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Injection of industrial wastewater in Israel: siting criteria for deep injection wells and associated problems

Ronit Nativ*, Ilan Hemo, Gavriel Weinberger

The Seagram Center for Soil and Water Sciences, Faculty of Agriculture, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 76100, Israel

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Abstract

Preliminary evaluations of potential sites for deep-well wastewater injection characteristically make use of existing data from deep boreholes drilled for other purposes. Unlike new drilling and logging operations specifically designed to address site-assessment needs, the quality of existing data may be questionable and requires special attention. In the present study, the desired features of a subsurface reservoir for wastewater injection are defined and a screening procedure for potential reservoirs is presented. Typical problems associated with data from deep oil- and gas-test wells are discussed, and guidelines for screening data of rock permeability and formation-water pressure, salinity and temperature are presented. These problems, as well as solution approaches, are illustrated for two different reservoirs, selected as potentially suitable for deep-well wastewater injection in west-central and northern Israel.

1. Introduction

Increasingly large volumes of waste are produced annually by industrialized societies. The disposal of industrial liquid waste is a major environmental problem. The presence of toxic compounds and trace metals in the waste and its heterogeneous composition result in expensive and uneconomical reclamation processes.

Within the past 30 years, subsurface injection has become the predominant method of disposing of liquid hazardous waste in the United States. Approximately 10 billion gallons, or 60% of all hazardous waste disposed, are injected annually into wells for subsurface burial. This is twice the amount going to surface impoundments. Ninety-five percent or more of the injected hazardous waste in the United States is directed to

* Corresponding author.

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deep wells and deposited at depths ranging from 400 to more than 1500 m below the surface (Gordon and Bloom, 1987). The majority of these wells are along the Gulf Coast and the Great Lakes region (Carpenter, 1987). This method of disposal is regulated by federal and state agencies through laws that have evolved in response to environmental concerns, preventing the contamination of groundwater resources via unsafe underground injection practices.

The estimated annual volume of industrial waste in Israel exceeds $50 \times 10^6\,m^3$ (Israeli Ministry of Agriculture, 1987); most of it is currently being disposed of in evaporation ponds. Frequent leakage of wastewater from these ponds poses a major threat to soil and groundwater resources. Deep-well injection of liquid waste is still in its preliminary stages in Israel. The oil refineries have initiated the injection of aromatic caustic soda through an abandoned oil well located in the southern Coastal Plain (Fig. 1). The liquid waste is being injected into Lower Cretaceous sands at a depth of 1500 m. Close to the land surface in this area is the Coastal Plain aquifer, one of the three major water supply reservoirs in Israel. The injection well is located in an old oil field where 26 wells have perforated the injection zone. None of these abandoned wells (except for the injection well) have been retrofitted to avoid shortcuts from the injection zone to the overlying aquifer. The study reported here was initiated because we felt that both the site and the well selected for the injection facility were inappropriate. However, at that time we could not propose a better site for these activities.

The purpose of this study was, therefore, to locate regions and subsurface intervals in Israel suitable for wastewater injection. We used existing published and unpublished geologic, geophysical, hydrologic and water quality data to describe the reservoir and confining potential of the rocks. The data were derived from old and recently drilled deep oil- and gas-test wells throughout Israel. Such data sources are typical of preliminary site assessments for wastewater injection facilities. Unlike new drilling and logging operations specifically designed to address site-assessment needs, the quality of existing data from oil- and gas-test wells may be questionable and requires special attention.

Although this study may be perceived as highly site specific, we maintain that the problems encountered throughout our investigation in Israel are typical, and that the solutions offered here can be applied elsewhere. These problems, as well as solution approaches, are illustrated in this article by two (of the final seven) reservoirs that were selected as potentially suitable for wastewater injection.

2. The characteristics of a subsurface reservoir for liquid waste

A potential subsurface reservoir for liquid waste should have the following characteristics: (1) a significant volume of porous and permeable reservoir rock containing nonpotable water, (2) surrounding rocks that can prevent the escape of waste fluid from the reservoir rock, (3) isolation from the surface environment and from potable groundwater, and (4) economically feasible drilling depths.

The criteria used in this study to determine whether these characteristics occurred at any site were as follows: (1) Sandstone, dolomite, or limestone with a continuous and relatively homogeneous thickness of at least 100 m were defined as potential reservoir intervals. Porosity and permeability values derived from core analyses were not used to screen potential host intervals for reasons to be discussed later. (2) At least 25 m of confining rock (shale, evaporite or unfractured volcanic rocks) should overlie and underlie the reservoir rock. Rocks that met these requirements were defined as potentially confining intervals in this study. (3) Groundwater in the potential reservoir should be non-potable and contain more than 10 000 mg L^{-1} total dissolved solids (TDS). (4) Rocks more than 2500 m below land surface were considered to be economically unsuitable for liquid-waste storage because of well-construction and operational costs.

Thus, the potential reservoir environment in the study area was defined as follows: a relatively homogeneous sandstone, dolomite, or limestone layer containing water having more than 10 000 mg L^{-1} TDS lying at a depth not exceeding 2500 m below the land surface. These formations are at least 100 m thick, and are overlain and underlain by a consecutive sequence (of at least 25 m thickness) of shale, evaporite, or unfractured volcanic rocks.

3. Methods of investigation

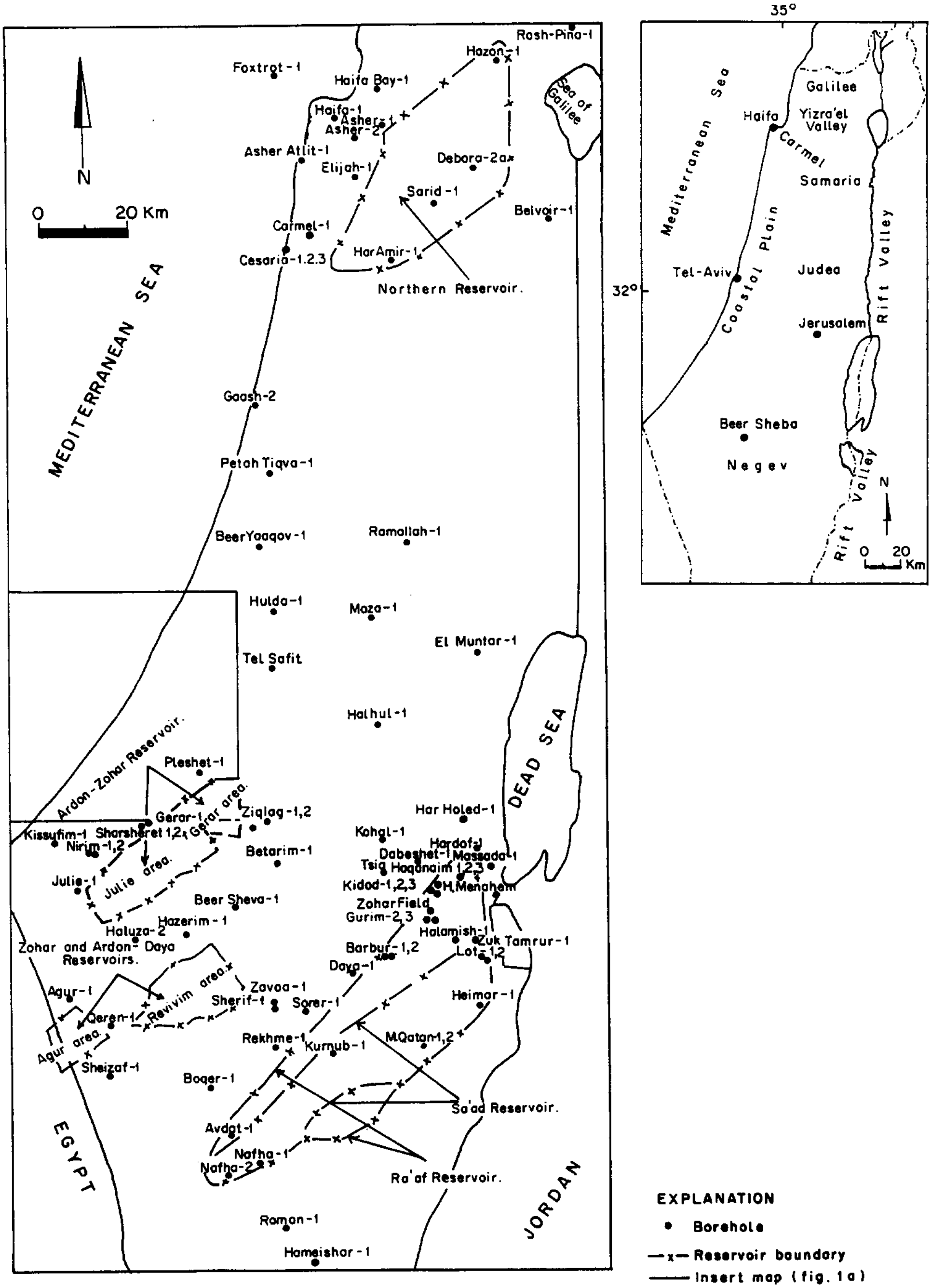
3.1. The screening procedure

The search throughout Israel for potential geologic layers suitable for wastewater injection consisted of the following steps.

(1) All rock formations containing groundwater with less than 10 000 mg L^{-1} TDS were excluded from further consideration as potential host rocks. Juxtaposed formations were also excluded. (In the United States, injection of wastewater into such aquifers is prohibited. This has come about under the assumption that the desalination of groundwater with salinity lower than sea water may some day prove to be less expensive (Lloyd and Reid, 1990).) Groundwater salinity was determined from water samples taken from oil- and gas-exploration wells.

(2) The remaining rock formations were re-examined using stratigraphic, structural and lithologic parameters to identify thick and permeable horizons suitable for injection and protected from leakage by juxtaposed low-permeability layers.

The stratigraphy was determined using borehole data and was displayed in geologic sections. The horizons proposed for injection and confinement were indicated in these sections. Isopach maps demonstrate the varying spatial thickness of these horizons. The structural geology of the proposed layers was examined in great detail at the Israel Institute for Petroleum Research and Geophysics to avoid faulted zones. Large-scale maps of the proposed sites indicate (a) the spatial distribution of faults and joints and (b) the depth to the top of the studied horizons. Cores from boreholes and geophysical logs were used for a detailed lithologic description of the studied horizons to determine their hydraulic features. As a result of this stage, some horizons and areas that appeared suitable for injection on the basis of their contained fluid salinity were eliminated.


N
0 20 Km
MEDITERRANEAN SEA
Foxtrot-1
Haifa Bay-1
Haifa-1
Asher-1
Asher-2
Asher Atlit-1
Elijah-1
Carmel-1
Cesaria-1.2.3
Rosh-Pina-1
Hazon-1
Sea of Galilee
Debora-2a
Sarid-1
Belvoir-1
Har Amir-1
Northern Reservoir.
Gaash-2
Petah Tiqva-1
BeerYaaqov-1
Ramallah-1
Hulda-1
Moza-1
El Muntar-1
Tel Safit
Halhul-1
DEAD SEA
Ardon-Zohar Reservoir.
Pleshet-1
Gerar-1
Gerar area
Ziqlag-1,2
Kissufim-1
Sharsheret 1,2
Nirim-1,2
Betarim-1
Julie area
Julie-1
Beer Sheva-1
Hazerim-1
Haluza-2
Zohar and Ardon-Daya Reservoirs.
Har Holed-1
Kohal-1
Hardof-1
Dabeshet-1
Massada-1
Tsig
Hoqdnaim 1,2,3
Kidod-1,2,3
H.Menahem
Zohar Field
Gurim-2,3
Halamish-1
Zuk Tamrur-1
Barbur-1,2
Lot-1,2
Daya-1
Agur-1
Revivim area
Zavoa-1
Sherif-1
Sorer-1
Heimar-1
Qeren-1
Agur area
Rekhme-1
Kurnub-1
MQatan-1,2
Sheizaf-1
Boqer-1
Sa'ad Reservoir.
Avdat-1
Nafha-1
Nafha-2
Ra'af Reservoir.
EGYPT
JORDAN
Ramon-1
Hameishar-1
35°
32°
Mediterranean Sea
Galilee
Haifa
Yizra'el Valley
Carmel
Samaria
Coastal Plain
Tel-Aviv
Judea
Rift Valley
Jerusalem
Beer Sheba
Negev
N
0 20 Km
EXPLANATION
Borehole
Reservoir boundary
Insert map (fig. 1a)

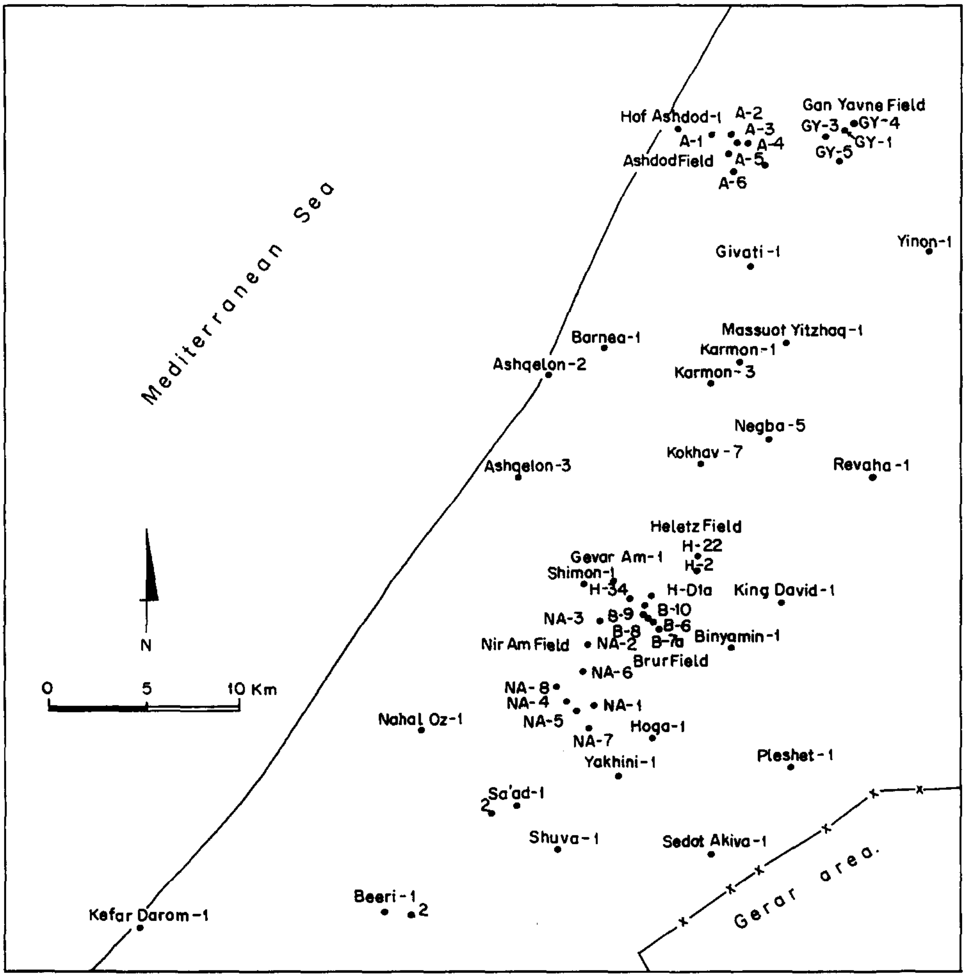


Fig. 1. Location map of deep wells and the suggested potential reservoirs for liquid waste injection. Physiographic provinces are marked in the inset map.

(3) The remaining horizons were further studied to determine the nature of their rocks and fluids. Porosity and permeability were determined using available core analyses and interpretations of drill-stem tests. Viscosity and density of formation water were calculated using measured salinity and temperature. Temperature was measured in the drilling mud (Levitte and Olshina, 1984) or during drill-stem tests. Salinity data were derived from production tests (drill-stem or swab tests). Formation-water pressure was examined using data from drill-stem tests.

(4) Formation-water flow directions were then calculated using measured pressure. Results from items (3) and (4) allowed further elimination of horizons owing to inadequate rock and fluid features or undesirable flow directions. The remaining

horizons were recommended as potential reservoirs for wastewater injection on the basis of existing geologic and hydrologic data.

3.2. The data base

We collected and examined geological and hydrologic data from all 137 deep oil and gas boreholes drilled across Israel (Fig. 1). Well completion reports, lithologic logs, sample descriptions, core analyses, geophysical logs, seismic surveys and other available and pertinent data obtained for individual wells were analyzed and synthesized during the study. Most of the hydraulic data came from drill-stem tests conducted at different depths inside the wells. Many of these tests, however, were performed incorrectly, and unreliable data had to be screened out. Tests having no or incorrect interpretations were interpreted as part of this study.

3.3. Salinity constraints

The selection criteria of rock units that (1) contain groundwater having more than 10 000 mg L^{-1} TDS and (2) do not directly overlie or underlie fresh/brackish water

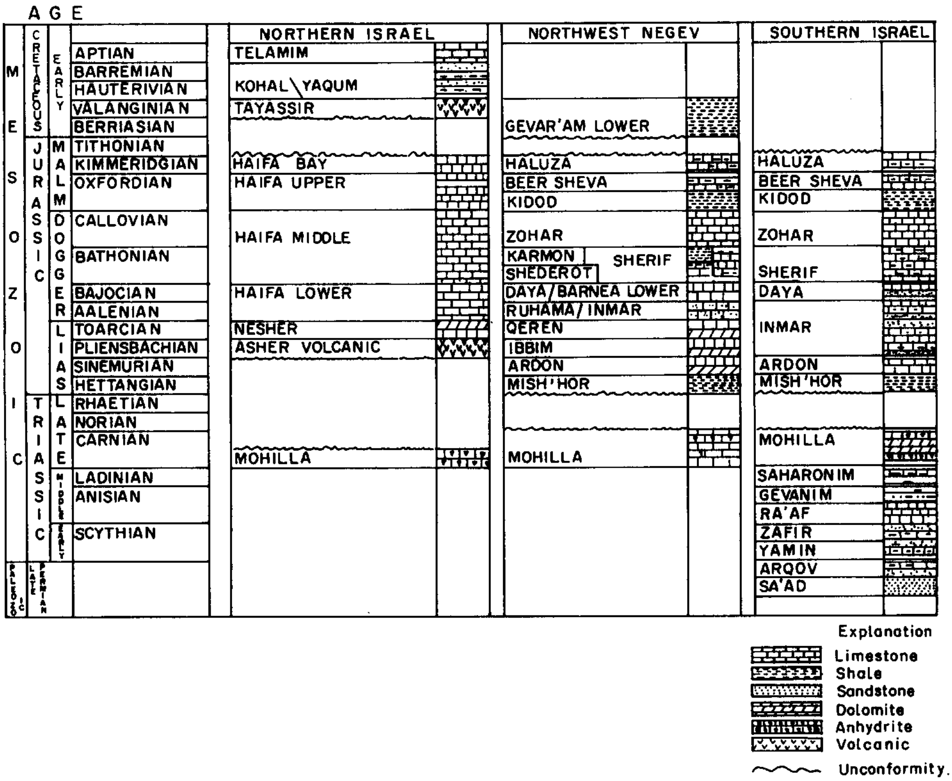


Fig. 2. Schematic columnar section of the early Cretaceous to late Permian rock formations examined in this study (after Cohen et al., 1987).

aquifers resulted in the exclusion of all formations more recent than early Cretaceous or Jurassic in northern and southern Israel, respectively (Fig. 2). Consequently, north of Beer Sheba (Fig. 1), only Jurassic, Triassic, and Paleozoic rock formations were considered for further study, since early and late Cretaceous limestone and dolomite form the mountain aquifer. South of Beer Sheba, Jurassic formations were considered only in the western and central Negev because in the eastern Negev, formation-water salinity is significantly lower than the above-mentioned limit (Nativ et al., 1987). Triassic and Paleozoic formations were considered only in the northern and central Negev because in the southern Negev, Triassic formations are absent (Druckman, 1974), and Paleozoic formations directly underlie a brackish water aquifer in early Cretaceous rocks (Weissbrod, 1981).

3.4. Lithologic constraints

The presence of confining units of sufficient thickness across large areas was the second constraint on the selection of horizons for wastewater injection. Shale, unfractured volcanic rocks, and evaporite were defined as aquitards. Confining layers were defined as adequate when their thickness exceeded 25 m over hundreds of square kilometers. Data and spatial correlations concerning the continuity of the host and confining units in the Negev were derived from Goldberg (1970), Druckman (1974) and Weissbrod (1981) and from geophysical and lithologic logs. Similar information for the area north of Beer Sheba was derived from geophysical logs and the Atlas Geologic Computerized Data Base (Flexer et al., 1981).

3.5. Potential breaches of the confining units

Faults are known to act as either barriers or channels to fluid movement. However, little is known in detail about how and why some faults are barriers and others are flow channels. In theory, no fault in a sedimentary rock sequence will be an absolute barrier, but a fault may be of so much lower permeability than the aquifer it cuts that it can be considered, for practical purposes, a barrier. Because, during preliminary site assessment, it was not possible to state whether a fault was a barrier or a flow path, any significant fault was viewed as a flow path (LaMoreaux and Vrba, 1990). A significant fault was defined as one that is of sufficient length, displacement and vertical persistence to provide a means of travel for injected wastewater to an undesirable location.

Faults and tight folds (separately or in combination) can also complicate reservoir-confining unit geometry and make it difficult to predict the effect of subsurface fluid injection without a great deal of expensive exploratory drilling (Lloyd and Reid, 1990).

The location and number of old and new oil- and gas-exploration and production boreholes must also be considered when assessing the confinement potential of rocks associated with any reservoir unit. Such holes penetrate confining units and, if not cased, maintained, or properly plugged, can provide avenues of escape for any fluid in the reservoir units (Gordon and Bloom, 1987; Warner et al., 1987; Lloyd and Reid, 1990).

Hence, all regions selected according to salinity and lithologic features were screened to exclude highly fractured areas or areas containing many deep boreholes. Consequently, the southern Coastal Plain, containing a large number of deep exploration and production wells (Fig. 1), was excluded from further study. Similarly, the size of the regions proposed earlier for further study on the basis of lithologic criteria was significantly reduced. An example of one geologic transect (Fig. 3) crossing fractured areas displays the distribution of faults as well as the extent of the vertical displacement along them and demonstrates the potential breaching of the confining units.

In some regions however, structural information regarding the distribution of fractures and faults was unavailable because seismic surveys had never been performed. These areas include the Carmel, Galilee, Samaria and Judea regions, as well as the eastern Negev, along the Rift Valley (for locations see Fig. 1). The evaluation of some potential reservoirs could not refer, therefore, to any structural information. Although some of these sites were included in the final list of suggested reservoirs, additional structural information regarding the spatial distribution of faults is clearly mandatory before they can be used for waste isolation.

3.6. Permeability and porosity

Permeability values of the host and confining units were interpreted from drill-stem tests (Horner, 1951). Because of incomplete penetration of the aquifer by the drill-stem test interval, the flow is not strictly radial during the test; rather, the flow lines are distorted. This distortion is a function of the vertical hydraulic conductivity, which is thus 'incorporated' into the determined bulk ('horizontal') permeability values interpreted from the drill-stem test data. Generally, tests were interpreted by the Petroleum Research Corporation (PRC) in Colorado or by Oil Exploration Investment (HANA) in Israel. However, tests having reliable data that had never been interpreted, or tests with faulty interpretations were interpreted as part of this study, and the respective permeability values were calculated.

Additional data regarding the permeability and the porosity of the intervals in question were obtained from core analyses. This information may prove non-representative of carbonate units because core analyses yield matrix permeability (which is typically low), whereas flow in carbonate rocks occurs through joints, fractures and stratification planes.

Finally, all confining units were checked for evidence of mud circulation loss within their rocks. This information, typically reported in drillers' logs, could help identify areas where (1) assumed confinement may be ineffective, or (2) solution channels and fissures may enhance groundwater flow in limestone and dolomite having primary poor porosity and permeability.

3.7. Formation-water pressure

Pressure data were determined from interpretations of the drill-stem tests performed in the studied intervals. The reliability of the data was determined according to the following considerations.

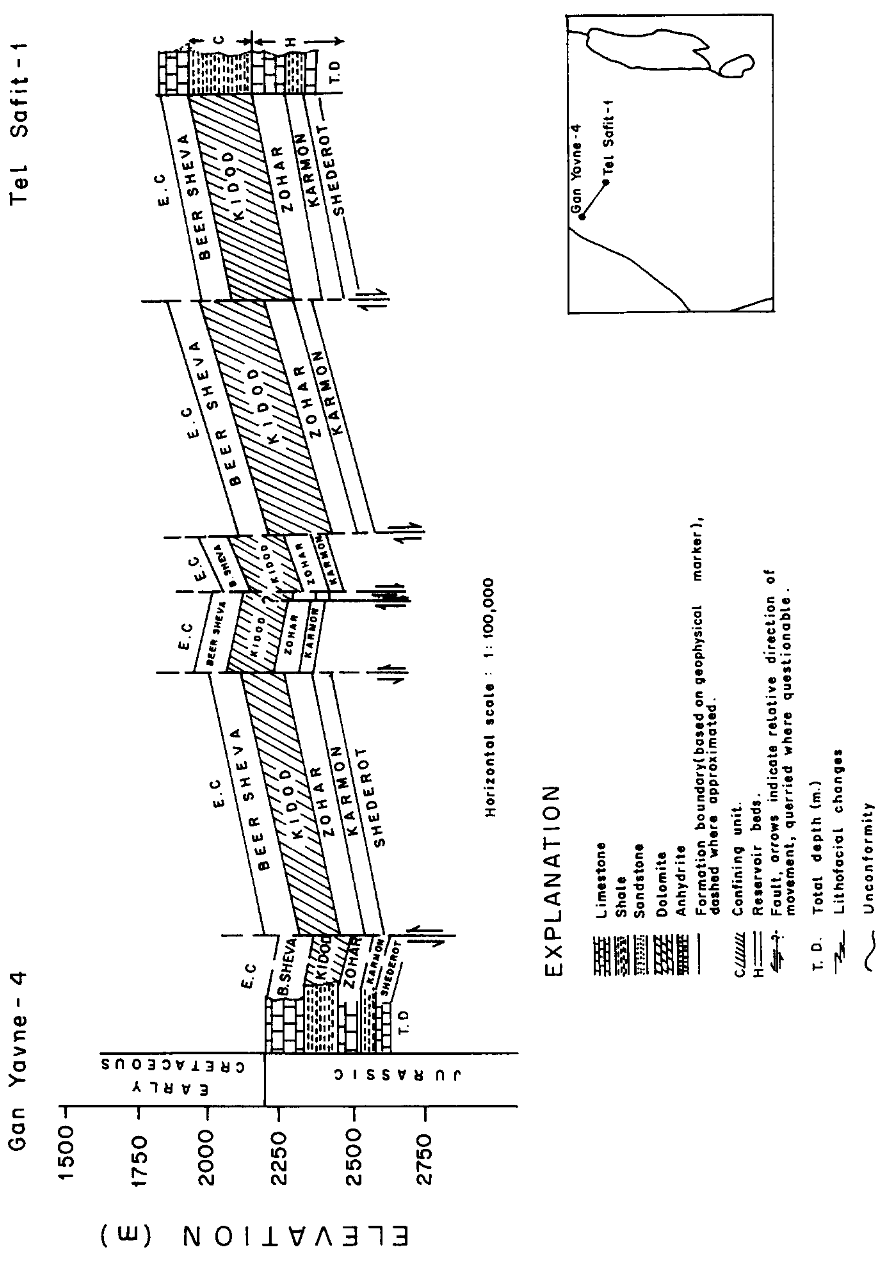


Fig. 3. Geologic cross-section from the Gan Yavne-4 to the Tel Safit-1 boreholes. Vertical displacements along faults were calculated using the top Zohar Formation structural map (Gelbermann and Grossovicz, 1990). Elevation is below sea level.

(1) Proper operation of the pressure recorders was established according to mud pressure measurements. Measured values of initial and final hydrostatic mud pressure had to be the same (maximum allowed deviation was 5%) and similar to the calculated hydrostatic mud pressure (maximum allowed deviation was 10%). Pressure recorders were generally also checked by comparing the measured (recorded) final flow pressure with its calculated value using the volume of recovered fluid and its density. The ratio between the calculated and measured values multiplied by 100 enabled an estimation of the recorder's accuracy; 95–105% was considered accurate. However, where gas and oil were recovered with the formation water, the accuracy of the recorders could not be checked because data about the proportions of the various fluids and the type of oil, necessary to calculate the sample density, were unavailable. In such cases, the only criterion for accuracy was the similarity between calculated and measured hydrostatic mud pressures.

(2) A test with two flow and shut-in periods was considered more reliable than a test with only one period, because the first flow and shut-in period allows the release of excessive formation pressure resulting from drilling activities.

(3) Extrapolation of the final shut-in pressure to formation pressure was considered reliable if the extrapolation line was supported by at least four pressure–time breakdown points (after a unit slope had been attained).

(4) The shape of the final shut-in curve had to be monotonous and undisturbed. 'Steps' on this curve are formed by sudden pressure changes, indicating mud plugging or recorder malfunction.

3.8. Chemical and isotopic analyses of formation water

Samples obtained during drill-stem or swab tests often do not represent formation fluids because of contaminants that affect their chemical composition. Contaminants may include one or more of the following: (1) lost mud or mud filtrate invading the formation, (2) drilling mud penetrating the tested interval through leaky packers, (3) cushion water, which is sometimes used to protect the drillers and well equipment from a blowout, should the packer fail, and (4) $CaCl_2$ or $CaSO_4$ salts forming as a result of carbonate rock dissolution following an acid treatment, often used to improve formation porosity in the vicinity of the borehole (Starinsky, 1974).

Recommendations regarding the appropriate length of fluid flow and the fluid volumes needed to acquire a representative formation-fluid sample can be found in the literature (e.g. Johnston Corporation, 1964); obviously, these recommendations should serve only as guidelines for the screening of representative formation-fluid samples from possibly contaminated samples. When the chemical composition of formation fluid samples is checked, special attention should be paid to previous acidification activities at the borehole, as well as to the volume of recovered fluids vs. (1) the volume of water used for mud preparation, (2) the volume of circulated mud lost when drilling into and near the tested interval, and (3) the volume of cushion water present during the test.

3.9. Formation-water temperature

Temperature measurements in deep formations are generally made by lowering a maximum thermometer into the borehole and correlating the recorded temperature to the total depth attained. However, the depth at which the maximum temperature is recorded may not necessarily be the maximum depth, and consequently the method may be inaccurate (until recently, a temperature log had not been frequently used with down-hole geophysical tools).

Another method is to record the temperature of a sample recovered during a drill-stem or swab test. Temperature data acquired in this way are also not highly reliable. In deep formations the drilling mud has a cooling effect, and achievement of thermal equilibrium between the borehole vicinity and the formation takes longer than the few days the drilling operation is normally stopped for sampling and measurement. Temperature measurements taken in a formation 2930 m deep following an equilibrium period of two months after cessation of drilling resulted in a temperature rise from 79°C to 122°C (Eckstein, 1975). This unique observation suggests that actual temperatures and thermal gradients may be much higher than their measured values, and the latter should therefore be referred to as minimum values. Nativ (1990) demonstrated that when temperature data are available from both bottom-hole measurements and drill-stem tests, the latter are more representative of the formation-water temperature.

3.10. Formation-water density and viscosity

Fluid density and viscosity are required parameters for calculations of hydraulic conductivity and fluid-flow velocity in saline, warm groundwater. However, viscosity has been measured in only a few wells, and fluid density has only been measured for a few samples, in the laboratory at 20°C (Starinsky, 1974). For this study, the values of formation-water density and viscosity were calculated using a table (Washburn, 1928) and a graph (Kraig, 1971), respectively, by relating them to measured fluid temperature and salinity as expressed in NaCl concentrations.

Calculations of density values using temperature and NaCl concentrations proved accurate when compared to density values of the same samples measured in the laboratory by Starinsky (1974). Ten cases resulted in a less than 10% difference between the calculated and measured values, whereas in three other cases, the difference varied between 18% and 30% (Menashe, 1991). The calculation of viscosity using Kraig's graph (1971) proved less accurate when compared with values measured in the field.

3.11. Hydraulic fracturing

During the injection of fluids, the total stress remains almost constant, formation-water pressure increases and the effective stress decreases. To avoid hydraulic fracturing, the pressure breakdown has to be evaluated for each reservoir and avoided during the injection process. The breakdown pressure was calculated according to the following equation (Bachu et al., 1989):

$$P_b \geq \mu/1 - \mu(S_v - P_f) + P_f \tag{1}$$

where P_b is the breakdown pressure, μ is Poisson's ratio, P_f is the formation-water pressure and S_v is the vertical stress (assumed to be the maximum principal stress).

$$S_v = g \int \rho_b(z)\,\mathrm{d}z \tag{2}$$

where ρ_b is the bulk density of the overlying rocks, g represents gravity and D is the depth from the ground surface to the point of interest.

Bulk density was estimated from core measurements, because density logs were unavailable. Boreholes with as many measured cores as possible were selected for this purpose. Typically, neither the bulk density of shale nor the Poisson's ratio had been measured and they had to be estimated using published values (Weast, 1974 and Hunt, 1984, respectively). Consequently, the breakdown pressure could only be estimated.

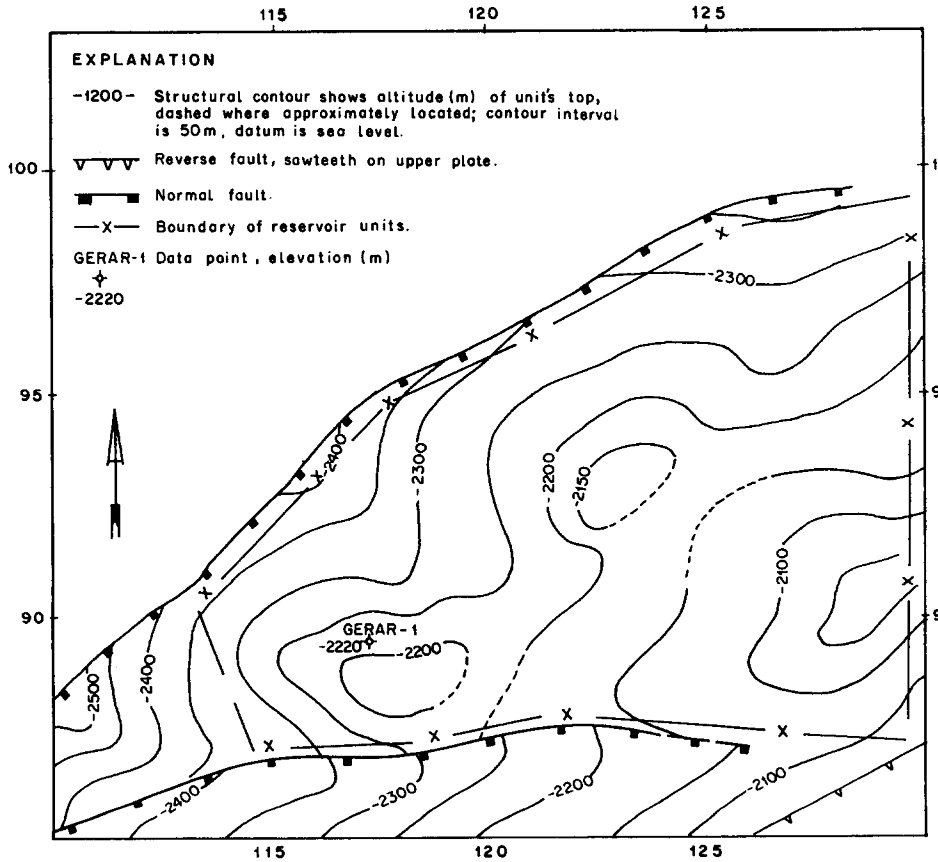


Fig. 4. Depth map to the top of the Gerar Reservoir (the top Zohar Formation structural map, Gelbermann, 1992).

4. Application

The methodology described above was implemented to screen and characterize potential host rocks and confining units throughout Israel. The following descriptions of two of the final seven potential reservoirs selected as a result of our study illustrate some of the typical problems associated with site evaluation. The Gerar Reservoir is an example of an area where existing data were ample for a fairly detailed preliminary characterization of the rock units as well as the contained fluid. The Northern Reservoir provides an opposite end member, where although at face value the site seems potentially appropriate, the information is scarce and existing data are not sufficient for satisfactory characterization.

4.1. The Gerar Reservoir

The Gerar area (Fig. 1) contains a potential reservoir (Fig. 4) in the Jurassic Ardon, Inmar (or its equivalents, Ruhama, Qeren and Ibbim), Daya, Sherif and Zohar formations (Figs. 2 and 5). The Ardon Formation is composed primarily of porous limestone and dolomite with some marl and clay. The Inmar (/Ruhama, Ibbim and

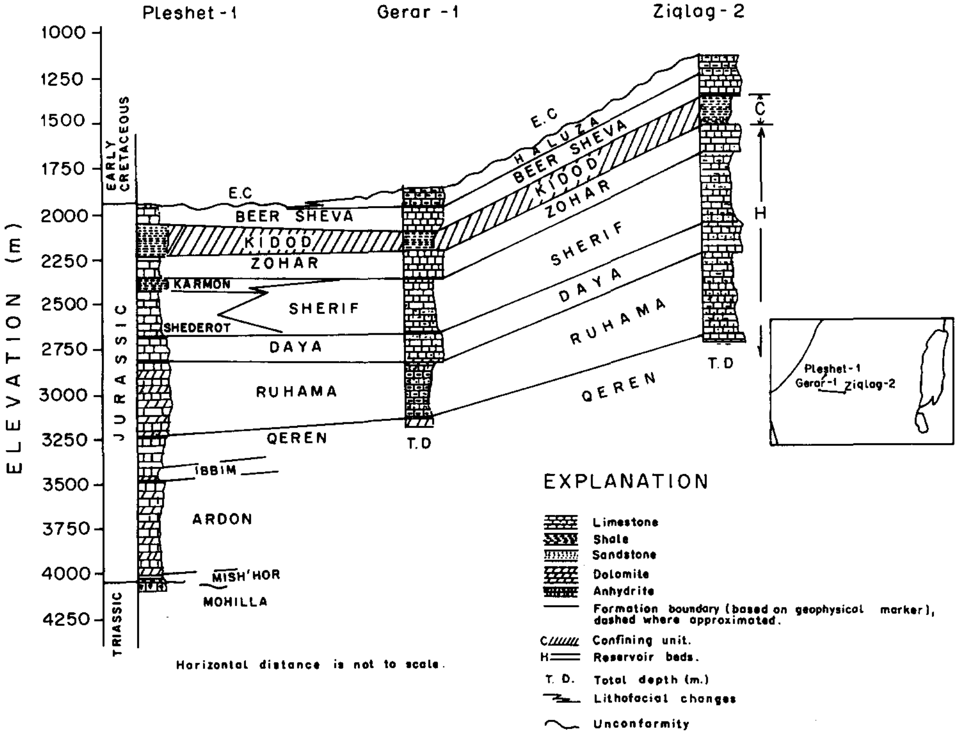


Fig. 5. Geologic cross-section through the Gerar Reservoir from the Pleshet-1 to the Ziqlag-2 boreholes. Elevation is below sea level.

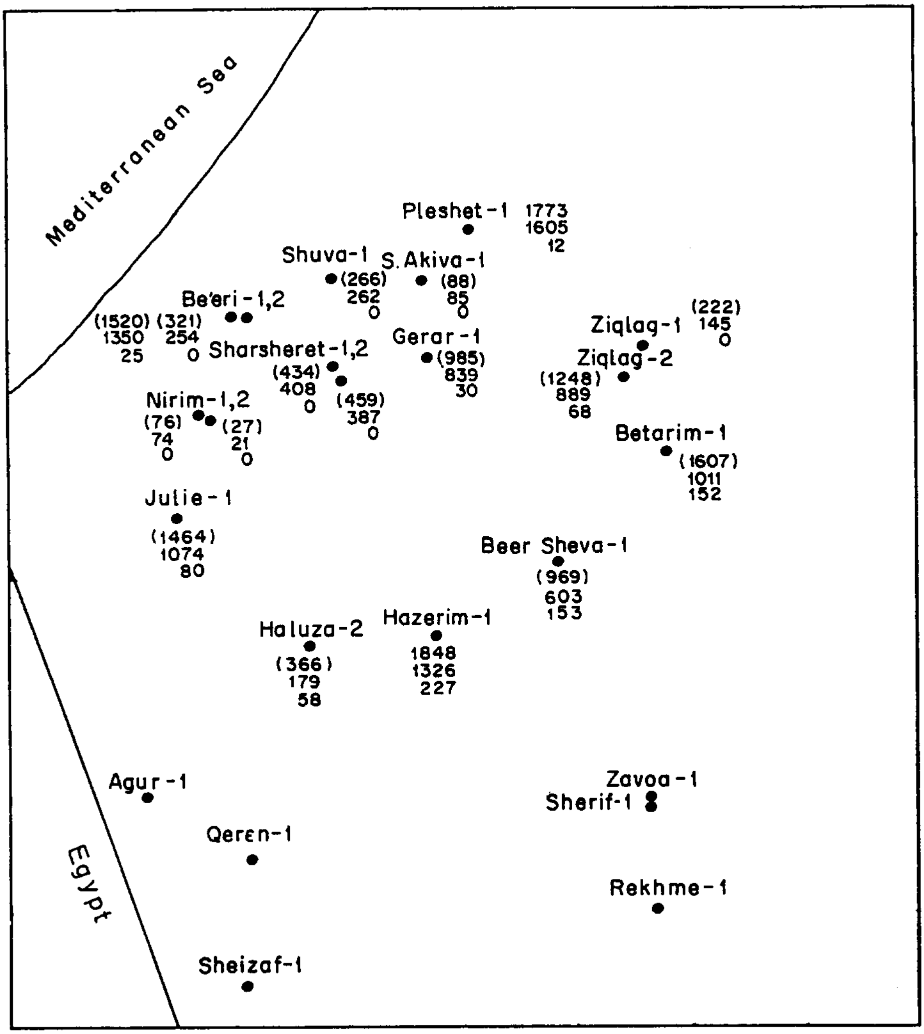


Fig. 6. Thickness of the Gerar Reservoir, and the cumulative thickness of its permeable constituents. Thickness data are from Druckman et al. (1983) and from well logs.
● Well
200 Total thickness (m)
100 Total thickness of carbonate rocks (m)
60 Total thickness of sandstone rocks (m)
(200) Partial thickness (m), (well does not fully penetrate the formation)
○ Formation/Lithology is absent in this well.

Qeren) Formation consists primarily of sandstone, carbonate and a small amount of shale, and the Daya Formation contains limestone and some shale. The Sherif Formation, typically containing shale in other parts of the Negev Desert, includes a large percentage of carbonate rock in the Gerar-1 borehole. The Zohar Formation

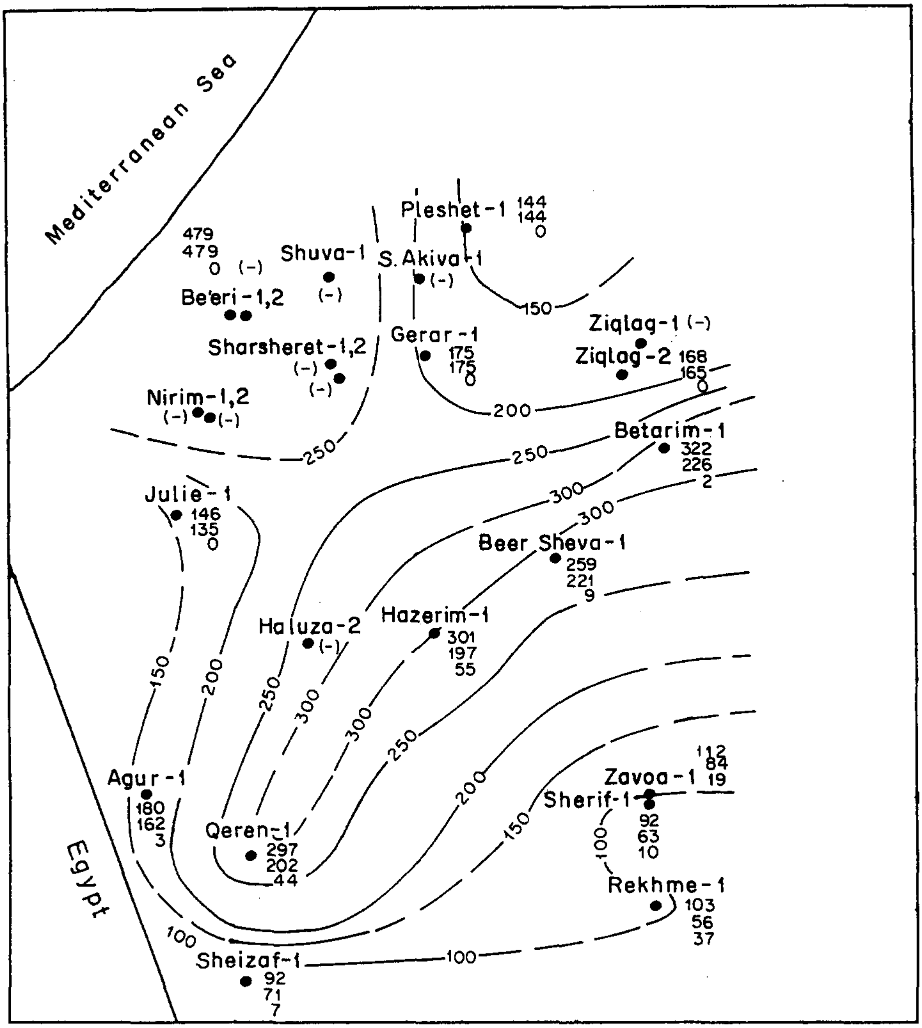


Fig. 7. Isopach map of the Daya Formation, displaying cumulative thickness of its permeable constituents. Thickness data are from Druckman et al. (1983) and from well logs.

- ● Well
- 200 Total thickness (m)
- 100 Total thickness of carbonate rocks (m)
- 60 Total thickness of sandstone rocks (m)
- — Line of equal thickness of unit (m), dashed where approximately located. Interval is 50 m thick
- (200) Partial thickness (m), (well does not fully penetrate the formation)
- (-) Formation was not penetrated by the well
- o Formation/lithology is absent in this well.

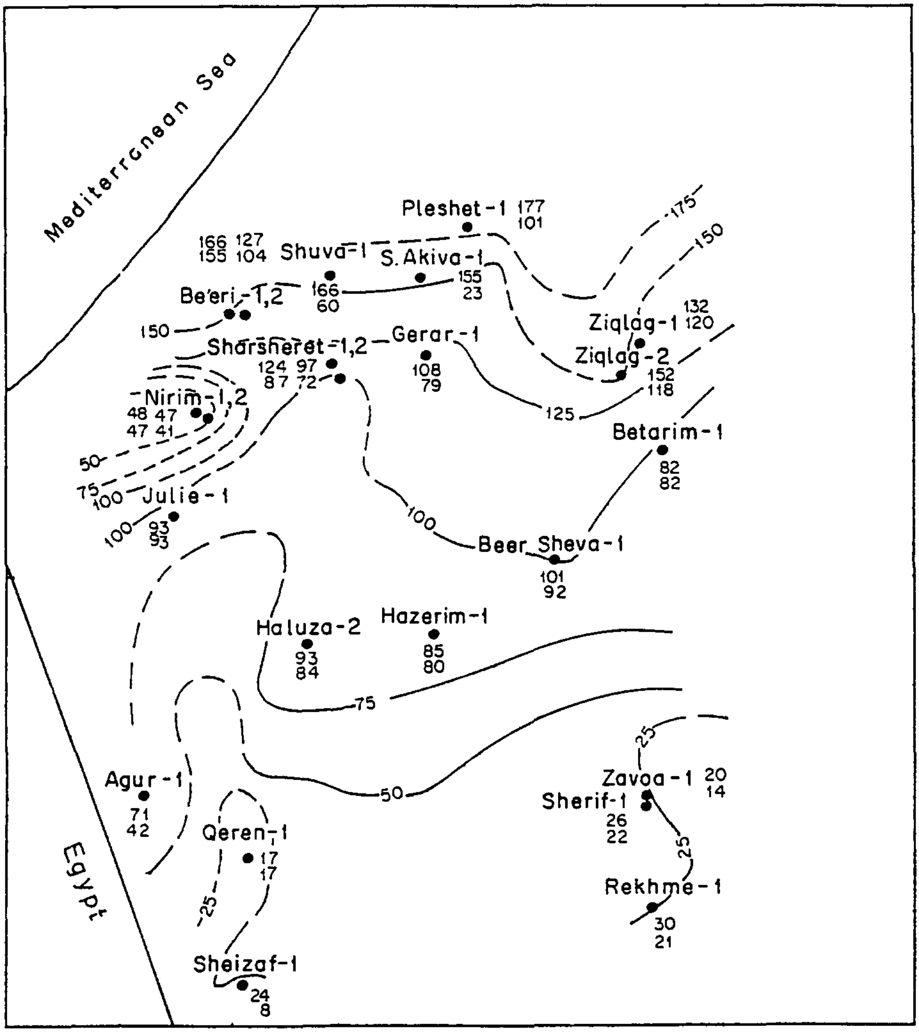


Fig. 8. Isopach map of the Kidod Formation, displaying cumulative shale thickness. Thickness data are from Druckman et al. (1983) and from well logs.

● Well
200 Total thickness (m)
100 total thickness of shale (m)
— Line of equal thickness of unit (m), dashed where approximately located. Interval is 25 m thick
(200) Partial thickness (m), (well does not fully penetrate the formation)
(-) Formation was not penetrated by the well
○ Formation/lithology is absent in this well.

is composed of limestone interbedded with some shale and sandstone. This sequence of potential host rocks attains a total thickness of at least 985 m in the Gerar-1 borehole (which partially penetrates the reservoir), 869 m of which are permeable carbonate and sandstone rocks (Fig. 6). An isopach map was produced for each of the reservoir's formations, indicating their areal thicknesses, as well as the cumulative thicknesses of their permeable (sandstone, carbonates) and less permeable (shale, anhydrite) rocks. Figure 7, the map prepared for the Daya Formation, is an example of these maps. Although the sequence defined as the Gerar Reservoir included all the above-mentioned formations, we decided to also characterize each formation separately, so that highly permeable zones could be easily identified.

The reservoir unit is unconformably underlain by the confining units of the Mohilla and Mish'hor anhydrite and shale, respectively (Figs. 2 and 5). These formations are not penetrated in the Gerar Reservoir area, and their thicknesses in the adjacent Hazerim-1 and Pleshet-1 boreholes (Fig. 1) are 126 and 83 m, respectively. The reservoir units are overlain by the Kidod Formation (Fig. 5), having a thickness of 108 m at the Gerar-1 borehole, 79 m of which is shale (Fig. 8).

The top of the Gerar Reservoir (Fig. 4) is highest in the east, where it reaches −2100 m. The altitude of the top slopes to the west, where it reaches a depth of −2500 m (Fig. 4). A new interpretation of existing seismic data prepared specifically for this area (Gelbermann, 1992) included lines that were not considered in previous mappings. The results suggest a structurally undisturbed area of about 120 km^2 available for the reservoir. When multiplied by the thickness of the reservoir units (~1 km, Fig. 6), a total rock volume of approximately 120 km^3 is attained.

Permeability data from drill-stem tests were available for the Gerar-1 borehole and the nearby Ziqlag-1 and Sharsheret-1 and -2 boreholes. Permeability of the Zohar Formation ranges from 0.14 and 20 md in the Gerar-1 and Ziqlag-1 boreholes, respectively, to 71, 35 and 200 md in the Sharsheret-1 and -2 boreholes. No permeability data from drill-stem tests were available for the underlying reservoir units in nearby boreholes. A permeability of 0.23 md was calculated from a test in shale and shaly carbonate in the overlying (confining) Kidod Formation, in the nearby Shuva-1 borehole.

Sixty-five core measurements of the Zohar limestone in the Gerar-1 borehole resulted in a porosity range of 0.5–13.3% and a permeability range of 0.01–1.6 md, with mean values of 4.84% and 0.15 md, respectively. Values measured for the Zohar Formation in the nearby Sharsheret-2 borehole ranged from 0.01 to 0.85 md, with two exceptions, 6 and 380 md. Similar values were measured in the nearby Shuva-1 borehole (0.01–1.89 md) and the Yakhini-1 borehole (0.01–0.08 md). These results should be carefully interpreted, because they probably represent the minimum permeability of the matrix. The few large measurements from the drill-stem tests and some cores display the potentially high permeability of the joints, fractures, or dissolution channels. Porosity measurements from these boreholes in the Zohar Formation ranged from 1 to 18.8%, with a mean value of 6.2%.

Core analyses from the Sherif limestone in the Gerar-1 borehole documented matrix permeability values ranging from 0.01 to 3.6 md; the several exceptions were 6, 12, 18, 40, 130 and 160 md. Porosity values in this borehole ranged from 1.4 to 26.7% with a mean value of 7.4%. In the adjacent Sharsheret-1 borehole, dolomite in the Sherif Formation yielded permeability values of 0.04–13 md with a mean of 3 md, and porosity values of 2.7–19% with a mean of 12.6%. Values of permeability and porosity for the Daya limestone were available only from the Beeri-1 well, where they varied from 0.25 to 0.99 md and from 6 to 8%, respectively. Permeability of the sandstone in the Inmar (Ruhama) Formation was measured on cores taken from the Beeri-1 well and varied from 1.8 to 6.7 md. Porosity range was from 5 to 13%. The Qeren carbonate member in the Inmar Formation was measured in the Gerar-1 borehole, and its permeability and porosity values ranged from 0.09 to 150 md and 0.6 to 12%, respectively. No core analyses were available for the Ardon limestone and dolomite near the reservoir boundaries. Permeability of the underlying confining unit was not measured; however, the overlying Kidod shale

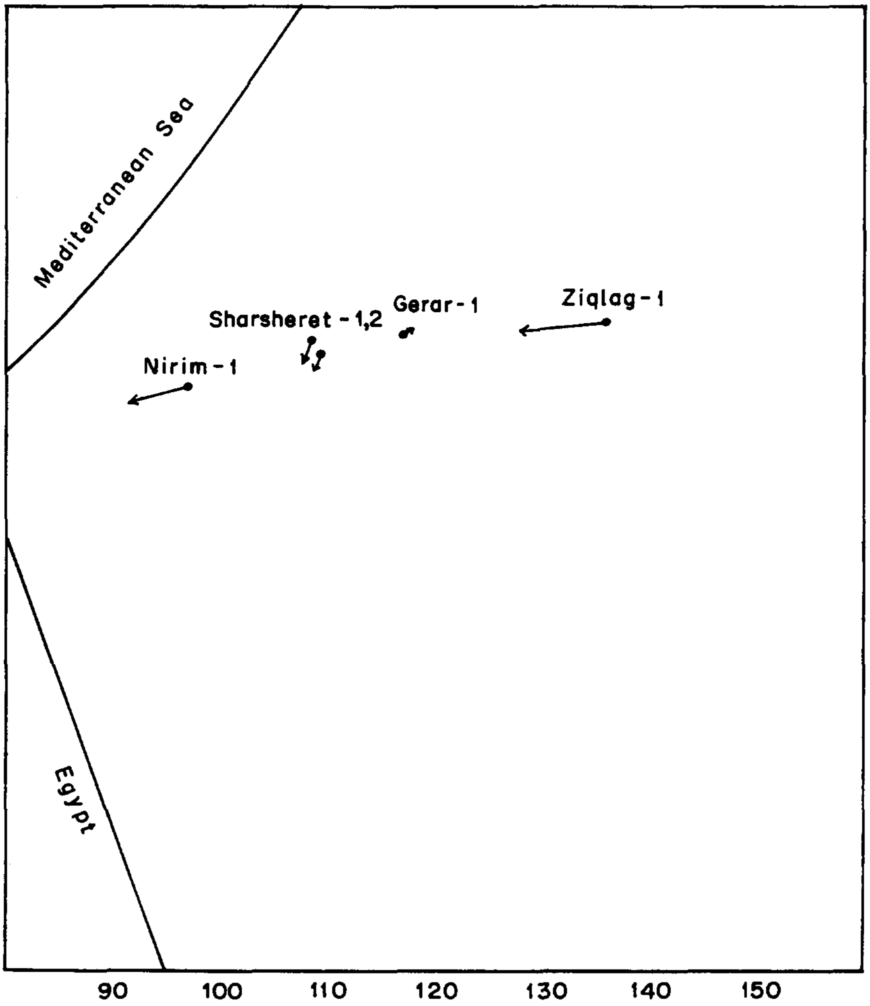


Fig. 9. Pressure distribution in the Zohar Formation, Gerar Reservoir. The pressure measurements at each borehole in the reservoir were normalized to a common datum (−2176 m), and the magnitude and direction of the pressure gradient were calculated using vector analysis.

was measured at the nearby Sharsheret-1 borehole, and its permeability and porosity ranged from 0.01 to 0.38 md and 1 to 2.8%, respectively. This core permeability of the confining shale — 0.38 md — correlates well with the value derived from drill-stem tests — 0.23 md.

Groundwater salinity in the Gerar Reservoir was 33 100 mg L^{-1} Cl in the Gerar-1 borehole (Zohar Formation). In its vicinity it varied from a minimum of 19 465 mg L^{-1} Cl (33 051 mg L^{-1} TDS) at the Sharsheret-1 borehole (Zohar Formation) to a maximum of 31 950 mg L^{-1} Cl (53 133 mg L^{-1} TDS) in the Sharsheret-2 borehole (Zohar Formation). Chemical analyses from the Ardon, Inmar and Daya formation waters were unavailable for the boreholes in the Gerar Reservoir and its vicinity.

In the Gerar-1 borehole, groundwater temperature was about 60°C at the Zohar Formation and varied from 82 to 90°C at the Inmar Formation. In the nearby boreholes, temperature varied from 57 (the Sedot Akiva-1 borehole) to 85°C (the Sharsheret-1 borehole) in the Zohar Formation, from 68 (the Yakhini-1 borehole) to 85°C (the Shuva-1 borehole) in the Sherif Formation, from 82 to 83°C (the Beeri-1 borehole) in the Daya Formation, from 87 to 88°C (the Beeri-1 borehole) in the Inmar Formation, and from 50 to 61°C (the Ziqlag-1 borehole) in the Ardon Formation.

Groundwater density and viscosity in the Gerar-1 borehole was 1.0219 g cm^{-3} and 0.54 cp, respectively (Zohar Formation). Groundwater density varied from 0.9969 to 1.0795 g cm^{-3} in the nearby boreholes (the Sharsheret-1 and -2 boreholes, respectively, Zohar Formation). Groundwater viscosity ranged from 0.37 (the Shuva-1 borehole, Sherif Formation) to 0.49 cp (the Sharsheret-2 borehole, Zohar Formation).

Pressure data for the Gerar Reservoir were available for the Zohar Formation (the Gerar-1, Sharsheret-1 and -2, Sa'ad-1, Ziqlag-1 and Nirim-1 boreholes) and the Sherif Formation (the Hoga-1 and Shuva-1 boreholes). No pressure data were available for the lower reservoir units in or near the Gerar Reservoir. Pressure gradient and flow direction were calculated for the Zohar Formation in the Gerar Reservoir, using data points from boreholes that are likely to be hydraulically connected. The pressure measurements at each borehole in the reservoir were normalized to a common datum, and the magnitude and direction of the pressure gradient were calculated using vector analysis (Fig. 9). Pressure measurements taken at boreholes separated from the reservoir units as a result of large vertical displacements along faulted zones were excluded. Pressure was measured in the Zohar Formation at several depth intervals in the Gerar-1 and Sharsheret-2 boreholes. However, because each of the measured pairs had one pressure measurement that could not be extrapolated, a calculation of potential vertical groundwater flow within the reservoir was avoided.

The estimated range for breakdown pressure was calculated for two depth intervals in the Zohar Formation to be (1) 251 and 364 atm (for limestone and shale, respectively) at 2393 m, where formation-water pressure is 211 atm, and (2) 269 and 392 atm (for limestone and shale, respectively) at 2432 m, where formation-water pressure is 225 atm.

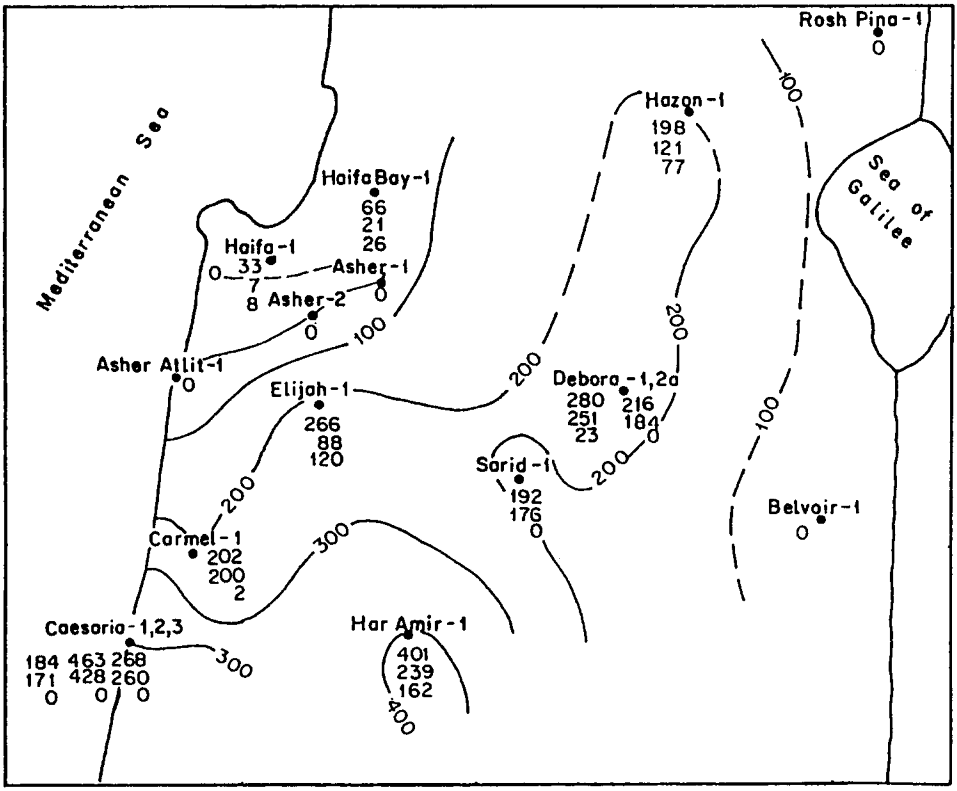


Fig. 10. Thickness map of the Northern Reservoir, displaying cumulative thickness of its permeable constituents. Map data are from well logs.

● Well
200 Total thickness (m)
100 Total thickness of carbonate rocks (m)
— Line of equal thickness of unit (m), dashed where approximately located. Interval is 100 m thick
(200) Partial thickness (m), (well does not fully penetrate the formation)
(-) Formation was not penetrated by the well
o Formation/lithology is absent in this well.

4.2. The Northern Reservoir

In contrast to the Gerar Reservoir, the area of the Northern Reservoir is much larger, amounting to $\sim$800 km^2, with sparse borehole distribution (Fig. 1). Consequently, the geologic cross-sections and spatial trends shown on maps for this reservoir should be treated with utmost caution. They represent our current understanding on the basis of only a few observation points. The Northern Reservoir includes the Jurassic Nesher, Haifa and Haifa Bay formations (Fig. 2). The thickness of each formation reaches several hundred meters, and their total thickness of 1931 m is penetrated only by the Debora-2a borehole (Fig. 10). The reservoir formations are composed primarily of carbonate rocks, and the cumulative thickness of these

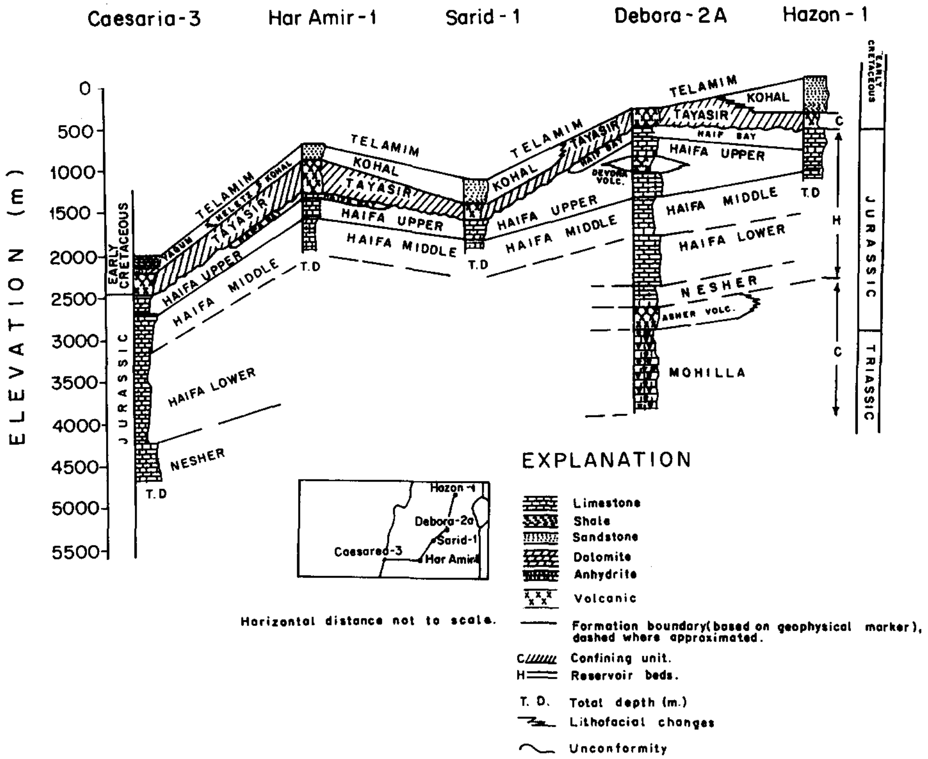


Fig. 11. Geologic cross-section through the Northern Reservoir from the Caesaria-3 to the Hazon-1 boreholes. Elevation is below sea level.

permeable units reaches 1885 m in the Debora-2a borehole. This sequence is confined by the underlying Asher Volcanics and Mohilla anhydrite (Fig. 11), penetrated only by the Debora-2a borehole, where their thickness reaches 272 m. The overlying tuff, basalt and shale of the Tayassir Formation confine this sequence from above (Fig. 11), and its total thickness within the reservoir boundaries varies from 192 m (the Sarid-1 borehole) to 401 m (the Har Amir-1 borehole) (Fig. 12). Loss of mud circulation was observed, however, near the boundary between the Tayassir and Telamim formations at the Debora-2a borehole.

In contrast to the Gerar Reservoir, the top of the Northern Reservoir could not be determined from a structural map (Fig. 4). Because of the rugged surface topography, seismic surveys were never performed in this area. We had to deduce the depth to the reservoir top from logs of the few boreholes in the reservoir area. The reservoir top is highest in the Yizra'el Valley, where it reaches −641 m in the Debora-2a borehole. It slopes deeper below the Galilee Mountains (−1012 m in the Hazon-1 borehole) and the Samaria area (−1569 m in the Har Amir-1 borehole). Although seismic data which could provide information regarding the location of faulted zones were unavailable, numerous faults were documented at land surface and shallow depths

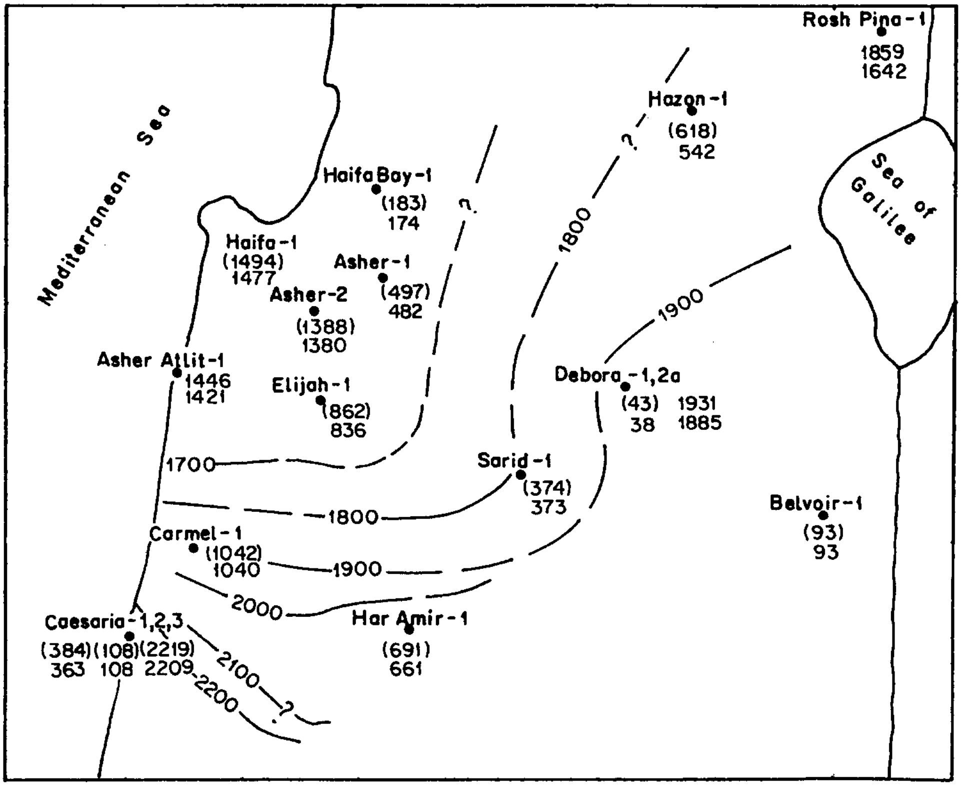


Fig. 12. Isopach map of the Tayassir Formation. Map data are from well logs.
● Well
200 Total thickness (m)
100 Total thickness of volcanic rocks (m)
60 Total thickness of shale (m)
— Line of equal thickness of unit (m), dashed where approximately located. Interval is 100 m thick
(200) Partial thickness (m), (well does not fully penetrate the formation)
(-) Formation was not penetrated by the well
○ Formation/lithology is absent in this well.

in the Galilee, the Carmel, the Yizra'el Valley and the Samaria Mountains (for locations see Fig. 1). Although the vertical distribution of these faults is unknown, it is safe to assume that many reached the reservoir's formations. Therefore, no attempt was made to produce a contour map for the reservoir top on the basis of the few boreholes in the reservoir area.

Permeability data from drill-stem tests were unavailable for the Northern Reservoir. Porosity and permeability measured in 163 cores taken from seven boreholes in the reservoir and its vicinity displayed low values, ranging from 0.16 to 14% for porosity and 0.01 to 4.8 md for permeability. Mean porosity and permeability values in the reservoir formations were as follows: 1.33% and 1.12 md in the Haifa Bay Formation (the Debora-2a borehole), 6.7% and 0.66 md in the Haifa Lower

Formation (the Debora-2a borehole), 5.1% and 0.32 md in the Haifa Middle Formation (the Asher-2, Carmel-1, Elijah-1, Hazon-1 and Sarid-1 boreholes), and 2.2% and 0.38 md in the Haifa Upper Formation (the Caesaria-1 and -3, Debora-2a and Sarid-1 boreholes). Again, it should be noted that these core measurements, taken from carbonate rock, are biased toward values that are typical of the low permeability matrix.

Groundwater analyses for the Northern Reservoir were unavailable. SP logs available for most boreholes penetrating the reservoir rocks were useless because of their poor response in hard, tight formations such as the reservoir carbonate rock (Dewan, 1983). Groundwater salinity in adjacent boreholes outside the reservoir boundaries varied from a minimum of 5926 mg L^{-1} Cl at the Asher-2 borehole (Haifa Upper Formation) to a maximum of 19 060 in the Asher-2 borehole (Haifa Middle Formation). Lowest groundwater temperature, 50°C, was observed at the Hazon-1 borehole (Haifa Upper Formation). Highest documented groundwater temperature, 59°C, was in the Sarid-1 borehole (Haifa Upper Formation). Groundwater density and viscosity values could not be calculated for the Northern Reservoir or even for the adjacent boreholes because where chemical analyses were available, temperature had never been measured.

The only pressure measurement within the boundaries of the Northern Reservoir was made in the confining unit, the Tayassir Formation. Pressure was found to be 59.4 atm at −663 m in the Debora-1 borehole. The only pressure measurement in the reservoir units was made outside the reservoir boundaries, in the Rosh Pina-1 borehole (the Haifa Lower Formation), and was found to be 199 atm at −2490 m. Consequently, vertical or lateral groundwater flow direction or breakdown pressure could not be calculated for the Northern Reservoir.

5. Discussion and summary

Preliminary evaluations of potential sites for wastewater injection are characterized by the use of existing, sometimes old and/or low-quality data from boreholes drilled for other purposes. The preliminary evaluation is an important phase, in which (1) the number of potential sites is reduced according to set criteria, and (2) the areas and intervals within a potential site for which new data are needed are identified. Hence, the analysis of existing data renders the high expense of newly drilled boreholes and surface/borehole geophysics more cost-effective.

The Gerar and Northern Reservoirs represent opposite ends of a full spectrum of field cases faced by hydrogeologists and environmentalists wishing to maximize all available data before spending more money to acquire new information. The area of the Gerar Reservoir is relatively small (~120 km^2), and has 10 boreholes drilled within it or near its boundaries. The area of the Northern Reservoir is much larger (~800 km^2) with only four boreholes within its boundaries and three more located at distances not exceeding 7 km.

Whereas for the Gerar Reservoir we could obtain new interpretations of recent seismic profiles (initiated and funded by other agencies) at a relatively low cost, seismic data were non-existent for the Northern Reservoir. The lack of seismic information resulted in a potential reservoir size which is probably unjustified, owing to existing faults which could not be identified. In addition, our knowledge regarding the drilling depth needed for a potential injection well below the reservoir's top was limited to the four available boreholes, as contouring the reservoir top could not be defended.

A number of drill-stem tests were performed in the Gerar Reservoir's boreholes, thus providing us with direct measurements of formation-water pressure, salinity and temperature. These measurements allowed us to calculate rock permeability, formation-water density and viscosity, breakdown pressure and groundwater flow directions. Conversely, drill-stem tests were not performed in any of the Northern Reservoir's boreholes, and none of the above measurements were available. Formation-water salinity could not be estimated from SP and resistivity logs, which do not produce good results in carbonate rock (Dewan, 1983). Data on formation-water temperature was restricted to bottom-hole measurements, which are less reliable than temperature measured in the recovered formation water during a drill-stem test. Permeability data were limited to core measurements, which are biased toward low matrix values in carbonate rock.

For obvious reasons, our conceptualization of the Northern Reservoir is only one of a number of possibilities, pending the accrual of more information about the area. In the meantime, we feel justified in keeping the Northern Reservoir on our list of potential reservoirs for wastewater injection. Although Israel is relatively small, the shipping of industrial wastewater from the northern part (where a large industrial complex is located near the city of Haifa) to the south (where all the other potential reservoirs are located (Fig. 1)) is expensive. Although we recognize that an injection well in the Northern Reservoir cannot be set up and operated on the basis of existing information, our study provides all the available information for this reservoir. Hopefully, this will help to focus future fieldwork in the area on badly needed seismic surveys and deep-well testing.

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