tectonic events at and near Wadi Bana basin may be considered of great impact to the geomorphology, hydrology and hydrogeology of the area.

Neogene structures are related to movement of the Arabian plate relative to the Africa and Somalia plates. The Wadi Bana basin occupies a corner originally shaped by the Red Sea and Gulf of Aden Rift structures trending northwest and northeast-east respectively. Structures associated with both plate boundaries (see plates 3 and 4) have been controlled by the present geomorphologic setting, drainage and rock distribution.

The great reach of the Wadi Bana course is controlled by Neogene faults as well as pre-Cambrian shear zones. The entire basin of Wadi Bana ends in the west in a great fault parallel to the Red Sea, readily detectable in Landsat image. This fault extends almost from Aden (Aden volcano) northward through Ad-Dhala' into the Yemen Arab Republic passing east of Aatabah in a northwestern direction almost to Dhamar. This fault was named the Ad-Dhala' fault zone by Darweeish (1988). Actually, the Ad-Dhala' fault zone constitutes a grabben west of Wadi Bana, ranging in width from 10-40 kilometres and running for 200 kilometres. Over this grabben, the basement rocks were downfaulted and a huge section of Jurassic limestone and Cretaceous sandstone is preserved, below a thick cover of the Yemen volcanic series. A strip of Cretaceous sandstone is exposed along the eastern boundary of the fault for a considerable extension in southern Yemen, and at higher ground in northern Yemen. The sandstone covers a considerable area over which the volcanic is removed by erosion. A possible northern extension of this fault passes over the road to Dhamar, Ma'bar and may probably extend to San'a. However, along these possible northern extensions, the fault zone is covered by volcanics and, of more interest, thick linear alluvial cover. The western boundary of this grabben is rather more complicated and covered by volcanic flow. The complicated system of faults may be extended from the Gulf coast west of Aden marked by a major volcano 15 kilometres west of Aden extending parallel to the Red Sea structure passing west Sakin Sa'id, Al-Qaidah Ibb, and may be even connected to Wadi Siham, in northern Yemen. This grabben no doubt is a major structural feature of both Yemens, preserving most of the Mesozoic sequence, covered by volcanic series and characterized by intra-continental rift magnetism. No doubt, relatively deep drilling at appropriate locations, where the volcanic cover thins out, will lead to major aquifers in the Mesozoic sediments. The northwest-trending lineament representing fault and fracture predominantly associated with Red Sea rifting should be considered as a significant feature affecting drainage, secondary porosity, permeability, displacement of aquifer formation, and consequently the ground-water occurrences and flow.

Therefore, though the northwest-trending lineament and associated fractures deviate in direction, they are mechanically related to the rifting process and represent structures of direct bearing on the hydrogeological modelling of the Wadi Bana basin and surrounding areas.

When such structures intersect pre-existing pre-Cambrian fractures and fault lineament, the value of the latter increase as a factor promoting circulation of ground water.

4.3.5. <u>Special examples detected from Landsat image interpretation bearing on the hydrogeology of the Wadi Bana basin</u>.

Some special products from Landsat images were presented here to demonstrate the validity of the technique as a powerful tool in hydrogeological studies.

1. A geological map of the Abyan delta showing major lithologies forming aquifer formations, major faults, and characteristic drainage pattern;

2. A map delineating the catchment area for Wadi Bana and other significant basins, over which annual isohyet contours were superimposed. This map is modified according to Rendell and Gupta (1985) using Landsat images;

3. Structure and geologic map of the southwestern part of Yemen showing the ability of Landsat images with a combination of geologic inputs to delineate major lithologic formation and faults.

5. Conclusions on water resources

The following conclusions can be made on the water resources potential in the Wadi Bana catchment area and its vicinity. The conclusions are mostly based on the interpretation of the Landsat images and partly supplemented, where possible, by other available hydrogeological data bases.

5.1. Ground water

Regional ground water flow systems almost do not exist within the Wadi Bana catchment. The reasons are the facts that most of the area is covered by igneous and metamorphic rocks whose primary porosity and permeability are very limited in the vertical direction as well as in the horizontal direction and these parametres are very much localized. Most important is the very limited extension of such porous and permeable rocks. Under such circumstances, local to intermediate ground-water flow systems can only occur with their recharge occurring locally from direct infiltration of rainwater or surface runoff. The primary porosity and permeability of these rocks are mainly caused by physical weathering. The effect of such process is usually limited to shallow depths. Therefore, a ground water reservoir of such shallow depth and limited area would have limited supply potential. In addition, the ground-water storage and depth of water in such localized aquifers would be greatly affected by climatic cycles and variations, both seasonally and annually. However, in the absence of other alternative surface or ground-water sources in such remote and inaccessible areas, such ground water resources would be valuable for the local domestic water supply. The ground-water quality in such reservoirs is expected to be very good, chemically speaking. However, it will be subjected to pollution from any soluble pollutants disposed of on the ground surface near the production wells.

The best locations for such potential sources would be in relatively low areas and at the intersections of faults, shear zones, weathered zones and stream channels. Some such locations are shown in plate 4, zone 3.

On the other hand, the cretaceous sandstone occurring in tectonic lows along the upper Abyan delta, could form a good water supply aquifer when overlain by reasonably thick alluvial deposits. Potential exploitation areas would be along stream channels and in alluvial fans where recharge from flood flows can occur. This sandstone formation forms one hydraulically interconnected system with the overlying alluvial deposits. The water quality of such potential aquifer would be good. Fluctuations in water level and ground water storage are expected with climatic cycles. Potential areas and drilling sites are shown on plate 4, zone 2.

The Jurassic limestone along the upper part of the Abyan delta would also be a potential aquifer. However, the well depths would be relatively high in this case. The yield-capacity is expected to be moderate. However, proper siting of the wells with considerations of the lineament pattern would enhance the yield-capacity of a well. Semi-confinement of the ground water may be observed. The water quality of this aquifer is expected to be poor. Therefore, this aquifer could be considered an alternative supplementary water supply for irrigation. Potential areas and proposed drilling sites are given in plate 4, zone 2.

The most important ground water system in the study area is that of the alluvial deposits. These deposits occur in the lower reaches of the main wadi and occur extensively in the delta area. This aquifer has been greatly developed for irrigation, in particular, for a long time. Such development has resulted in some adverse effects on the ground water in terms of quality and water levels. Proper management of this aquifer therefore necessitates an adequate monitoring program. The recharge for this aquifer is mainly from infiltration of flood flows. Therefore, enhancement of this recharge by artificial means should be considered as top priority for the following reasons:

- To increase the water supply availability.

- To restore the aquifer properties in terms of enhancement of the water quality, raising the water level and increasing ground water storage.

The remote sensing role in deviating potential aquifers in such sediments will be in identifying and delineating old alluvial channels, especially those inhibiting major tectonically controlled valleys.

Outside the Wadi Bana area, to the west of the Wadi Bana catchment is the most significant structure and promising ground water reservoir. This applies to the sandstone and limestone underlying the volcanic rocks, as well as their possible extension and eventual termination in the Wadi Taban delta area along the coastal area.

5.2. Potential areas for ground-water exploration

Based on the results of the interpretation of the topography, drainage, gemorphology, geology, hydrology and hydrogeology, the most promising areas for ground water exploration have been determined (plate 4). Pilot drilling sites within each of these areas have also been selected. The delineated exploration areas and the selected drilling sites apply to all the potential aquifers existing at each specific site as inferred from the local geology. The well depths would depend on the target aquifers intended to be explored.

5.3. Surface runoff, infiltration and vegetation

For a given set of climatic conditions, infiltration and surface runoff go in opposite directions, i.e. increased infiltration would give rise to less surface runoff and vice-versa. Meanwhile, infiltration and vegetation are comparable and correlatable with each other, i.e. areas where infiltration is high and reflects well developed vegetative cover and enhances chances for dry farming activities. A similar positive relationship occurs between infiltration and ground-water recharge, and consequently the occurrence of spring, seeps and perennial stream flow. Vegetative cover concentrations are also found along the major stream channels following the rainy season. However, by the end of the dry season, vegetation can only survive along stream channels maintaining perennial flow from ground-water discharge. The selected Landsat images for this study showed the deterioration of perennial streams through the detection of vegetation concentrations which appear in red colour on these photos.

The upper main channels and tributaries of Wadi Bana, particularly within the Yemen Arab Republic, very clearly show that the main tributaries have base flow until February, which ends a four-month relatively dry period starting in November. Upper Wadi Bana and its tributary, Wadi Yahar, are good examples of streams having perennial flows and this feature shows on the Landsat photos. The very small flood flows in Wadi Yahar, which has a 200 km^2 catchment, are, in spite of the relatively high rainfall, very good evidence of high infiltration and ground-water recharge in the catchment. However, the baseflow at the outlet of Wadi Yahar was measured as 25 litres/second by Sogreach, 1981, which is relatively too low for the expected high recharge. This implies that the ground-water potential within this area is by far greater than indicated by the local ground-water discharge. The ground-water balance can therefore be extracted or intercepted by wells within or around this catchment.

In another location, at the lower 18 to 20 km of Wadi Bana before Batais Weir structure, thick vegetative cover occurs in the relatively broad channel which is filled by apparently thick alluvial deposits. Shallow water table conditions exist in this area. The conclusion on the thickness of alluvial deposits is confirmed by the storage capability of this valley floor aquifer to maintain significant base flow of several hundreds litres per second throughout the year as estimated by Sogreah in 1981.

As the Wadi Bana baseflow leaves the main channel and enters the alluvial fan of the Abyan delta, stream flow losses begin into the highly permeable and porous alluvium. Most of the lost stream flow, however, would be intercepted by irrigation wells southward. However, there is some ground-water flow that cannot be intercepted by wells and discharges along the coastline.

The average annual steam flow for Wadi Bana at Batais Weir structure was estimated by Sogreah as 140 million cubic metres. A great portion of this flow is uncontrollable under the present natural conditions. A multiple purpose storage-recharge dam is therefore proposed at the narrows at the main outlet of Wadi Bana from the mountainous area upstream of Batais in the upper Abyan delta. Such a dam will have a very significant role in the proper management of both surface water and ground water, particularly in this area where they are closely related. Direct use of the stored water by diversion or direct release from the dam for irrigation or direct use after letting the flood water infiltrate into the alluvial aquifer can all be considered as options.

Detailed topographic geophysical, geotechnical, hydrological and hydrogeological investigations need to be conducted to test the overall physical and technical feasibility of such a dam. The economic feasibility of such an important water project is believed predetermined from the social aspect.

In the upper areas of Wadi Bana catchment, ground-water recharge by infiltration of rain and flood water is already enhanced by human activities through the irrigated terraces developed in this area. Improvements and/or modifications of these structures by applying modern rainwater harvesting techniques and approaches could add further enhancement to the ground-water recharge process.

A storage dam is also recommended at the confluence of Wadi Bana and Wadi Yahar. The purpose of this dam is to store flood water for utilization to expand irrigation development in this area. Similar surveys as mentioned above for the proposed downstream dam site will be needed. Meanwhile, it is necessary to collect additional hydrometeorological data which will be needed for such proposed projects.

The following would be a minimum requirement:

1. Two complete weather stations to be constructed at the two proposed dam sites;

2. Two flood flow hydrometric stations at or near the same sites given above;

3. Automatic recording rain gauges within the proposed weather stations;

4. Up to 10 storage-type rain gauges for measuring the total seasonal precipitation scattered in the upper Wadi Bana.

Plate 3. Geomorphic map of Wadi Bana basin

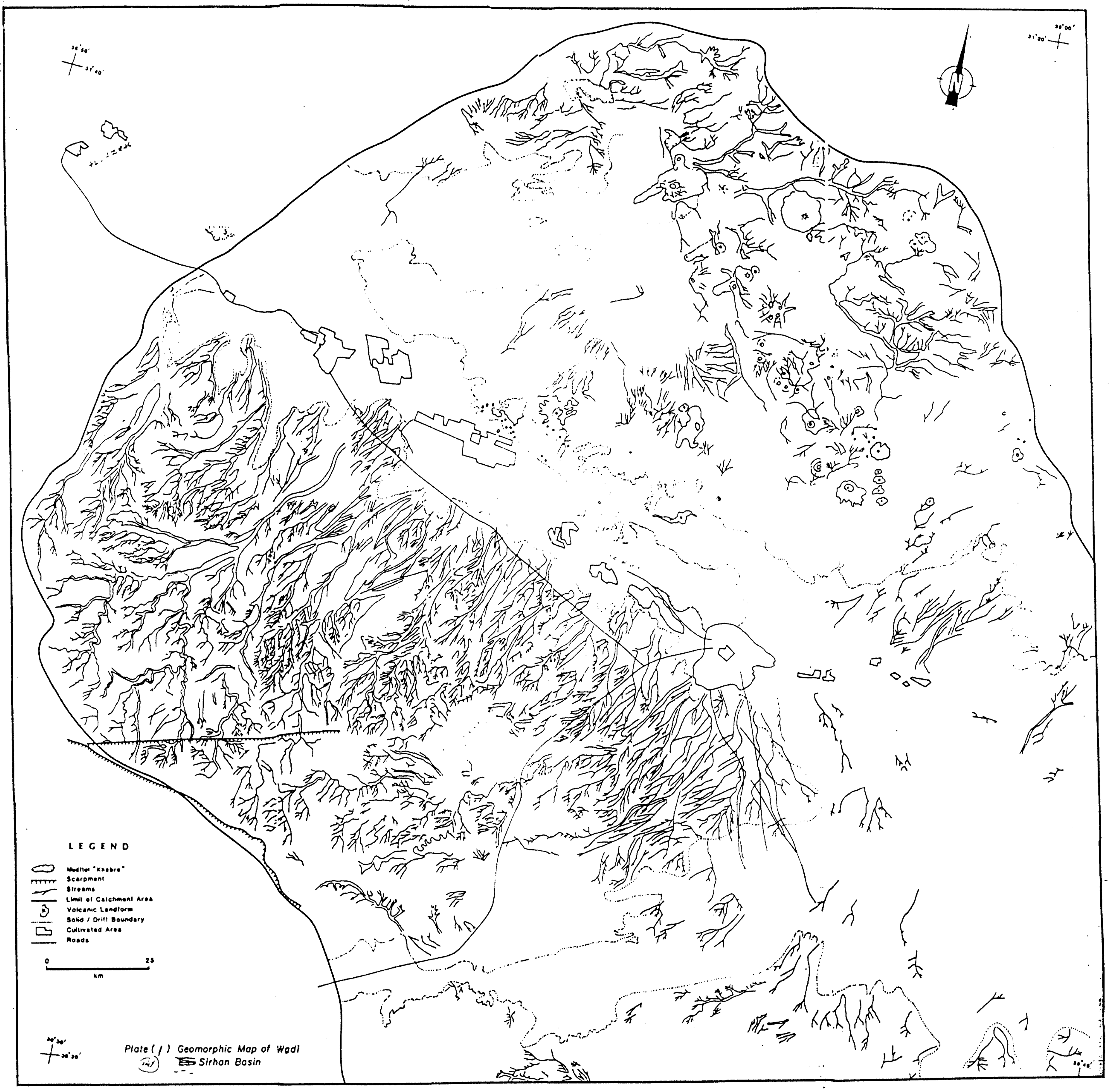


Plate 4. Geological and lineament map of Wadi Bana basin

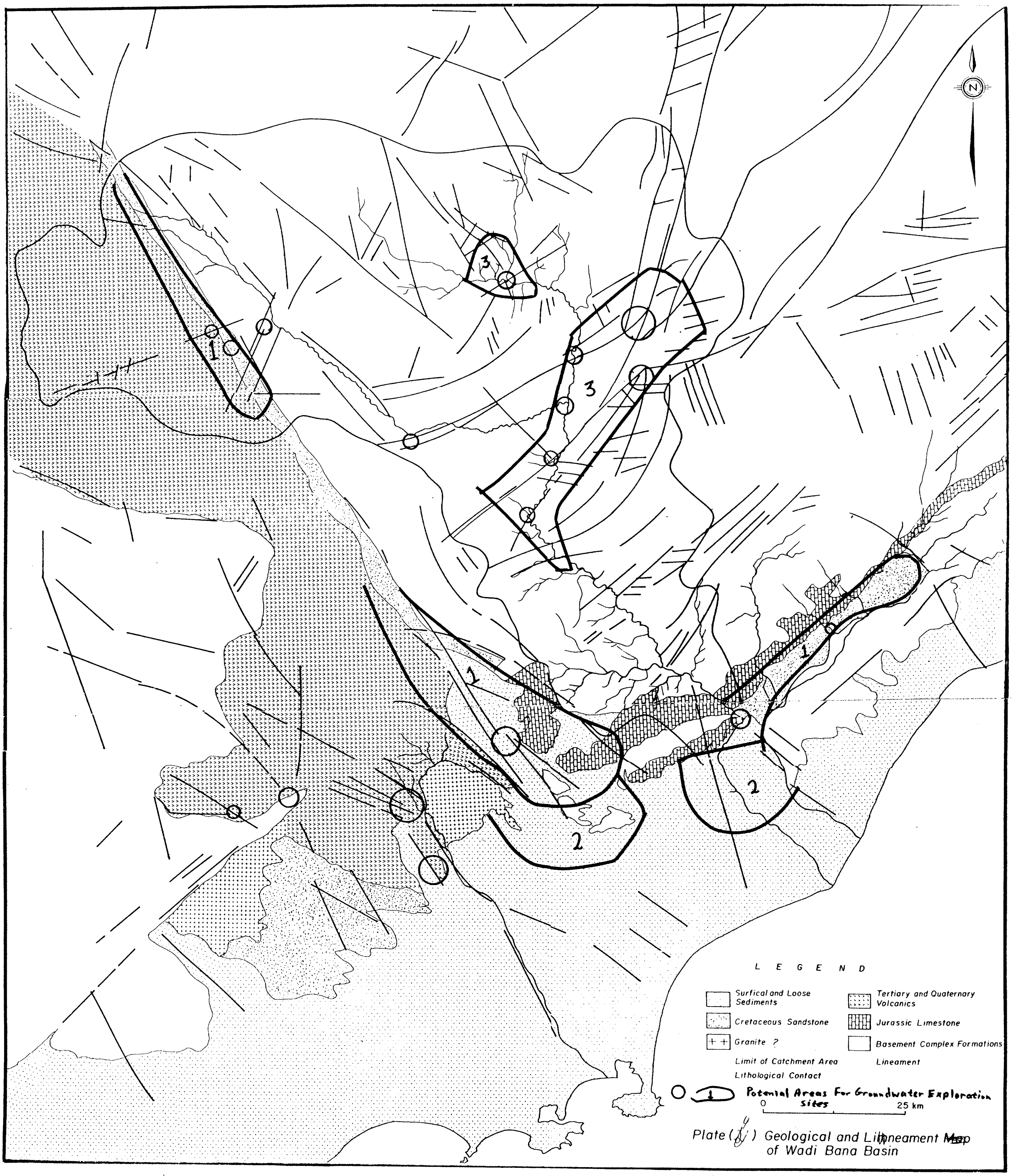


Figure 9. Location of the study area and the main drainage basins in Yemen

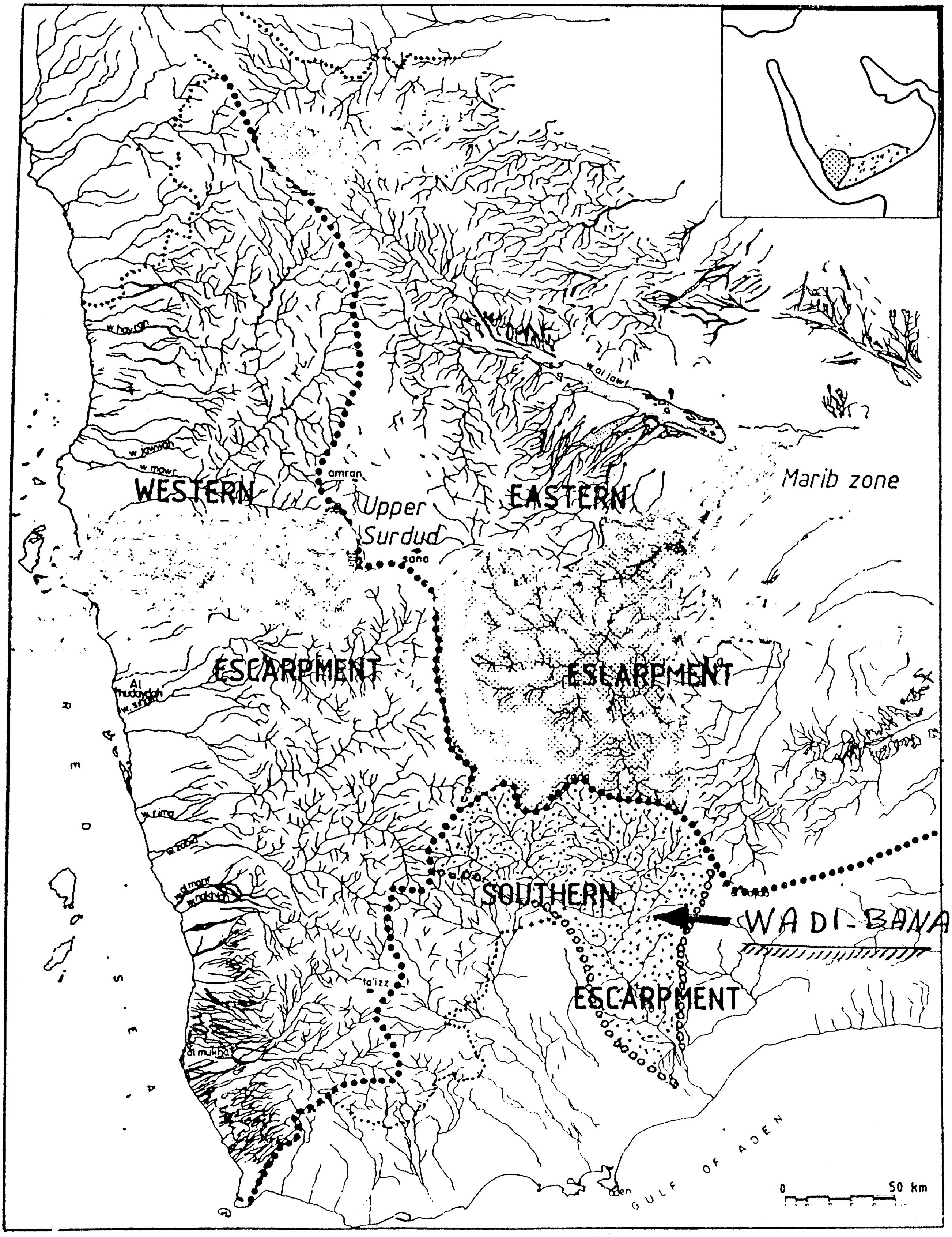


Figure 10. Hydrological map showing the catchment areas and the annual isohyets of Wadi Bana and Wadi Hassan

(Modified after Rendell and Gupta, 1985)

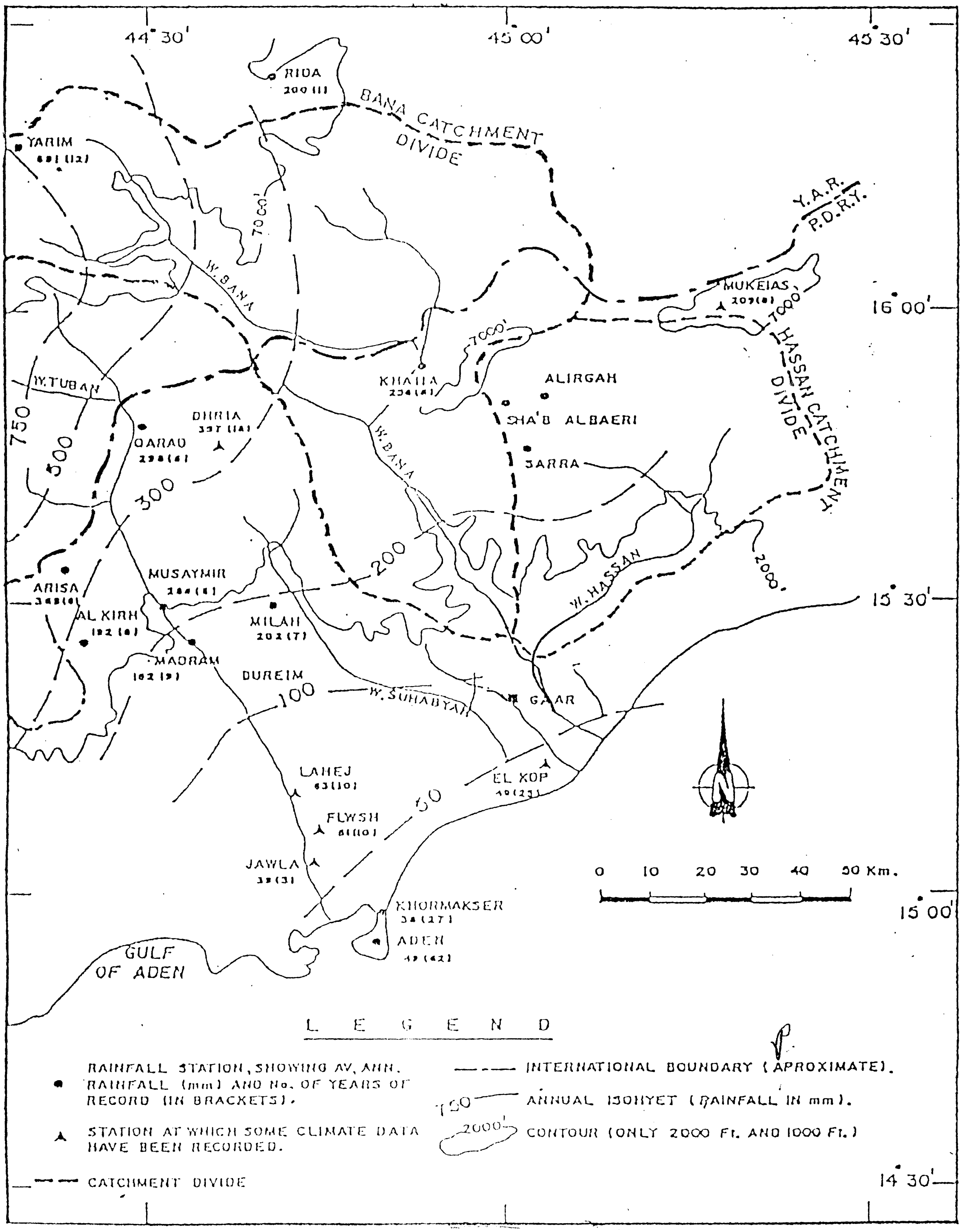


Figure 11. Geological composition of the southern part of Yemen showing Addhale'ya Rift and part of Wadi Bana basin

(From Landsat colour composite)

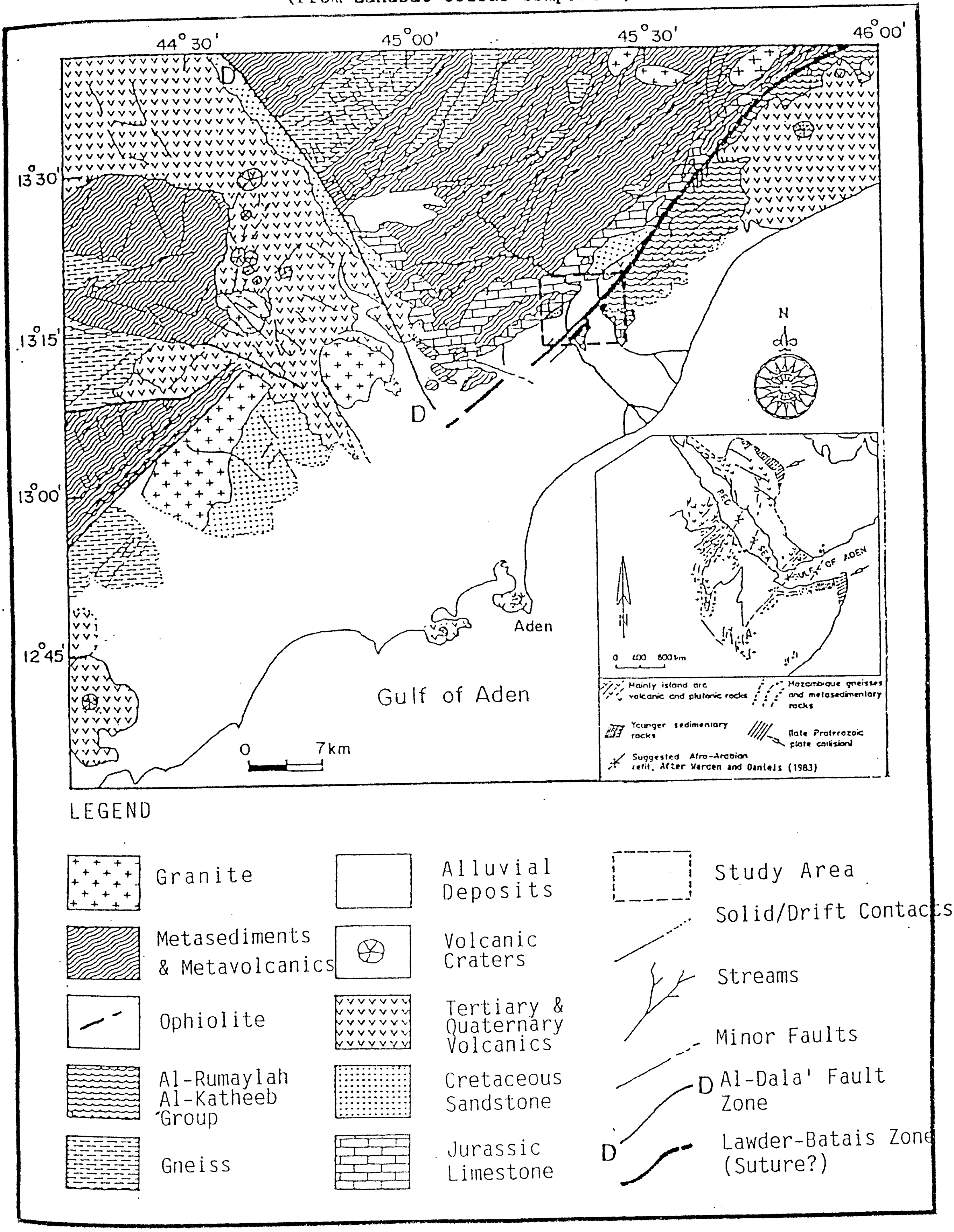


Figure 12. Geological map of Abyan delta showing the southern occurrence of Wadi Bana basin. Aquifer lithologies are underlain in the legend

(Modified after Al-Darweeish and Rabaa, 1988)

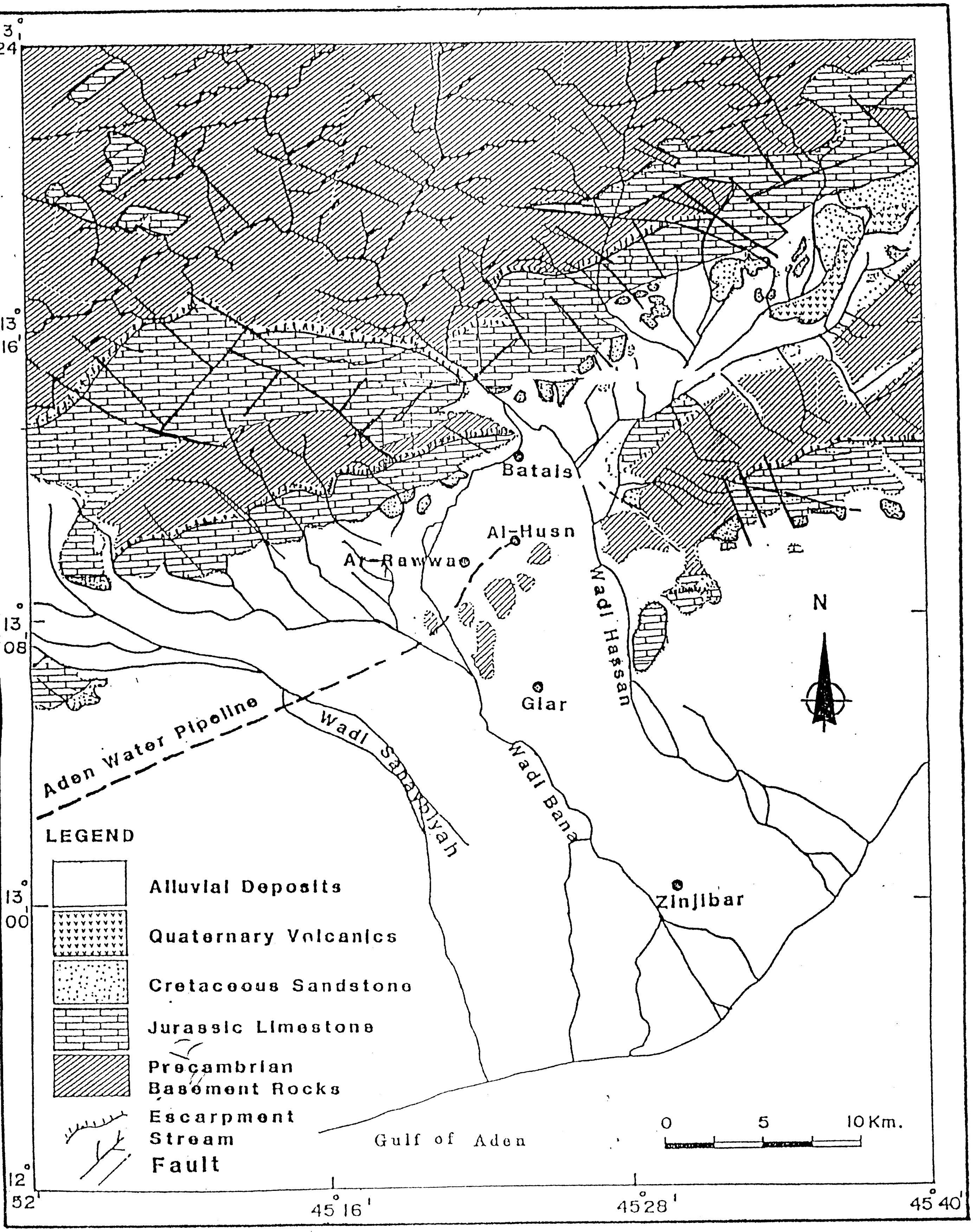
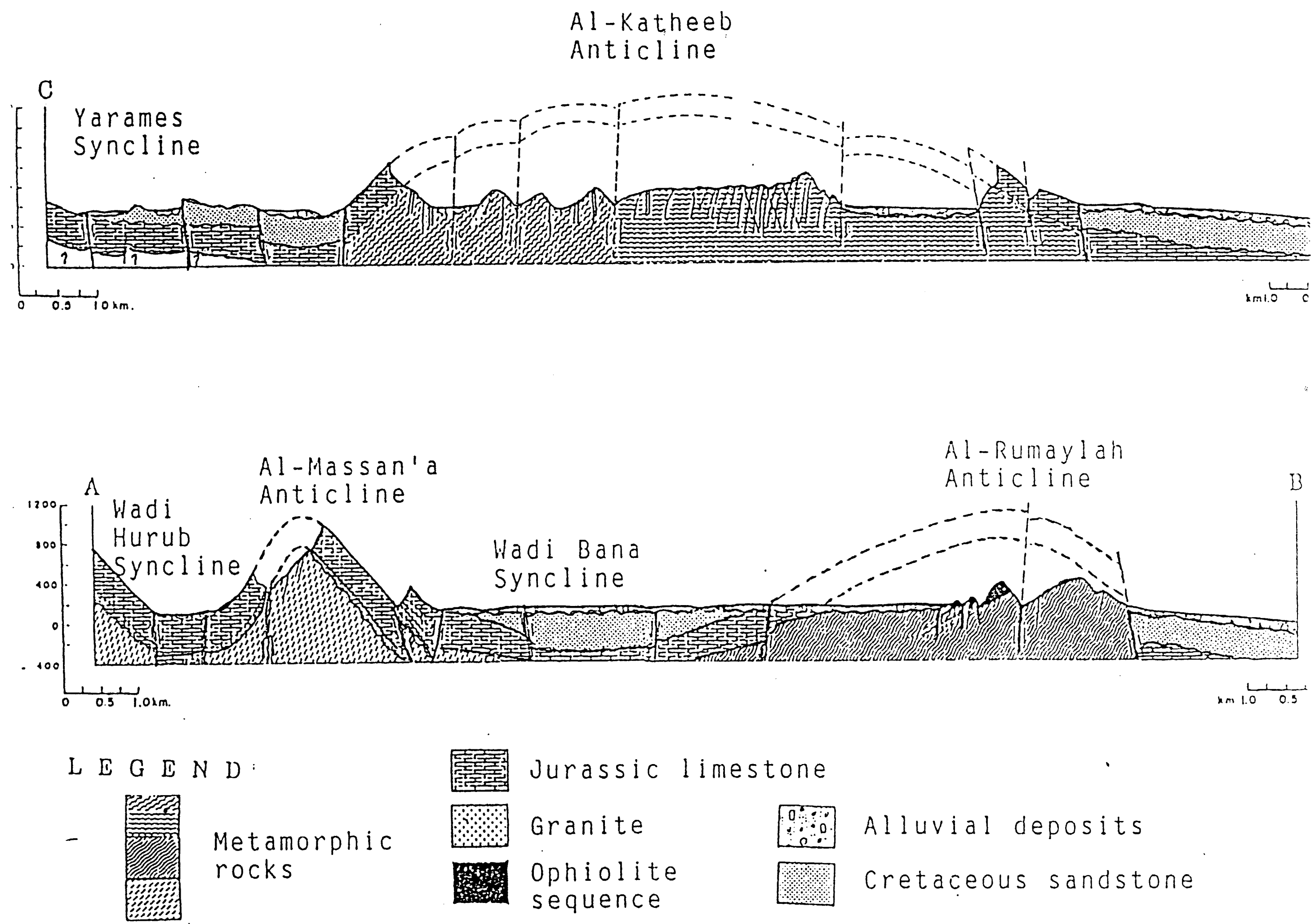


Figure 13. Cross-sections showing post-Jurassic flexuring at Batais Al-Husn area in Upper Abyan delta

(Al-Darweeish, 1988)



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