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ARIE ISSAR & DROR GILAD

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Groundwater flow systems in the arid crystalline province of Southern Sinai

ARIE ISSAR
The Jacob Blaustein Institute for Desert Research, Sede Boqer, and Department of Geology, Ben-Gurion University of the Negev, Beer Sheva, Israel
DROR GILAD
Hydrological Service, Ministry of Agriculture, Israel

ABSTRACT A hydrogeological research project was conducted in the arid crystalline province of the Southern Sinai. To gain a better understanding of regional groundwater flow patterns, Landsat images as well as air photos were used. Three main flow systems were investigated: (1) The flow system occurring along longitudinal regional crustal fractures with the direction parallel to the Gulf of Elat Rift; this system captures the flow in the main wadi beds draining eastwards. (2) The flow system found in shallow fractured rocks, capturing the flow in small tributaries in the upper part of the drainage basin. (3) The system of dikes governing the flow regime in wadi beds draining westwards. The preliminary estimate of the recharge into the fractured crystalline aquifers and the interconnected gravel bed aquifers is in the order of magnitude of 10-15% of the total precipitation.

Compréhension de l'écoulement des systèmes d'eaux souterraines dans la province cristalline aride du Sud du Sinaï

RESUME Un projet de recherche hydrogéologique a été mené dans la province cristalline aride du Sud du Sinaï. Pour arriver à une meilleure compréhension du schéma de l'écoulement des eaux souterraines dans cette région on a utilisé l'imagerie Landsat et les photos aériennes. On a procédé à des recherches sur trois systèmes principaux d'écoulements: (1) Le système d'écoulement que l'on trouve le long de fractures longitudinales de la croûte avec une direction parallèle à celle du Golfe d'Eilat. Ce système capte les eaux des lits des principaux ouadis qui coulent vers l'est. (2) Le système d'écoulement que l'on trouve dans les roches fracturées sur une faible profondeur qui captent l'écoulement dans les petits tributaires à la partie supérieure des bassins versants. (3) Le système de dikes contrôlant le régime de l'écoulement dans le lit des ouadis s'écoulant vers l'ouest. L'estimation préliminaire de la recharge des

aquifères situés dans les roches cristallines fracturées et des aquifères interconnectés dans les lits de graviers conduit à un ordre de grandeur de 10 à 15% du montant total des précipitations.

INTRODUCTION

Geographical background, objectives and methods of research (Figs 1 and 2)

The crystalline province of the Southern Sinai has a rugged, mountainous topography. The mountains rise to a maximal elevation of 2641 m (Gebel Katherina), and the elevation of most of the province is about 1000 m. The mountains are incised by deep wadis, which are usually the only way by which the area may be reached from the coastal plains. The scarcity and randomness of rains and floods,

Fig. 1 Composite Landsat 1 and 2 images of Southern Sinai.

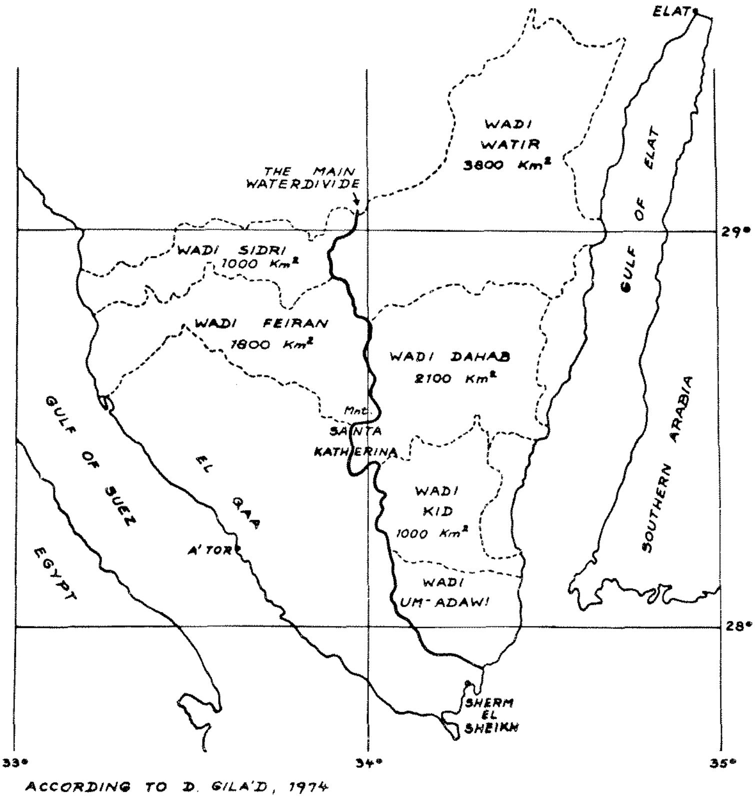

Fig. 2 Drainage basins map, Southern Sinai.

the difficult topography and the meagre population, have resulted in a scarcity of hydrological data; this in turn has prohibited any extensive investment in water development projects and thus in networks for hydrological data collection. The surveys carried out in the crystalline province therefore had to adopt methods based on the interpretation of miscellaneous observations collected from a few stations spread all over the region; the basic approach was to concentrate on the study of the groundwater flow systems as these were believed to regulate, by means of their storage capacity, the extremities of the seasonal fluctuations of the rains and floods.

The methodology adopted for this purpose was the following:

Stage 1 (a) Reconnaissance survey aimed at understanding the major flow system; (b) selection of special key problems and areas to be investigated in detail.

Stage 2 Detailed hydrological research on selected key problems and areas, up to the stage of preliminary quantitative evaluation followed by recommendation of development projects.

Stage 3 Follow up of execution of projects: collection of data, pumping tests, etc.

Stage 4 Re-evaluation of data and suggestions for advanced stages.

The reconnaissance stage was based mainly on 1:250 000 scale maps, NASA Landsat images and air photos. The succeeding stages were based on 1:100 000 scale maps and 1:50 000 colour air photos. The Landsat composite false colour images were found to be excellent tools for understanding the regional hydrogeological conceptual models, while colour air photos were found to be of high value for the more detailed survey. While the first stage was carried out over most of the crystalline province, the second stage was executed in regions inhabited by relatively dense populations. Such areas were mainly the alluvial fans of big wadis bordering the crystalline province (Gilboa, 1972; Kolton, 1980). In the crystalline province itself the advanced stages were executed in the Wadi Feiran Oasis (Ben Zvi & Gilad, 1970; Gilad, 1974).

Climate

The region is typically arid; precipitation is scarce and random and temperatures are high throughout most of the year. The rain that does occur falls in winter (November-March) when temperatures are relatively low (Fig.3).

The distribution of the scant precipitation appears to be mainly controlled by topography; thus, the low coastal areas seldom get more than 15 mm of rain per year. The higher regions, such as Gebel Katherina, receive approximately 50 mm $year^{-1}$ of precipitation, partly as snow. During exceptional years, torrential rains can raise the annual precipitation total to more than 100 mm.

Surface hydrology

The province is drained by a system of wadis extending to the Gulfs of Elat and Suez. The watershed bisecting the province runs approximately along a north-south line (Fig.2). Typical desert flash floods occur every few years, and some of them even reach the alluvial fans bordering the crystalline province. In the eastern part of the province floods may reach the sea after crossing the alluvial fans, while in the west they generally flood the Qaa plain of A-Tor. In the main wadis only random events have been recorded.

Geology (Fig.1)

The crystalline basement province of the Southern Sinai has a triangular shape with its vertex pointing to the south. Its flanks are faulted against the Gulf of Suez coastal plain in the west, and the Gulf of Elat in the east. Its base, running east to west, is overlain by a sequence of clastic rocks (several hundred metres thick) of Palaeozoic to Lower Cretaceous age. These rocks dip northwards and are covered by a sequence of Upper Cretaceous and Tertiary sedimentary rocks, several hundred metres thick (Said, 1962; Issar *et al.*, 1972).

The province is predominantly composed of Pre-Cambrian granitic metamorphic and volcanic rocks intruded by many acid to basic

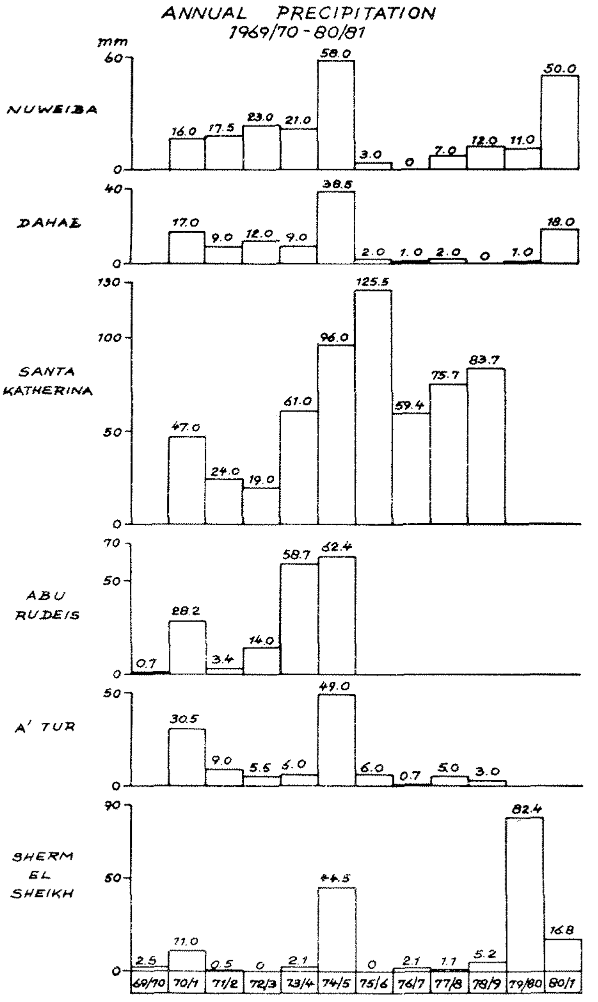

Fig. 3 Precipitation records.

Pre-Cambrian dikes, the dominant direction of which is NNE. In the Santa Katherina and Wadi Kid regions, meta-volcanic and meta-sedimentary rocks are found. In the far northeastern and northwestern corners of the province, gneisses, migmatites, gneissified granites, meta-volcanics and meta-sedimentary rocks are found (Bartov *et al.*, 1974; Eyal, 1975; Shimron, 1973).

The tectonic rifts bordering the Sinai on the west and east differ in both character and scale. The western rift, which forms the Gulf of Suez, is relatively shallow and wide, and is bordered by normal faults and tilted sedimentary blocks (Said, 1962; Garfunkel & Bartov, 1977). The eastern rift, which forms the Gulf of Elat, is delineated by a series of shear faults that form narrow, elongated down-faulted rift valleys (Eyal, 1973; Bartov *et al.*, 1979) built of Palaeozoic clastics and carbonates, overlain by young alluvium fill. The main rift forming the Gulf of Elat is deep and narrow, and the sea reaches the crystalline coastal cliffs. In the down-faulted narrow rift valleys, Palaeozoic and Cretaceous sandstone and limestones are found, overlain by Quaternary and recent alluvium.

GROUNDWATER FLOW SYSTEMS

Flow influenced by the eastern rift system

Upon examination of the Landsat images (Fig.1), the role of the eastern rifts in determining the direction of the surface drainage pattern can be seen.

Owing to the fact that the rifts are filled with permeable, down-faulted Palaeozoic and Mesozoic sandstones, overlain by younger alluvial sediments, the subsurface flow pattern appears to be closely related to that of the surface.

This interrelation is clearly illustrated by the Bir Zreir rift (Figs 1 and 4) (Bartov *et al.*, 1979). A shallow fresh groundwater body, on which the oasis thrives, was found there. The local

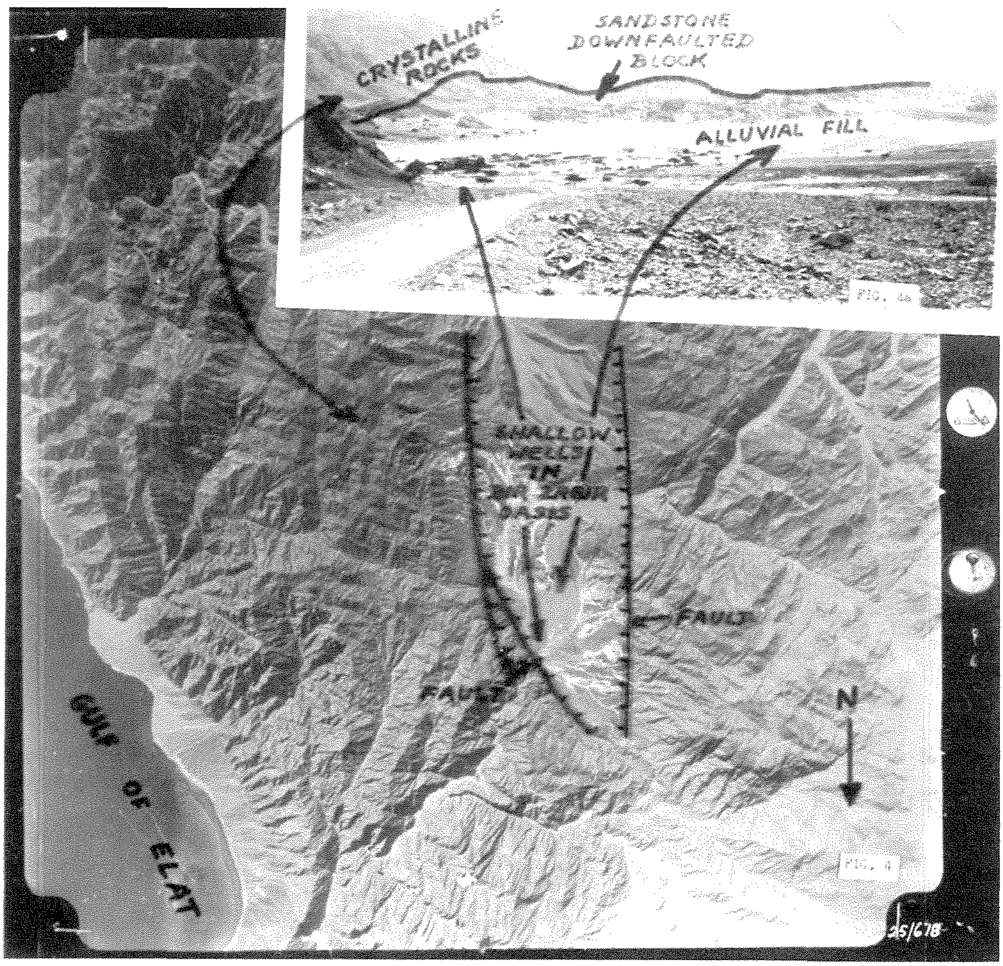

Fig. 4 Air photo of Bir Zreir region. **4a** Panoramic view.

Bedouin have dug shallow wells near the canyon outlet of the graben, taking advantage of the fact that at this point the water table is very shallow.

The existence of groundwater flow in sandstones of a similar rift was proved in Wadi Dahab (W.D. on Fig.1) where a well was drilled into the river bed found in the rift. No water was found in the alluvium, but water was found at a depth of about 35 m in the Mesozoic sandstone.

Another case where water was located with the aid of regional fracturing lines is that of Sherm-el-Sheikh (Fig.1). Extremely arid climatic conditions exist in this area. The average annual precipitation is less than 10 mm.

A well drilled into the alluvium of a river bed running along such a structure failed to locate water, whilst a well dug deeper into the Neogene sandstone below the alluvium struck fresh water. Two other wells reached brackish water. The fact that the occurrence of a water table was confined, points to the possibility that the water was not recharged through the alluvium. On the other hand, the environmental isotopic content of the water as well as

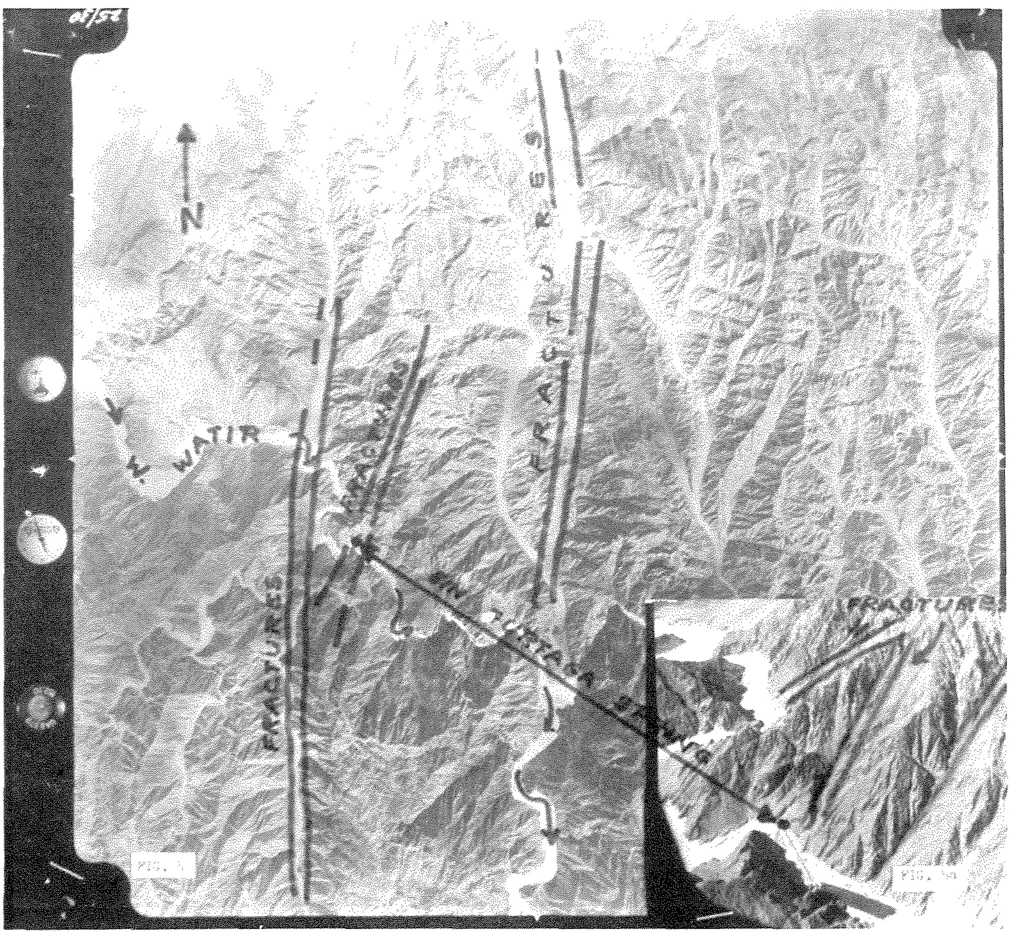

Fig. 5 Air photo of Ein Furtaga region. **5a** Oblique photograph of spring from helicopter.

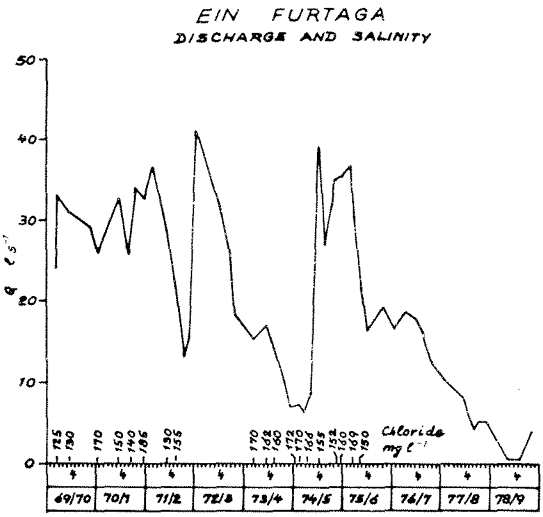

Fig. 6 Records of flows of Ein Furtaga.

its tritium content indicated that the water cannot be regarded as "fossil" (Gat & Issar, 1974), and therefore the only feasible mechanism is that of a subsurface flow from the north.

A diversion of the flow from one drainage basin to another through the regional fractures may explain the fact that several wells drilled at the apex of the alluvial fan of Wadi Kid (Fig.1), which is one of the largest drainage systems of the Sinai, failed to locate any water in the alluvium. Some water was found in the fractured granites below the alluvium. On the other hand, a well (Bir Nabek) which has a permanent water table was dug in the alluvial fan of Wadi Um Adawi which drains a much smaller area of lower rainfall. Moreover, exploration wells excavated at the apex of the alluvial fan of this river bed showed that the water table extends over a wide area and its salinity decreases. The explanation for this diversity is that the system of fractures leading to and traversing the surface drainage pattern directs the subsurface water from the Wadi Kid basin on to the Wadi Um Adawi basin, and even as far as Sherm-el-Sheikh.

Ein Furtaga represents a case where the fractured zone feeds the alluvial aquifers. This spring, which flows from the gravels of Wadi Watir, is the largest in the crystalline province (Figs 2, 5 and 6). Thus the appearance of flow in a region with a high density of fractures may suggest that a substantial flow exists from the regional fractures which recharge the river gravel.

The variance of the yearly discharge of the spring, its dependence on the annual precipitation, as well as its low salinity and high tritium content (158 ± 5 TU) (Gat & Issar, 1974) point to the fact that the recharge is local. On the other hand, it could not have come from the upper part of the drainage basin because wells situated about 20 km upstream, where the river bed leaves the sedimentary province to enter the crystalline province (Fig.6), were found to be very saline.

The shallow, fractured rock system

The system functions mainly in the mountain ridges surrounding Santa Katherina. The rocks are highly jointed and faulted (Figs 7, 8) volcanics and Pre-Cambrian granites (Eyal, 1975). Numerous small springs emerge from these fractures and many shallow wells excavated into the bedrock were found in this region.

A geochemical study based on chemical and stable isotope analyses ($\delta^{18}O$ and $\delta^{2}H$) has shown that, at higher elevation, the isotopic composition of the groundwater is very similar to that of the precipitation (Gat & Issar, 1974). This shows that evaporation is slight and that the water finds its way into the open fractures immediately upon reaching the surface.

Field observations during rainstorms indicated that most of the recharge and flow is through open fractures. Part of it is through mylonized zones formed in areas of cross faulting and fracturing. These areas are characteristic of the high ridges surrounding the Santa Katherina Monastery (Figs 7, 8). They form small arable plots (locally called "Farschs") on top of the mountains which are tilled

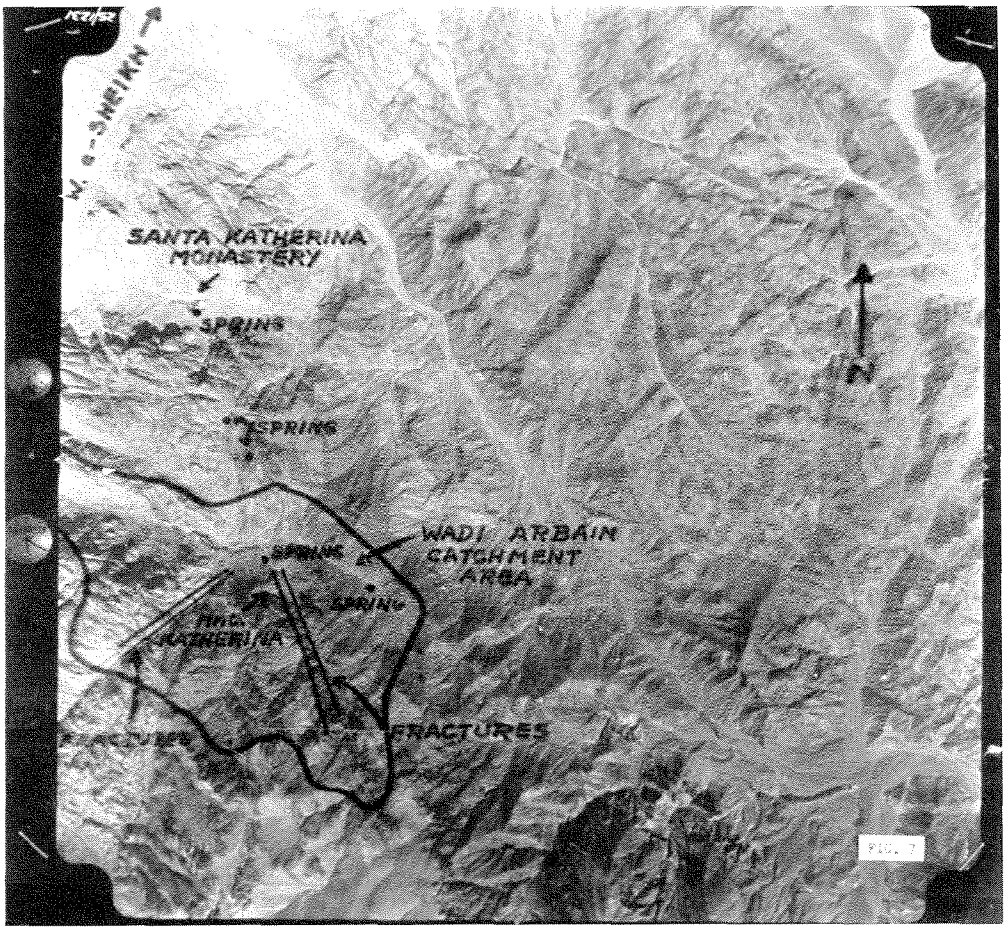

Fig. 7 Air photo of Santa Katherina region.

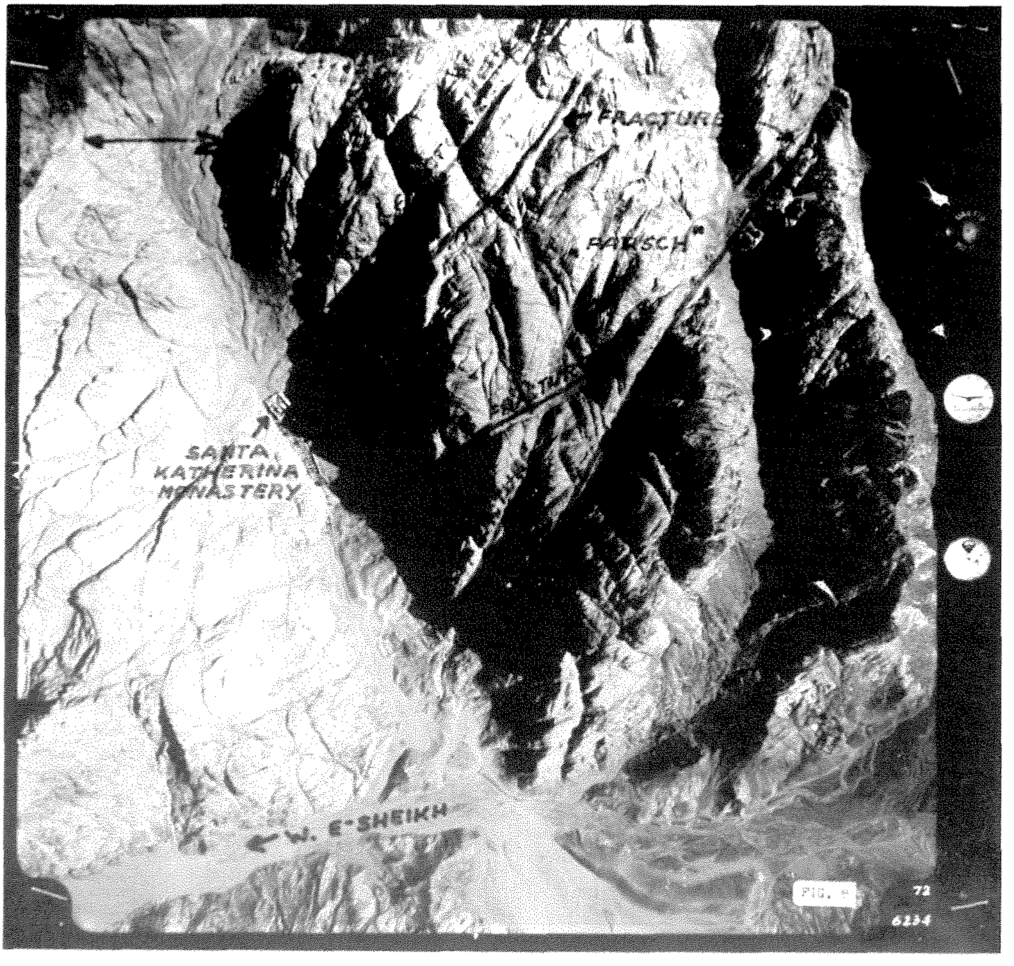

Fig. 8 Air photo of Santa Katherina Monastery.

by monks and their Bedouin workers. These small valleys form small closed drainage basins which collect the water that falls on the bare rocks surrounding them. In especially rainy years, these Farschs may turn into seasonally flooded basins.

Many springs and seepages appear where the fractured granitic rocks meet the decomposed basic dikes or the kaolinized fault faces. The local inhabitants make use of this fact by excavating their wells into the soft dikes, leaving the face of the fractured granitic or porphyric rock exposed in the pit. They thus get water which flows from the fractured rock into the pit (Fig.9).

Direct observations in addition to pumping tests conducted in these wells show that the flow in the fractured rock is more similar to flow in open channels than to flow through porous media. This could be directly observed in the large diameter wells where the water emerges from the open fractures. It could also be seen from the abrupt decline of the water table in the wells as soon as the pumping rate exceeded the basic flow of the supplying fractures.

In crystalline rocks, the permeability changes as a function of

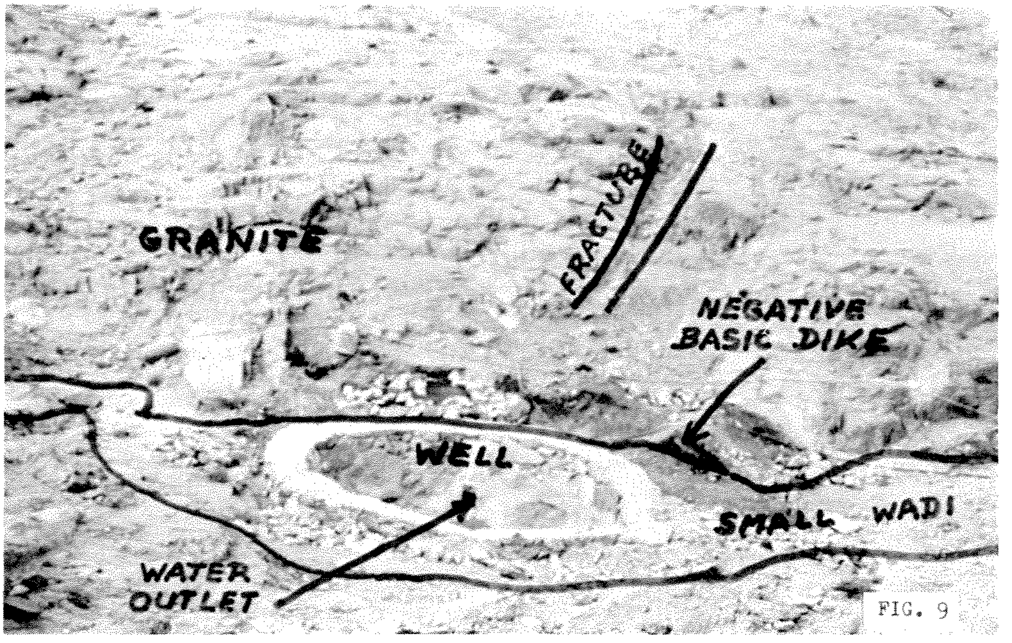

Fig. 9 A well excavated in a basic dike, Santa Katherina region.

the degree of fracturing undergone by the rocks. This affects the anisotropic character of the aquifer, and is expressed in the variation of the hydraulic parameters when the cone of depression develops around a pumping well. Thus, in the Bir Ahdar well in which some fractures are open and others are filled with mylonite, the influence of both flow regimes can be observed during pumping tests (Fig.10).

The abundance of faults and fractures observed from air photos and field observations indicates, even for small drainage basins, a rather large storage capacity in the rocks. This is why most springs remain perennial even in years when precipitation does not reach 30 mm. However, the cumulative effect of the last three or four years of low precipitation (probably less than 20 mm year^{-1}) caused many springs to dry up in the summer of 1979. Some of them did continue to flow even during this year.

Wadi beds and dike systems

As seen from the Landsat images and air photos (Figs 1 and 11), the northwestern part of the province has a meandering drainage pattern, as opposed to the wadi beds to the south and east which follow regional rifts. A closer examination of these images and air photos reveals that the area is characterized by dikes running in a north-south direction, perpendicular to the direction of the surface drainage systems.

The porphyritic dikes which are more resistant to erosion than the granites and other crystalline rocks form "positive" wall-like features, and are found to have a retarding effect on the subsurface flow. Thus they cause the accumulation of water and the creation of

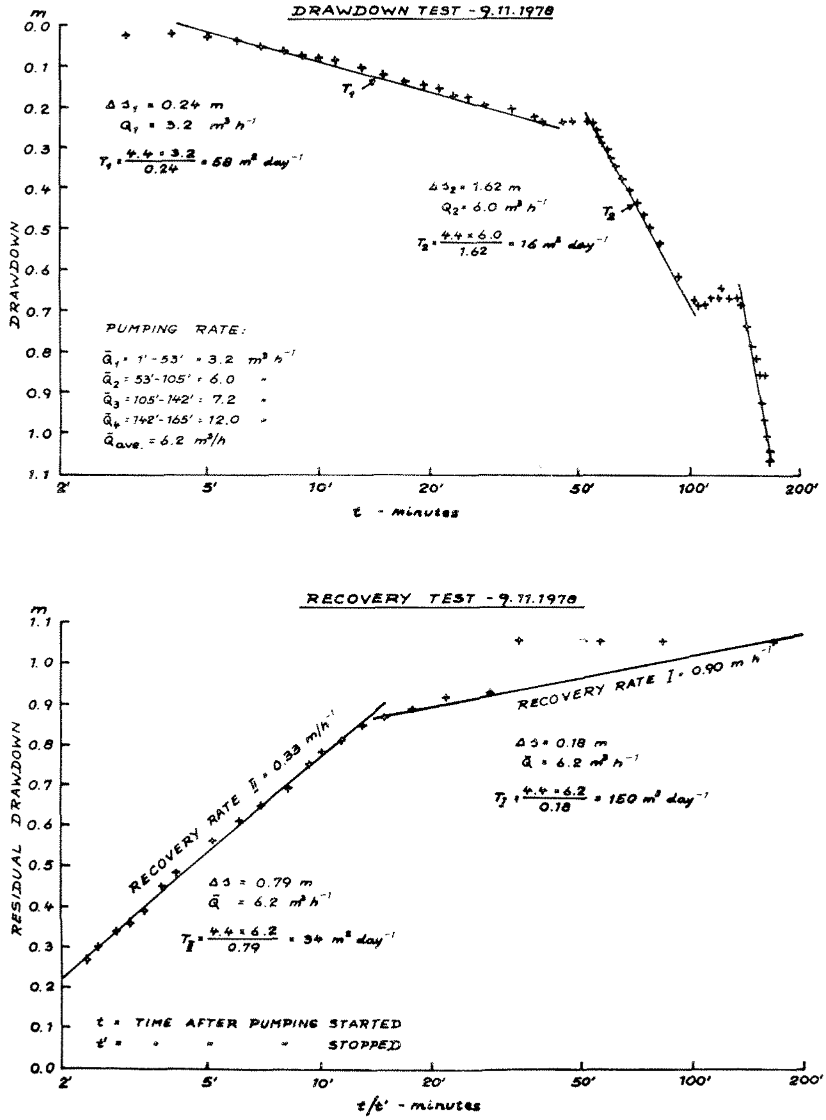

Fig. 10 Pumping tests of Bir Ahdar.

oases, the main one being the Feiran Oasis.

The damming effect of the dikes began during the Pleistocene when more humid conditions prevailed, and when the floods retained behind these dams formed shallow lakes and marshes, in which silts, sands and fresh water limestones were deposited (Issar & Eckstein, 1969). Today, the influence of dikes can be observed only in the subsurface, as seen from the distribution of oases and the step-like water table in Wadi Feiran (Fig.12). The lacustrine deposits as well as the younger alluvium form the main aquifer in this region. Further west, Wadi Feiran, after being joined by several tributaries, leaves the crystalline province. It crosses a region composed of sedimentary rocks of Palaeozoic to Mesozoic sandstones, carbonates and Tertiary

Fig. 11 Air photographs of Wadi Feiran Oasis.

rocks as well as sands and gypsum. This region forms the northern part of the Qaa plain of A-Tor. The Landsat images show (Fig.1) that the whole region south of the Wadi Feiran drainage system is drained by wadis that follow regional fractures. These fractures cross the province in a SSW direction toward the Qaa plain.

The wadis are narrow and their beds are covered by a thin layer of gravel not deeper than 2 or 3 m. In places where these wadis cross a positive dike, the bedrock is exposed. In most cases, seepages from gravel beds cause surface flow on the exposed bedrock. In rainy years, these wadis flow throughout the year along the exposed sections. When the wadis reach the upper margins of the Qaa plain, the flows disappear into the alluvial fans. The Qaa plain thus serves as the drainage basin for most of the surface water as well as for the groundwater in the western part of the crystalline

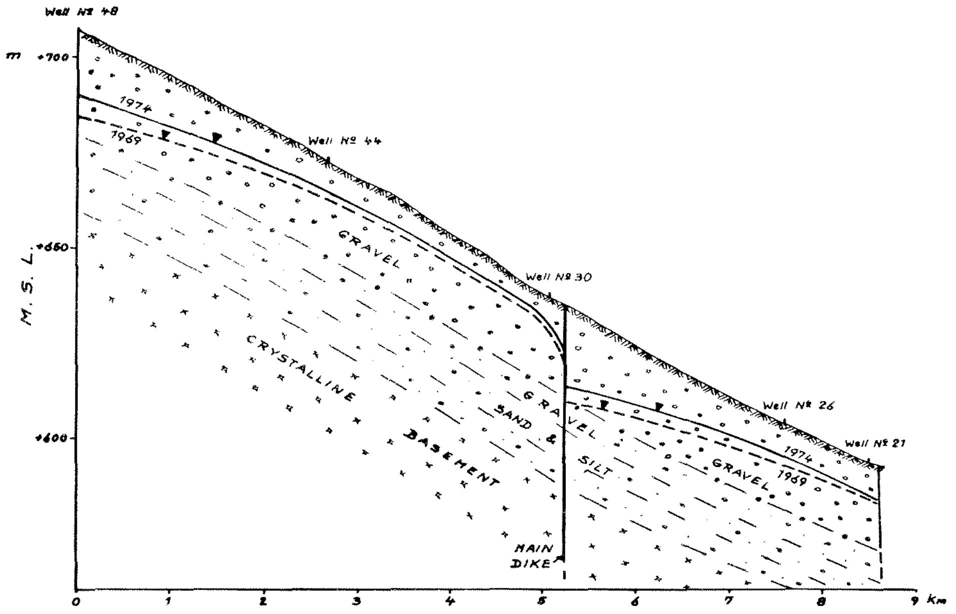

Fig. 12 Water table section Wadi Feiran Oasis.

province of the Sinai.

Hydrogeological research studies in the Qaa plain have shown that most of the outflow from the plain to the sea occurs at the oasis of A-Tor south of the Qabeliat range (Gilboa, 1972; Issar, 1973).

QUANTITATIVE HYDROLOGICAL EVALUATION

The general evaluation of the order of magnitude of the recharge to the crystalline fractured aquifers and the alluvial aquifers interconnected with them will be presented in the present section.

A preliminary hydrological quantitative evaluation of the regime of flow in the limited catchment area of Gebel Santa Katherina (Fig.7) gives an idea of the order of magnitude of the volume recharged into the fracture system.

The catchment area of the ridges feeding the springs of Wadi Arbain is about 12 km^2; the average annual precipitation in the years preceding the measurement was 50 mm while the annual flow of springs and small wells in the river bed amounted to about 90 000 m^3. Thus the order of magnitude of the recharge to groundwater can be estimated to reach about 15% of the total precipitation. This figure should of course be taken as a general approximation, but it still gives a quantitative idea of the subsurface flow. As is further shown, part of the recharge (exceeding the previously mentioned 15%) is believed to find deeper and bigger fractures, and flows outside the region. The hydrological regime of Wadi Feiran gives the same order of magnitude of recharge. The upper well field in Wadi Feiran is that of Tarfat Kudren (Fig.1); in this oasis, pumping tests (Fig.6) and gradient measurement were carried out by the Hydrological Service in 1970, when the groundwater flow through the oasis was estimated at 1.2 x $10^6 m^3 year^{-1}$.

Taking into account that the drainage area of this Wadi to the point where the measurement was taken is about 170 km and that average annual precipitation at Santa Katherina Monastery is about 50 mm, the flow in the gravel amounts to about 13% of the total precipitation. This quantity could have been attributed to the volumes of water percolating through the river bed gravel from the floods. Another measurement made in the Wadi Feiran oasis about 40 km downstream gives a lower figure (0.6 $10^6 m^3 year^{-1}$) of subsurface flow (Ben Zvi & Gilad, 1970). As no wells, vegetation or springs are found between the two oases, it seems possible that the groundwater flow is not restricted to the alluvial lacustrine deposits but is connected with the fracture systems traversing the Wadi bed. Thus the flow measured in the upper oasis at Tarfat Kudren was a result partly of flood enrichment and partly of water fed from fractures in the bedrock. The amount of water lost between Tarfat Kudren and the oasis of Feiran found its way into the relatively numerous fractures which cross the river beds.

The difference in tritium contents between the water in the two oases (46 ± 7 TU in Tarfat Kudren and 0 ± 3 TU in the oasis of Feiran) (Gat & Issar, 1974) also suggests a rather lower enrichment range from recent floods, compared with the retarded flow through fractures and gravel bed, or at least to a rather significant influence of older water, particularly in the lower parts of the drainage basin.

Further west, the Wadi Feiran, after being joined by a few tributaries, leaves the crystalline province and traverses a region built of sedimentary rocks of Palaeozoic, Mesozoic and Tertiary rocks built of sandstones and carbonates as well as sands and gypsum. This region forms the northern part, "El Qaa", of A-Tor.

El Qaa is bordered on its eastern side by a regional fault line which faulted down the sedimentary sequence topped by Neogene lagoonal and continental clastics against the Pre-Cambrian crystalline basement. To the west, El Qaa is bordered by the anticline of Qabeliat which dips down below El Qaa and is faulted on its western side against the Gulf of Suez. This anticline forms a barrier to all the surface flow and groundwater, directing it towards the southern edge of the anticline where the water appears near the surface in numerous shallow wells.

At present Wadi Feiran flows out through a narrow bottleneck cut into the Neogene marls and gypsum, to the sea north of the range of Qabeliat. Water wells drilled into this bottleneck, intended to exploit the underflow of the Wadi, encountered very shallow (20 m) alluvium and no exploitable water reserves. Detailed investigation revealed that the river underflow finds its way into Neogene sandstone and partly into the Nubian sandstones folded against the basement and the alluvium. This is possible owing to the fact that, until quite recently, Wadi Feiran did not flow directly to the sea, but drained mainly into El Qaa. This alluvial fan can be traced along the northern margins of El Qaa and overlies clastic Neogene rocks in which brackish groundwater was found.

As indicated by the tritium content, deuterium, and ^{18}O isotopes ratio (Gat & Issar, 1974), the water of the Neogene is ancient; its present rate of recharge is small. It is thus assumed that the underflow of Wadi Feiran finds its way to El Qaa of A-Tor through different conduits: some of it percolates from its beds into its ancient alluvial fans, and from there into the Neogene sandstones towards the thermal spring of Hamam Musa (Gat & Issar, 1974) which has a quite steady annual discharge of about 300 000 m^3. Another part finds its way through fractures incising the crystalline rocks in a SSW direction, towards the Qaa. This basin serves as the drainage base to most of the surface water and to the groundwater draining the western part of the crystalline province of the Sinai.

Hydrological studies in El Qaa (Gilboa, 1972; Issar, 1973) have shown that most of the outflow from El Qaa to the sea is at the A-Tor oasis. In this area pumping tests and water table measurements enabled the estimation of the annual flow to the sea. According to Issar (1973), the flow through a 10 km front reached $2.0 \times 10^6 m^3 year^{-1}$. In the same area and for a similar section, Gilboa (1972) estimated a flow of $2.5 \times 10^6 m^3 year^{-1}$.

Calculating the total precipitation falling on the region draining to El Qaa, and considering the altitude, the quantity of $22 \times 10^6 m^3 year^{-1}$ over an area of about 900 km^2 is estimated. The outflow to the sea amounts to approximately 10-13% of this figure. Although this is a rough estimate and includes both surface and subsurface flow, it provides an order of magnitude of the quantities which evaporate from a basin of such a type and magnitude.

CONCLUSIONS

An hydrogeological interpretation of an arid region with very scarce hydrological data has yielded preliminary quantitative evaluation; this was achieved by the combined use of Landsat images, air photos and field surveys. The water isotope analysis of tritium, deuterium and ^{18}O together with conventional chemical and hydrological data helped in the understanding of the groundwater flow systems.

Although crystalline rocks are believed to be impermeable, it was found that, owing to the tectonic history of the region, these rocks form, owing to their fractures, a water-transmitting medium which, together with the alluvial deposits and down faulted blocks, may transfer between 10% and 15% of the total precipitation in the region. In some parts of the area (as in the lacustrine deposits of the main wadis, in the sedimentary fill of the rifts and in the sedimentary basins bordering the crystalline province), large volumes of water suitable for exploitation during drought years may be located.

REFERENCES

Bartov, Y., Steinitz, G., Eyal, M. & Eyal, Y. (1979) The development of the Arava Rift Valley and the Red Sea. New evidence for Cenzoic strike slip faults in Eastern Sinai. *Abstracts, Annual Meeting of Sede Boqer*, p. 8. Israel Geological Society.

Bartov, Y., Steinitz, G., Eyal, M. & Eyal, Y. (1979) Horizontal displacement along faults, Bir Zreir Eastern Sinai. *Abstract, Annual Meeting at Sede Boqer*, p. 10. Israel Geological Society.

Ben Zvi, M. & Gilad, D. (1970) *An Hydrogeological Research at the Oasis of Feiran*. Hydrological Service, Ministry of Agriculture, Jerusalem.

Eyal, Y. (1973) The tectonics of the Shelomo and Yotam Grabens, Eilat, Israel. *Israel J. Earth Sci.* 22, 165-184.

Eyal, M. (1975) Stages in the magmatic history of the Precambrian in Sinai and Southern Negev (in Hebrew). PhD Thesis, Hebrew University, Jerusalem.

Garfunkel, Z. & Bartov, Y. (1977) The tectonics of the Suez Rift. *Geol. Surv. Israel Bull. no. 71.*

Gat, A. & Issar, A. (1974) Desert isotopes hydrology, water resources of the Sinai Desert. *Geochim. et Cosmoch. Acta* 38, 1117-1131.

Gilad, D. (1974) Description of hydrological situation in Southern Sinai (in Hebrew). *Hydrological Service Report 1974/75.*

Gilboa, Y. (1972) *Survey of Water Resources at A-Tor.* Tahal, Water Planning for Israel Ltd., Tel Aviv.

Issar, A. (1973) Preliminary report on the results of the hydrogeological research in the Shlomo region, South Sinai. Summary of Survey edited by the Authority for Nature Conservation, Tel Aviv.

Issar, A., Bein, A. & Michaeli, M. (1972) On the ancient water of the Nubian sandstone aquifer in Central Sinai and Southern Israel. *J. Hydrol.* 17, 353-374.

Issar, A. & Eckstein, Y. (1969) The lacustrine beds of Wadi Feiran, Sinai: their origin and significance. *Israel J. Earth Sci.* 18, 21-27.

Kolton, J. (1980) The hydrogeology of alluvial fans in Southern Sinai (in Hebrew with English abstract). PhD Thesis, Tel Aviv University.

Said, R. (1962) *The Geology of Egypt.* Elsevier, Amsterdam.

Shimron, A.E. (1973) The Precambrian structural and metamorphic history of the Eilat Area with comparative notes of the Sinai Peninsula. PhD Thesis, Hebrew University, Jerusalem.

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