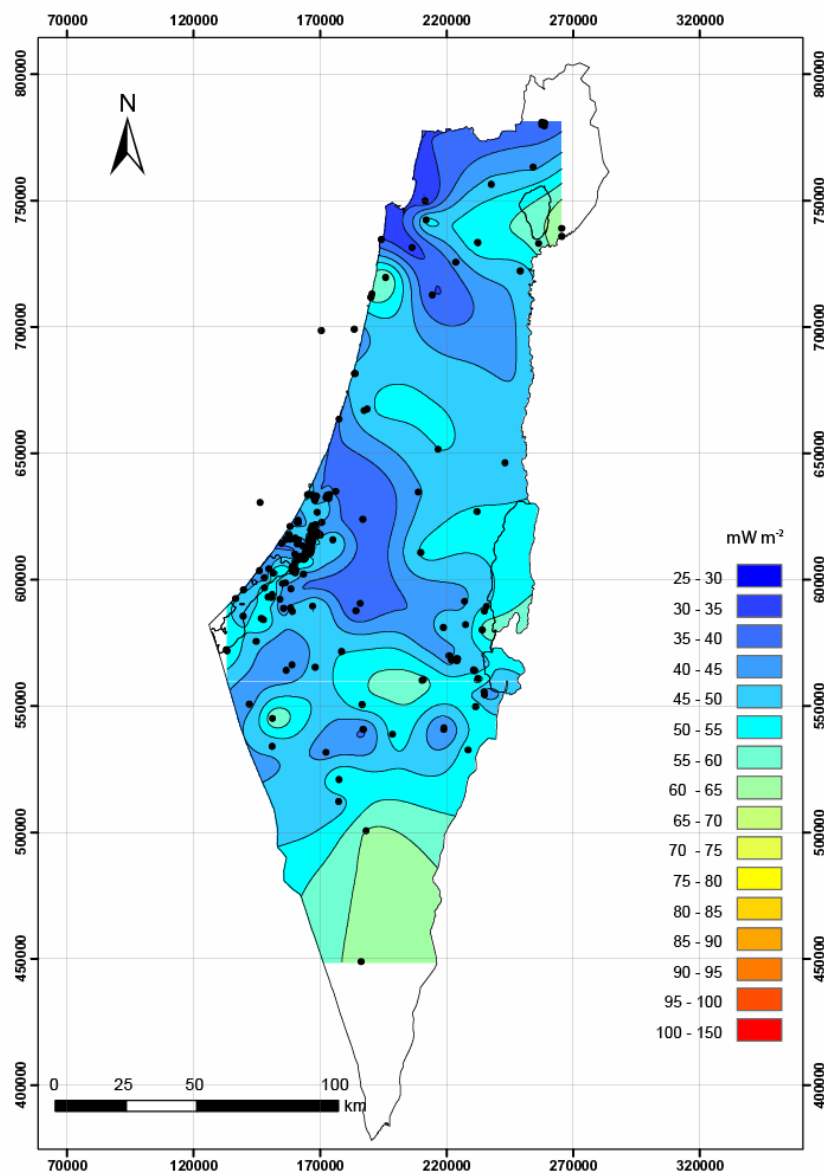




THE MINISTRY OF NATIONAL INFRASTRUCTURES
GEOLOGICAL SURVEY OF ISRAEL

Assessment of Geothermal Resources in Israel

Eyal Shalev, Dov Levitte, Ran Gabay, and Ezra Zemach





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Abstract

This report assesses the geothermal resources in Israel. Temperature depth data from the oil industry and the water supply system is analyzed and used to produce temperature at depth maps. Heat flux is relatively high at the south end of the Golan Heights and in southern Israel. In Northern Israel Heat flux is attributed to a possible magmatic source and groundwater upwelling whereas in southern Israel, it is due to shallow basement with high thermal conductivity. In most of Israel temperatures are higher than 150⁰C at depths greater than 6 km and close to 200⁰C at depths of 8 km. The crystalline basement, which is made of granite-like material, is a preferable target for EGS (Enhanced/Engineered Geothermal Systems) because of its mechanical properties. In Israel the basement is exposed in the south and its depth gradually increases to the north. According to the MIT report on geothermal energy (Tester et al., 2006) these depths of 6-10 km are suitable for EGS development anywhere on Earth, and thus in Israel as well.

The geothermal system at the south end of the Golan Heights was studied in detail. The Arad Group in this area is predicted to have relatively high temperature (150⁰C) and high groundwater pressure (> 10 bar) at shallow depth (<3,000 m). The permeability and porosity of Arad Group are high and therefore this location might be a potential geothermal site.

We recommend further activity to confirm the new geothermal maps presented in the report including new field measurements in new and abandoned boreholes.

1. Introduction.

A recent comprehensive study carried out by world experts has found that provisional estimate of the power generation potential from the application of unconventional, Enhanced Geothermal Systems (EGS) technology has an enormous potential anywhere in the world (Tester et al, 2006). Geothermal energy is present everywhere in Earth because temperature increases with depth. Existing technologies can extract heat from deep layers and utilize it to produce electricity. Geothermal energy is one of the few renewable energy resources that can provide continuous power with minimal visual and other environmental impacts. Geothermal systems have a small footprint and no carbon dioxide emissions.

Although geothermal energy has provided commercial load electricity for more than a century, it has often been ignored in developing Israel's energy supply. Perhaps this is due to discouraging reports claiming that the geothermal heat flux in Israel is low (Keller, 1977; Eckstein and Simmons, 1978; Ben-Avraham et al. 1978; Maurath, 1989).

The goal of this report is to provide a detailed regional assessment of the geothermal state of the crust in Israel. Two main questions will be dealt in this report: 1) Do conditions for conventional geothermal energy production in Israel exist? and 2) Are there available sites for EGS in Israel? After a short geological background (chapter 2) and a literature review (chapter 3) we present the new calculated temperature at depth data (chapter 4). We then present temperature-depth maps (chapter 5) followed by implication for development of EGS (chapter 6). A detailed study is presented for an area at the south end of the Golan Heights where high temperatures and groundwater pressure are predicted (chapter 7). Finally, we end with conclusions (chapter 8).

2. The Geological Structure of Israel

Israel is underlain by normal continental crust with sedimentary cover overlying a crystalline basement. The basement consists of metamorphic and plutonic rocks (mainly granite and diorite compositions). These old rocks (older than 550 Million years) are exposed only in the Eilat area and are covered by thick sedimentary sequences in most of Israel (figure 1). This sedimentary cover, which consists mainly of limestone and dolomite and also chalk, sandstone, clay and other evaporates, thickens towards north-west. The tectonic regime of Israel has considerably changed about 15 Million years ago.

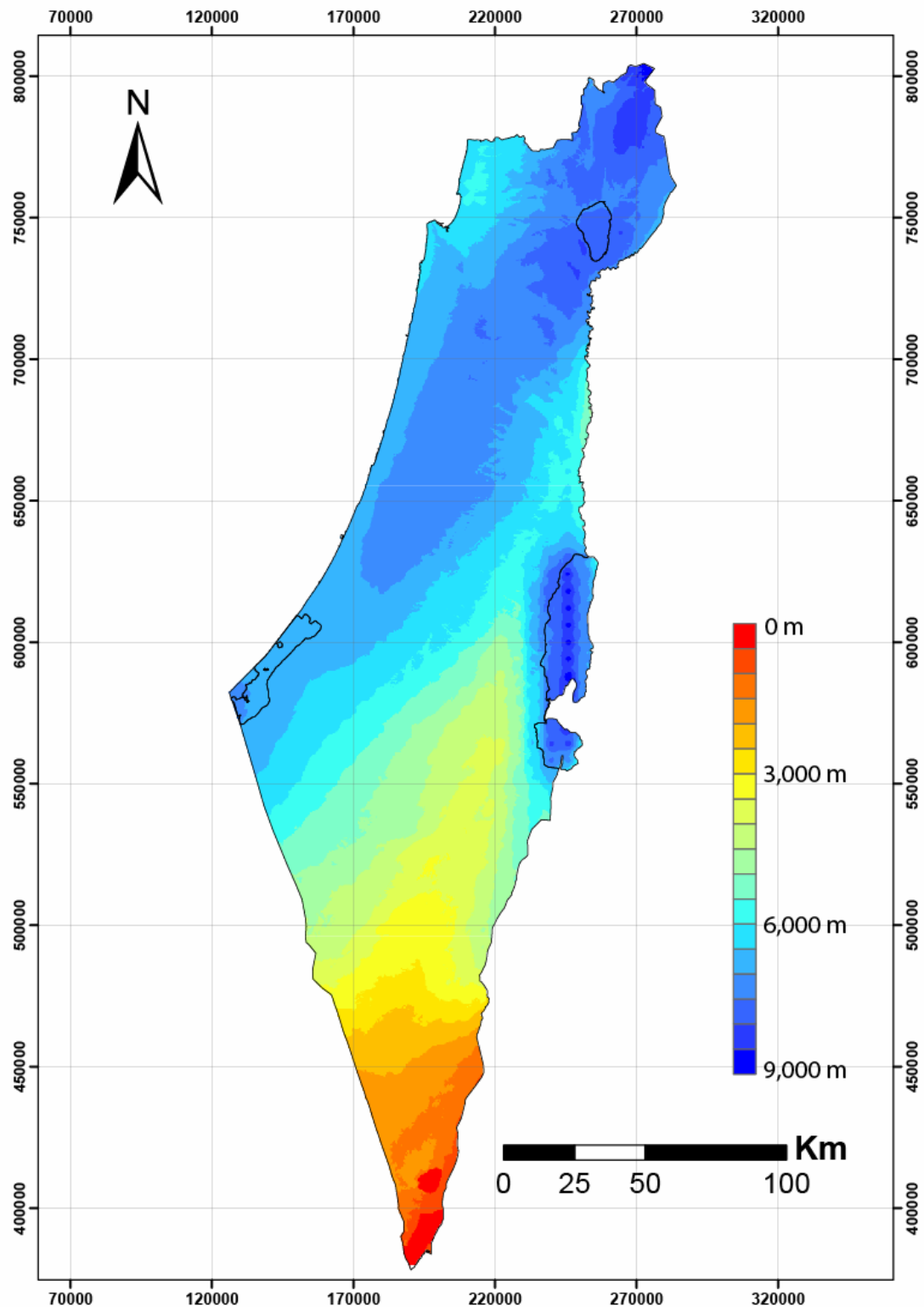


Figure 1: The depth of the crystalline basement from the surface (after Rybakov and Segev, 2004 and Segev et al., 2006). This depth represents the sediment thickness. In southern Israel the basement is exposed.

Faulting produced new plate boundaries in the region including the Dead Sea transform which separates the Sinai sub-plate and the Arabian plate. The Sinai sub-plate has been displaced by 105 km southwards relative to the Arabian plate. Along the Dead Sea transform, several deep basins were formed as a result of its irregular shape (Gulf of Eilat, Dead Sea, Sea of Galilee, Hula Valley). These basins are topographically low and their sedimentary cover is very thick.

Some layers of the rocks that form the sedimentary cover are very permeable and serve as large groundwater reservoirs. These layers can serve in some cases as conventional geothermal reservoirs. The permeability in sandstone reservoirs is high as a result of high porosity and connectivity between the pores. Fractures in sandstone tend to seal in a relatively short time. Other sedimentary rocks like dolomite tend to keep fractures open. However, dolomite is not always massive and appears with different sediments that tend to seal the fractures. On the other hand, natural fractures that are artificially reactivated in granite are likely to remain open for a long period of time (Cuenot et al., 2008). Therefore, in general, the basement which is made of granite-like material is the preferred target for Enhanced Geothermal Systems (EGS). Figure 1 shows the depth to the top of basement.

3. Geothermal research in Israel

Modern systematic studies of the geothermal regime of Israel began in the 1970's after the visit of Dr. J.R. McNitt of the United Nations to Israel (McNitt, 1967). Prior to that, only a few studies were carried out, mainly for recreational and medical use of geothermal water (balneology) in the Sea of Galilee and Dead Sea vicinity. Because of McNitt discouraging findings, only a small group of scientists carried on the geothermal research in Israel. Following Prof. Gene Simmons of M.I.T. who lent equipment for geothermal measurements, a few works were accomplished in the late 1970's. Eckstein (1976) and Eckstein and Simmons (1978) measured thermal gradients and thermal conductivity and obtained the heat flux in abandoned oil wells and unused water boreholes distributed over Israel. They calculated an average heat flux of 42 mW/m^2 which is relatively low compared to the average overall heat flux through the crust ($\sim 60 \text{ mW/m}^2$). For comparison, the approximate heat flux in western United States is $\sim 100 \text{ mW/m}^2$ (Tester et al, 2006) and it is redistributed and diminished by circulating

groundwater. Faults associated with the rift system act as conduits for ascending hot water causing local elevated heat flow.

Levitte and Eckstein (1978) Levitte et al. (1978) and Starinsky et al. (1979) conducted a geochemical study on the thermal springs along the Jordan-Dead Sea Rift Valley. They concluded that deep reservoirs with temperatures of 115°C and 90°C exist in the Kinneret and in the Dead Sea basins, respectively. However, Mazor et al. (1980) did not find any indication of the existence of a deep seated geothermal system of elevated temperature.

Levitte and Olshina (1978) and Levitte and Olshina (1982) defined the Brur and part of the Kidod formations in the Ashdod area as permeable rock strata with elevated temperatures. Koifman (1980) recommended utilizing the geothermal energy stored in these formations. However, the temperature of 110-125°C suggested by Koifman (1980) are higher than the actual temperatures measured in the wells.

Maurath (1989) examined the temperature profile of Zemach 1 well and compared it to heat flow measurements in the region. He measured the geothermal gradient to be 25°C/km with temperature of 130°C at depth of 3.5 km. However, since he assumed very low thermal conductivities for the rocks, the calculated heat flux was also low.

The Institute of Petroleum Research and Geophysics conducted several extensive geothermal explorations of different regions by electrical mapping (Rotstein et al., 1977a,b; Rotstein et al., 1978; Klang and Levanon, 1977a,b,c). The conclusions in all of their reports were either inconclusive or negative. Furthermore, their results were never tested with any temperature measurements. Indeed, Keller (1977) who visited the Institute of Petroleum Research and Geophysics concluded that the data was incomplete and suggested further hydrological exploration and analysis.

Temperature gradients and thermal conductivities measured at the bottom of the Dead Sea indicate a very low heat flux (Ben-Avraham et al. 1978). Based on coal rank measurements, Bein & Feinstein (1988) showed that a low heat flux has prevailed in the Dead Sea area since the mid-Miocene period. The heat flux was reported to gradually increase from south of the Dead Sea towards the Gulf of Eilat (Eckstein & Simmons 1978) where it is higher than the average heat flux in Israel of 42 mW/m², (Ben-Avraham et al. 1978). Shalev et al., (2006, 2007) modeled the discharge of the thermal springs at the Dead Sea and also concluded that the heat flux in this area is low. Eppelbaum et al.

(1996) suggested that horizontal temperature gradients may cause groundwater migration at the Dead Sea area.

At the Sea of Galilee Gvirtzman et al. (1997) suggested two different mechanisms for the convection of hot waters from deep seated aquifers; forced gravity driven flow convection at the western side of the Rift (Tiberias) and free buoyancy driven flow convection at the eastern side. At the western side of the rift meteoric fresh groundwater and hot brines from deep aquifers mix while emerging from several springs. Their model explains the seasonal changes in the discharge and salinity of the thermal springs by the changing water level and the specific hydrogeologic configuration. At the eastern side of the Sea of Galilee (Golan Heights) the high geothermal fluxes are attributed to groundwater convection that redistributes the heat. On the other hand, Michelson (1983) suggested that the appearance of the thermal spring at the Golan Heights and the high geothermal anomaly there result from regional gravity driven groundwater flow. Recharge from the Hermon Mountain at the north and from Zarqa at the south flows to the lowest structural point and ascends through faults at the southern Golan Heights.

In Jordan, Galanis et al. (1986) found very high heat flux ($\sim 460 \text{ mW/m}^2$) and geothermal gradient (175°C/km), at the Zerqa Ma'in area (Dead Sea area) associated with ascending groundwater. This area was later recommended for geothermal energy development by Myslil (1988). Förster et al. (2007) measured the temperature profile and the rock thermal conductivity at five boreholes in southern Jordan and found a heat flux of 60 mW/m^2 . The broad similarity in lithosphere structure and composition lead the authors to conclude that a value of 60 mW/m^2 may not just express the conductive surface heat flow in southern Jordan, but typifies the Arabian shield unaffected by young geodynamic reactivation.

4. Temperature Data

4.1 Temperature Logging

Logs of continuous temperatures were taken in several oil and water wells in Israel with a precision of $\pm 0.001^\circ\text{C}$. These measurements, when done years after drilling, are considered to be the most reliable data, representing the true formation temperature (the temperature of the geological formation). Frequently during drilling, cement is used to plug various intervals. Cement generates considerable heat while setting. In fact, temperature logs are regularly taken in order to follow the state of the setting cement. Such logs, performed during and close after drilling, do not represent the true temperature and are ignored in this study.

4.2 Drill Stem Test (DST)

Drill Stem Test is a procedure used to determine the productive capacity, pressure, permeability or extent of an oil or gas reservoir. DST is usually conducted with a downhole shut-in tool that allows the well to be opened and closed at the bottom of the hole or above the screen with a surface-actuated valve. Often, temperature is also measured during the test. These temperature measurements are considered to be a reliable formation temperature when the test has recovered a fair amount of formation water.

4.3 Bottom-hole temperature (BHT)

Bottom-hole temperature is the temperature in the borehole at total depth at the time it is measured. BHT data are routinely obtained during wire-line logging operations and are taken as the maximum recorded temperature during a logging run. The data are typically lower than the true virgin rock temperature of the formation due to the cooling effect of drill fluid circulation. If a bottom-hole temperature can be measured several times at a fixed depth while the well is shut in (no drill fluid circulation), it is possible to monitor the well bore temperature as it recovers toward its pre-drilling state, thus permitting extrapolation to virgin rock temperature. However, in the oil wells in Israel, BHT was not measured in every logging operation. In many cases; the temperature from one logging run was often copied later to another log. Therefore, every depth has only one record of measured temperature.

4.4 Calculated temperature-depth data base

Förster (2001) showed that in the German basin temperatures perturbed by drilling and mud circulation are higher than the true formation temperature at shallow depth and, below the pivot point, they are lower. In this study, we used Harrison et al. (1983) correction that was developed from North American data, which relates the difference between the formation temperature and BHT to the depth (Z) at which it is measured:

$$(1) \quad T_{cor} = -16.51213476 + 0.01826842109 * Z - 2.344936959 * 10^{-6} * Z^2$$

The T_{cor} values are added to the original BHT values. Z is the depth in meters. The equation is similar to ones originally proposed by Kehle et al. (1970) and was applied to produce geothermal maps for North America (Blackwell and Richards, 2004a,b; Blackwell et al., 2006; Tester et al., 2006).

Figure 2 shows that the newly corrected BHT closely fits with temperature logs and DST data. These corrected values are used below for calculating temperature at depth and heat flux maps. In this analysis, only wells that have more than three measurements in different depths are included in this data set (221 wells).

5. Data Interpolation

5.1 Heat flux Map

A geothermal gradient was calculated for each well with reliable newly generated temperature data. The thermal conductivity was estimated for every section of each well from its lithology (table 1). The product of the geothermal gradient and the thermal conductivity yields the heat flux (figure 3). In some cases the geothermal gradient changes within the well with the lithology, conserving the heat flux. In other cases the temperature gradient was calculated only on one segment of the well with the same lithology. In cases where there was a uniform gradient over the entire well which penetrated mixed lithology of limestone, dolomite, chalk, clay, and marl, an average thermal conductivity of $1.8 \text{ W/}^\circ\text{C/m}$ was assumed.

The results show that south east of the Sea of Galilee and in southern Israel the heat flux exceeds 60 mW/m^2 .

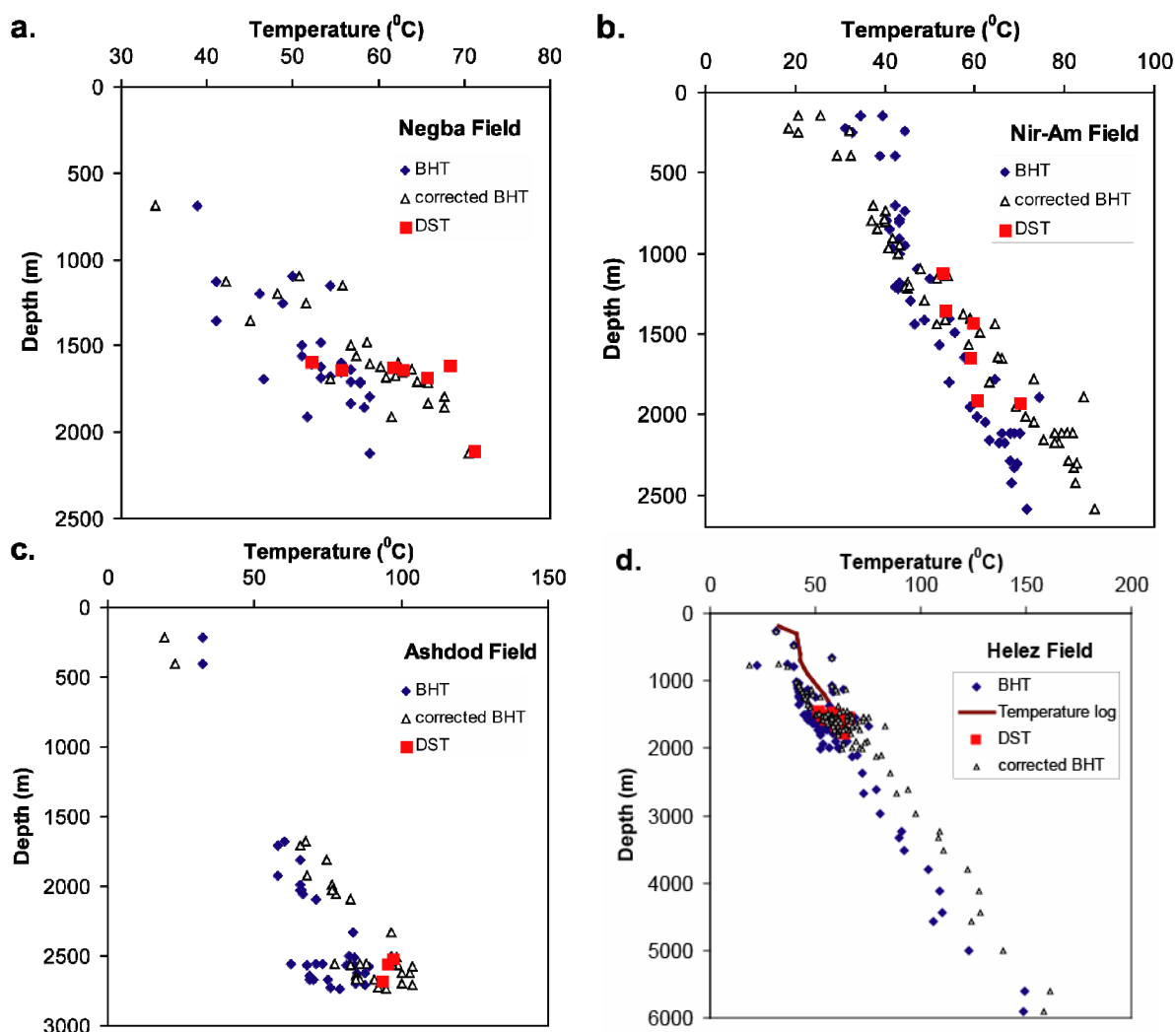


Figure 2: Measured bottom-hole temperature and its correction along with measured drill stem temperature and temperature logs in a. Negba, b. Nir-Am, C. Ashdod, and d. Helez fields.

Table 1: Thermal conductivities of different rocks (data from Eckstein and Simmons, 1987 and Maurath, 1989)

Rock type	Thermal Conductivity (W/°C/m)
Limestone	2.1
Dolomite	3.5
Chalk and Marl	1.3
Clay and Shales	1.2
Sandstone	2.1
Salt	3.2
Basalt	1.7
Granite	2.7

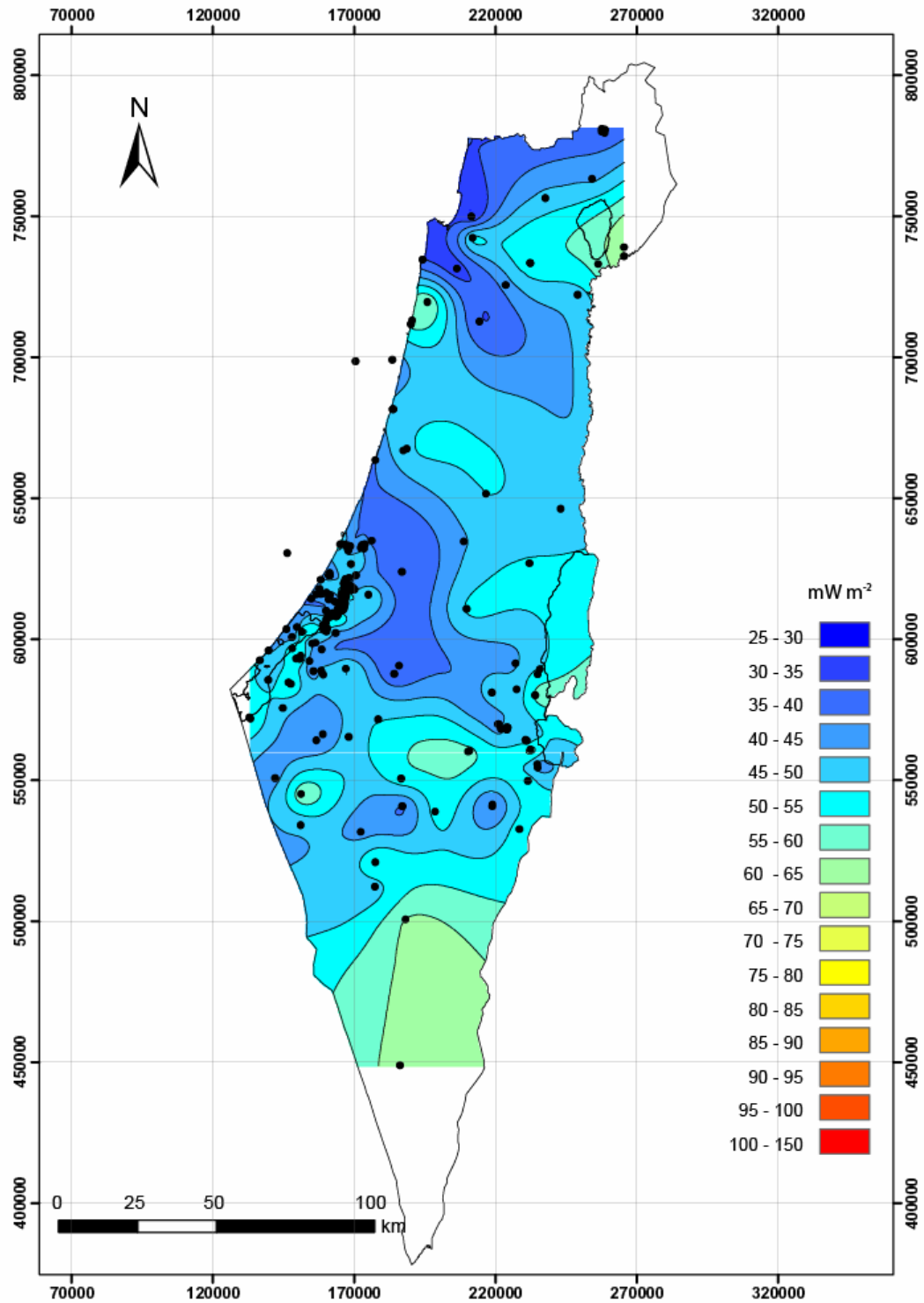


Figure 3: Calculated geothermal heat flux in Israel from borehole temperature measurements. South east of the Sea of Galilee and in southern Israel the heat flux is relatively high. Black circles represent the boreholes used for the calculation and interpolation.

5.2 Temperature at Depth maps

Following Turcotte and Schubert (1992), we assume that the heat production due to radioactive elements per unit mass decreases exponentially with depth as:

$$(2) \quad T = T_0 + \frac{q_m X}{K} + \frac{\rho_c H_0 h_r^2}{K} \left(1 - e^{-X/h_r} \right)$$

where X is depth beneath surface, T_0 is the temperature on surface, K is the thermal conductivity, q_m is the mantle heat flux, H_0 is the radiogenic heat production, and h_r is a length scale. Following Turcotte and Schubert (1992), we use $H_0=10\text{km}$, $\rho_c H_0=0.0037 \text{ mW/m}^{-3}$ for the basement. Because most of Israel's sedimentary cover consists of chalk, limestone, and dolomite, no radiogenic heat production is assumed for this part.

A depth-temperature profile was fitted to each borehole using equation (2). q_m was iteratively changed until the surface heat flux was equal to the heat flux in that borehole. Temperature at 4, 6, 8, and 10 km depth are shown in figures 4-7. In each map, the contouring is based on the values of the boreholes (black circles) and is linearly distributed between the boreholes using ANUDEM - a computer algorithm (Hutchinson, 1989). The reliability of the presented results decreases with depth since only few measurements were taken at depths greater 6 km and none were taken below 6.5 km. Accordingly, the temperature at depths of 6, 8, and 10 km strongly depend on the calculated surface heat flux. Since the thermal conductivity was estimated from the rock type and not measured everywhere, the calculated heat flux is also not very accurate. Because the heat flux dictates the geothermal gradient, an inaccurate value of the heat flux will cause an error in the calculated temperature that will increase with depth.

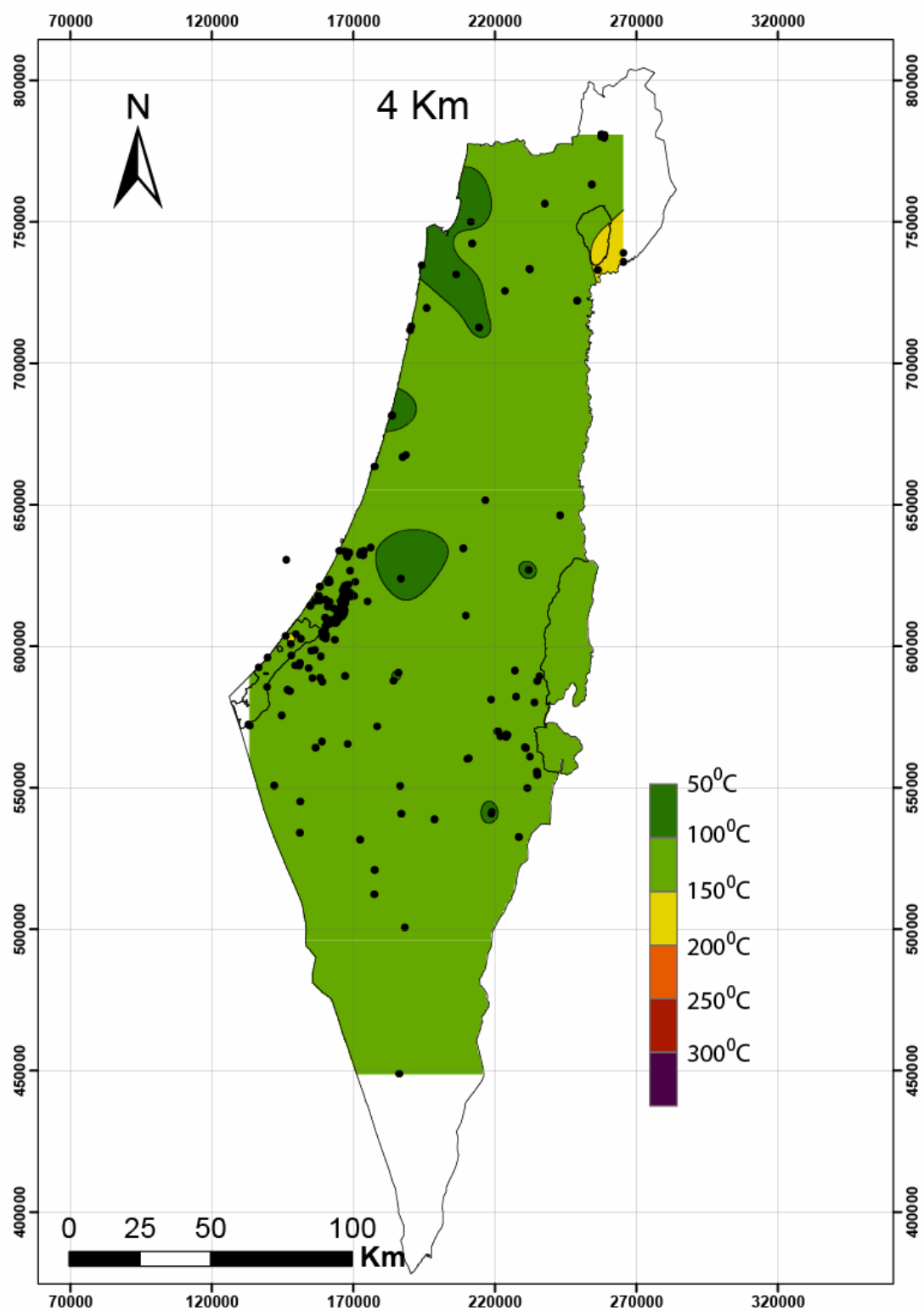


Figure 4: Average temperature at 4 km.

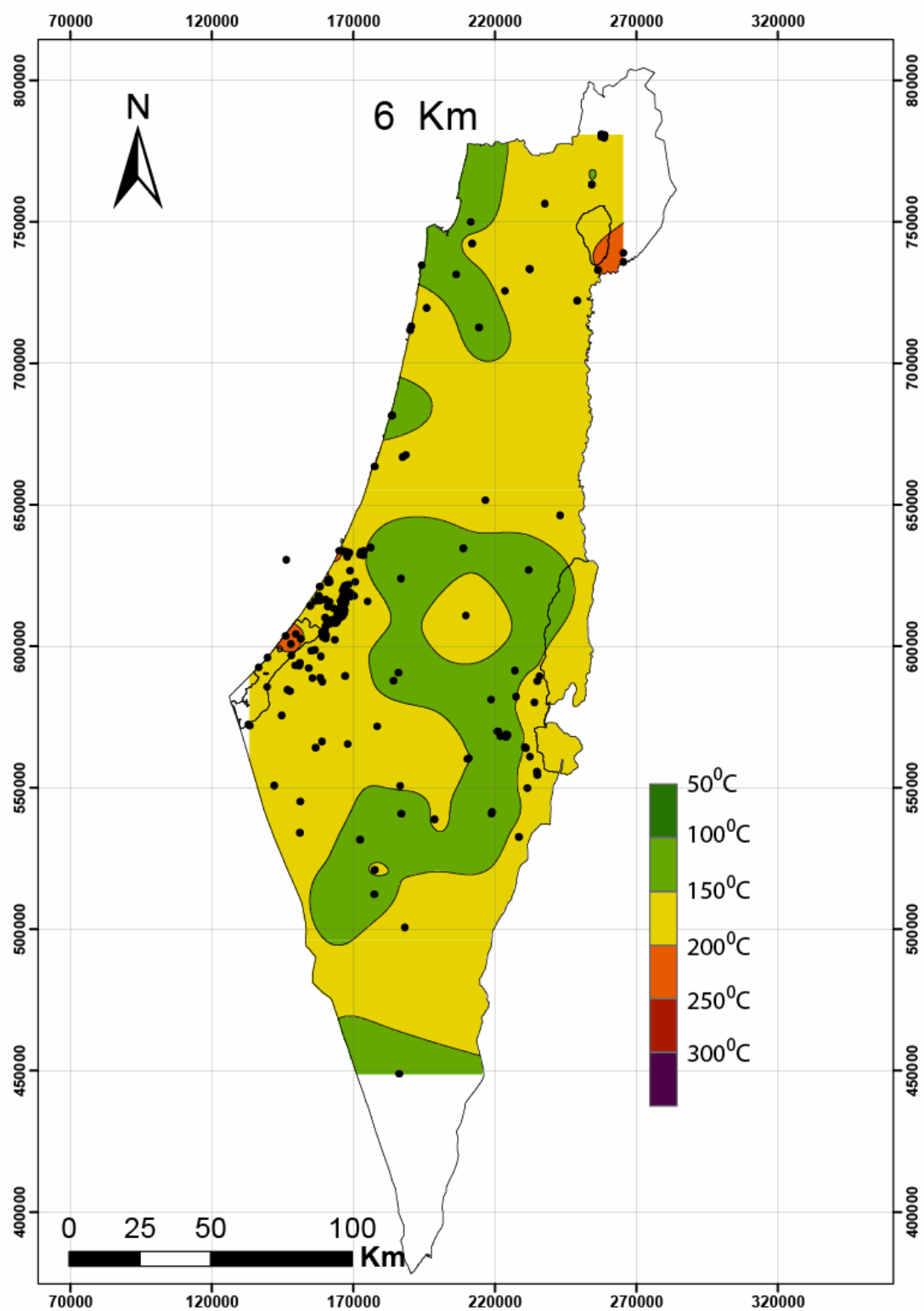


Figure 5: Average temperature at 6 km.

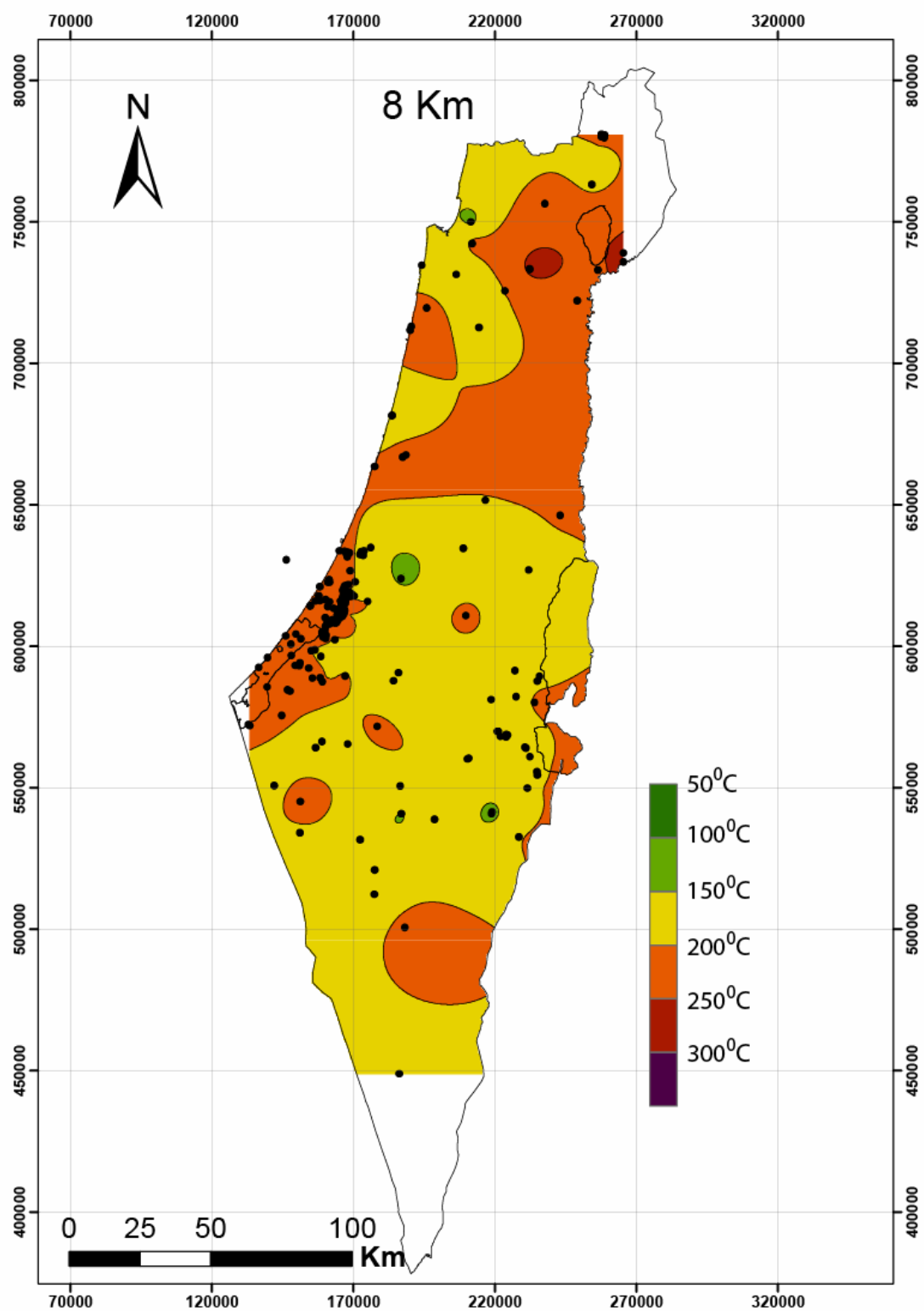


Figure 6: Average temperature at 8 km.

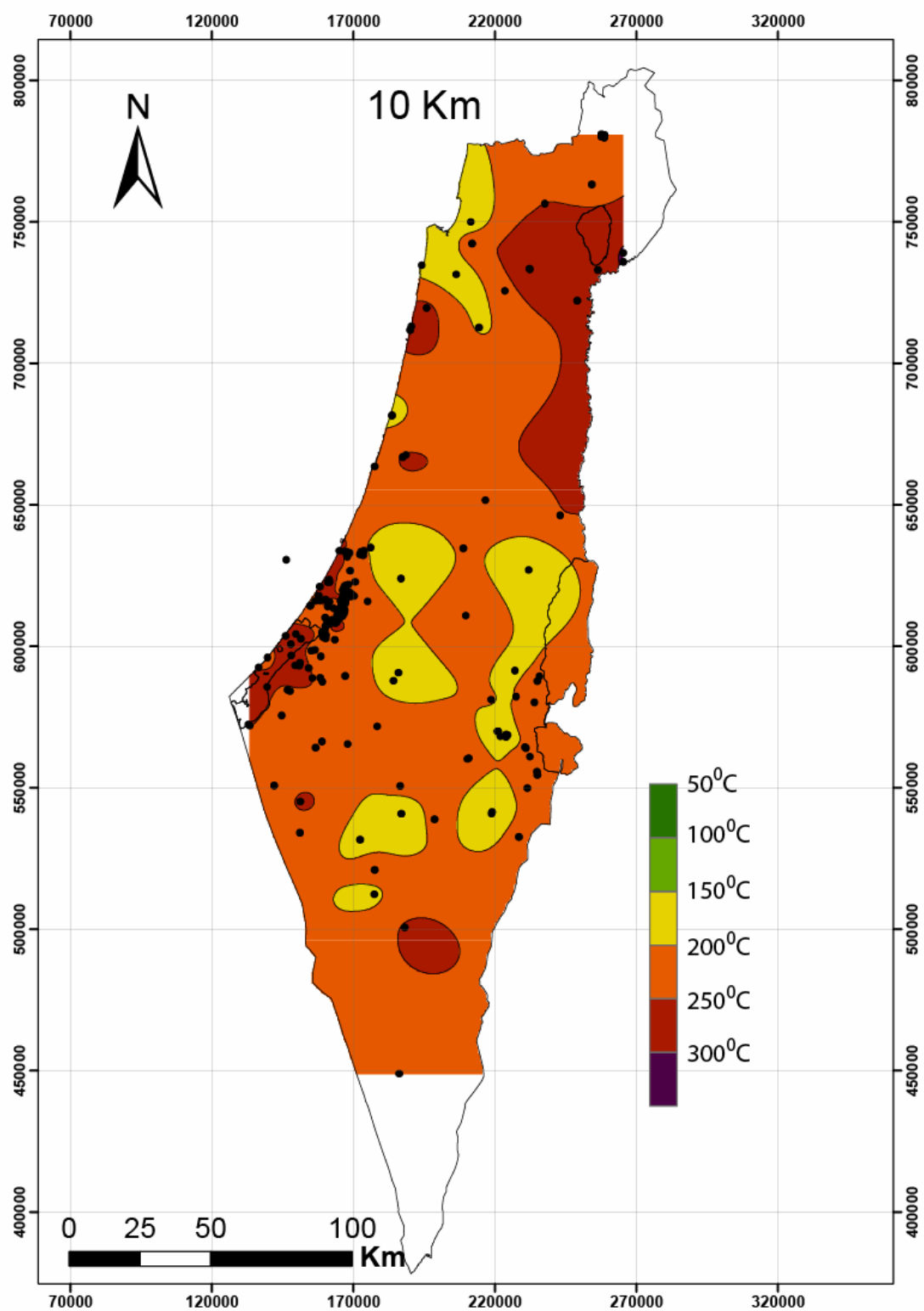


Figure 7: Average temperature at 10 km.

6. Enhanced Geothermal Systems (EGS)

When temperatures are high ($>150^{\circ}\text{C}$) but the permeability is low or there is no groundwater, the permeability could be artificially enhanced. As mentioned before, the preferable rock type for EGS is the basement because fractures that are artificially produced in granite are likely to remain open for long periods (Cuenot et al., 2008). Our results show that temperatures are higher than 150°C at depths greater than 6 km and close to 200°C at depths of 8 km in most of Israel. These results agree with the MIT report (Tester et al., 2006) which states that EGS could be developed anywhere on Earth. However, Israel potential for EGS is shown here to be average.

7. Conventional Geothermal System - Mezar Geothermal Wells

A geothermal anomaly was found by Michelson (1983) at the southern border of the Golan Heights (Figure 8). A similar anomaly exists just across the Yarmuk River, in the Mukhebeh boreholes in Jordan (Bajjali et al., 1997). A temperature profile from Mezar 1 borehole is shown in Figure 9 (data from Dr. A. Burg – personal communication). The average gradient in this borehole is $45^{\circ}\text{C}/\text{km}$. At the time of drilling a temperature of 79°C was recorded at a depth of 1,200 m (Michelson, 1981). The temperature has dropped by 8°C since the drilling of this borehole in 1981 probably because of extensive pumping from this aquifer ($\sim 2000\text{GPM}$). A similar geothermal anomaly was later found in Mezar 2 and 3 boreholes. Under undisturbed conditions, most of the boreholes in the area are artesian with pressure up to 5 bars in Mezar 2 (Mero and Rosner, 1984; Simon et al., 1997). Mezar 2 and 3 boreholes have been pumped considerably since 1998 (Figure 10). In Jordan pumping took place on the other side of the Yarmuk River since the 1980's at a grater rate but we do not have the relevant data. The drop in the pressure in Mezar 2 and 3 boreholes (Figure 10a) is probably due to pumping but could also be explained by a technical failure close to the boreholes since their hydraulic behavior (seasonally water level fluctuations) has changed. Temperature and salinity data from these boreholes is not routinely measured. Since 2001 the temperature and the salinity of Mezar 2 and 3 boreholes are similar perhaps because of a local connection between the boreholes (Figure 10b, c).



Figure 8: Location of the geothermal system east of the Sea of Galilee. Red circles represent boreholes tapping the Judean aquifer and white circles represent boreholes tapping shallower aquifers. The deep Zemah 1 borehole (4250 m) is drilled into the basin fill.

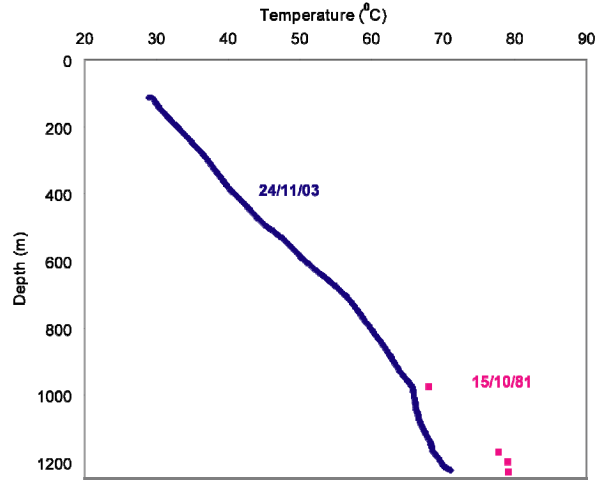


Figure 9: Temperature profile in Mezar 1 measured on 24/11/03 (Dr. A. Burg - Geological Survey of Israel, personal communication) and 15/10/81

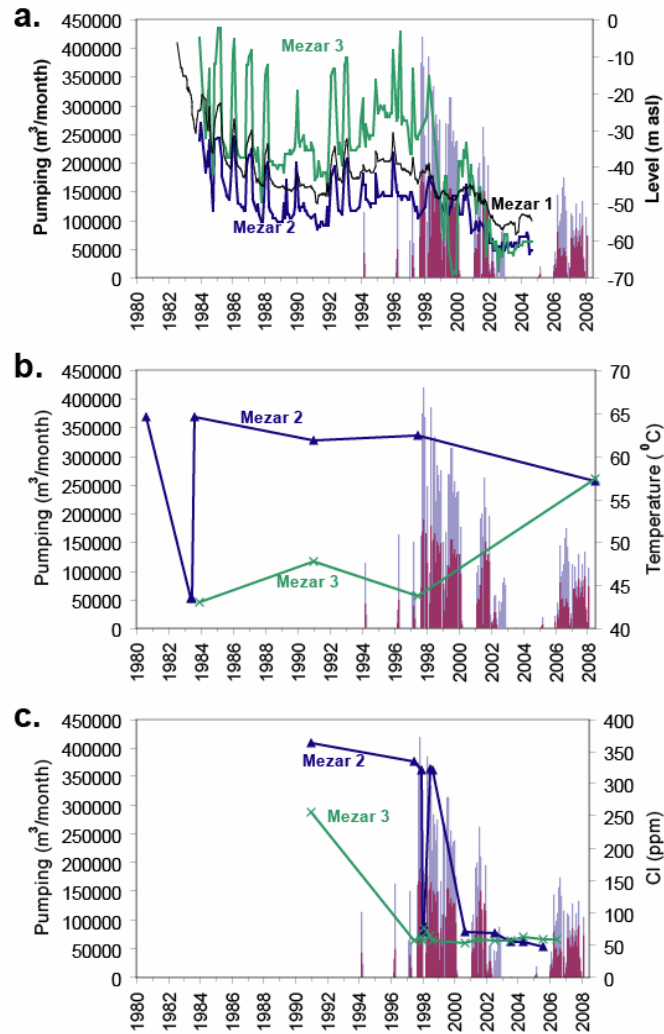


Figure 10: Pumping and water level (a) temperature (b) and salinity (c) in the Mezar boreholes.

A N-S cross section from the Mt. Hermon to Zarqa (Figure 11) is shown in Figure 12. The Mt. Scopus group consists mainly of chalk and is generally considered to have low permeability. The limestone of the Judea group is the main regional aquifer. Below the Judea group there are three large aquifers (Kurnub, Arad, Ramon) that are made of sandstone and limestone and are separated in places by clay layers (Kidod fm.).

All wells in the Yarmuk area pump from the Judea and Mt. Scopus groups. Aquifers in the deeper Arad group are recharged at Mt. Hermon and at Zarqa but have no apparent natural discharge, although some of the water might possibly discharge at the Hamat Gader springs. The groundwater in the Arad Group is highly pressured as measured at the Shamir 1 borehole (13 bar). The Arad Group includes mainly limestone and dolomite at Mt. Hermon and mainly sandstone at Zarqa. The thickness of the group drops from 2,300 meters at Mt. Hermon to 315 meters at Zarqa. The shales of the Kidod formation, which are impermeable to groundwater, disappear under the Golan Heights.

On the basis of the heat flux and the lithology at the Mezar area, we predict that the depth of the 150 °C isotherm is shallower than 3 km. A postulated lithology and temperature depth profiles close to Mezar 2 borehole is shown in Figure 13. The thickness of Arad and Ramon groups is about 1 km for about 100 km (figure 12). Assuming that this cross-section represents a strip with a width of 10 km, a volume of $1 \times 100 \times 10 \text{ km}^3$ is calculated. Assuming a conservative porosity value of 1%, results in a water reservoir volume of 10 km^3 (10^{10} m^3).

8. Conclusion

Israel's average geothermal heat flux is lower than the world average of 60 mW/m². Temperatures are higher than 150°C at depths greater than 6 km and close to 200°C at depths of 8 km in most of Israel. These results agree with the MIT report (Tester et al., 2006) that EGS could be developed anywhere on Earth.

A geothermal system with high temperature and groundwater pressure occurs at the south border of the Golan Heights at relatively shallow depth and is suggested for further exploration toward generating geothermal energy.

8. Acknowledgment

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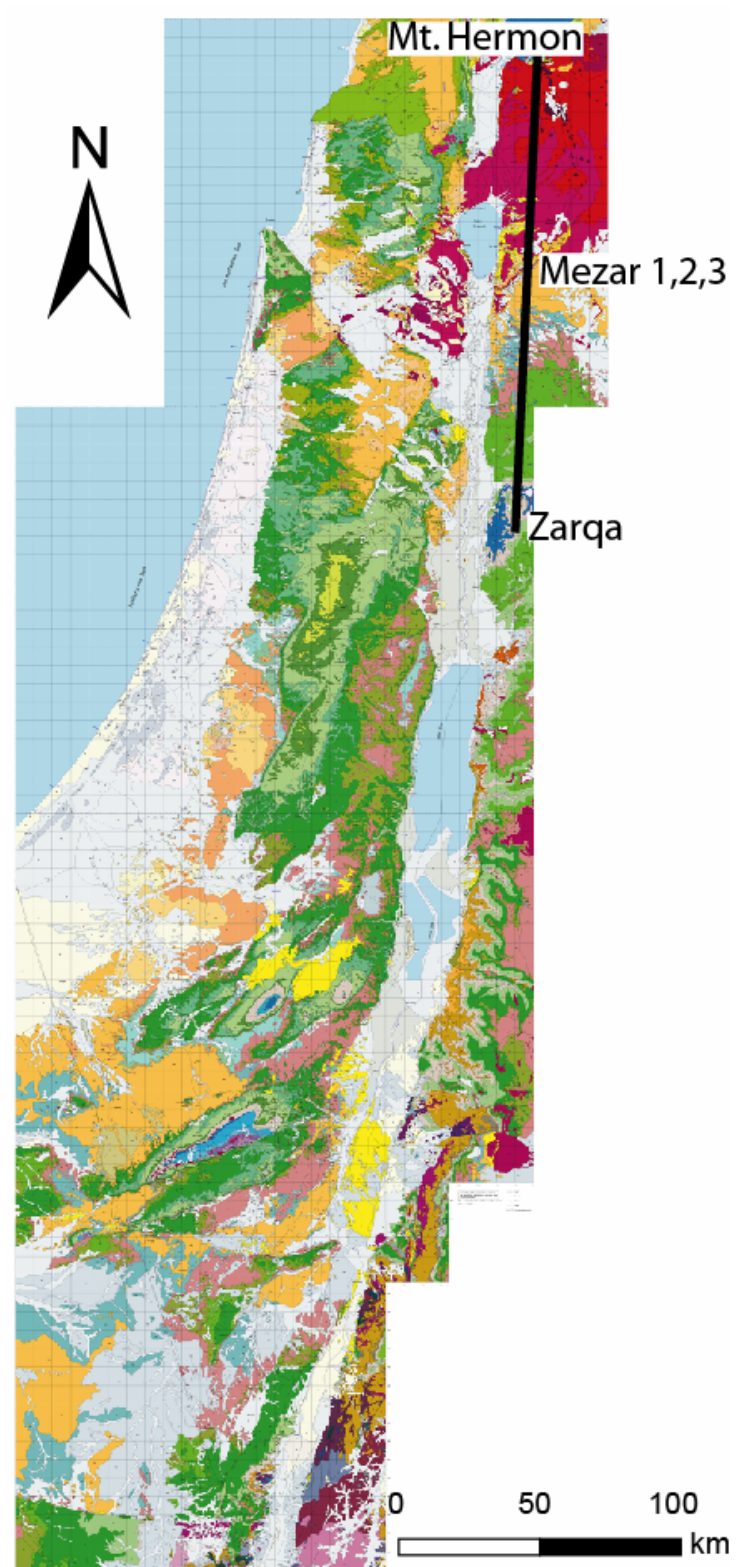


Figure 11: Geological map of Israel showing the location of the cross-section in Figure 12 (Sneh et al., 1998).

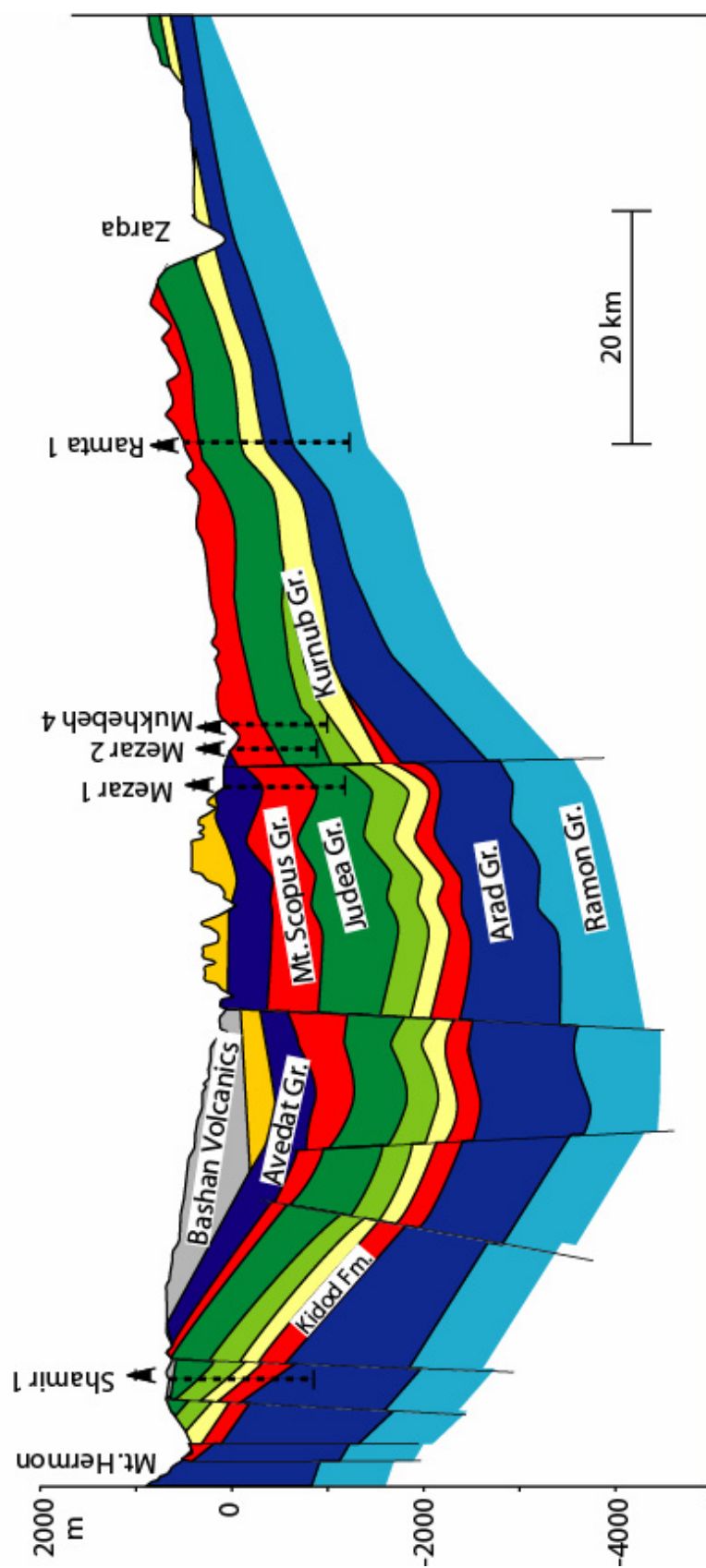


Figure 12: Geological cross-section from Mt. Hermon to Zarqa (based on Michelson, 1983).

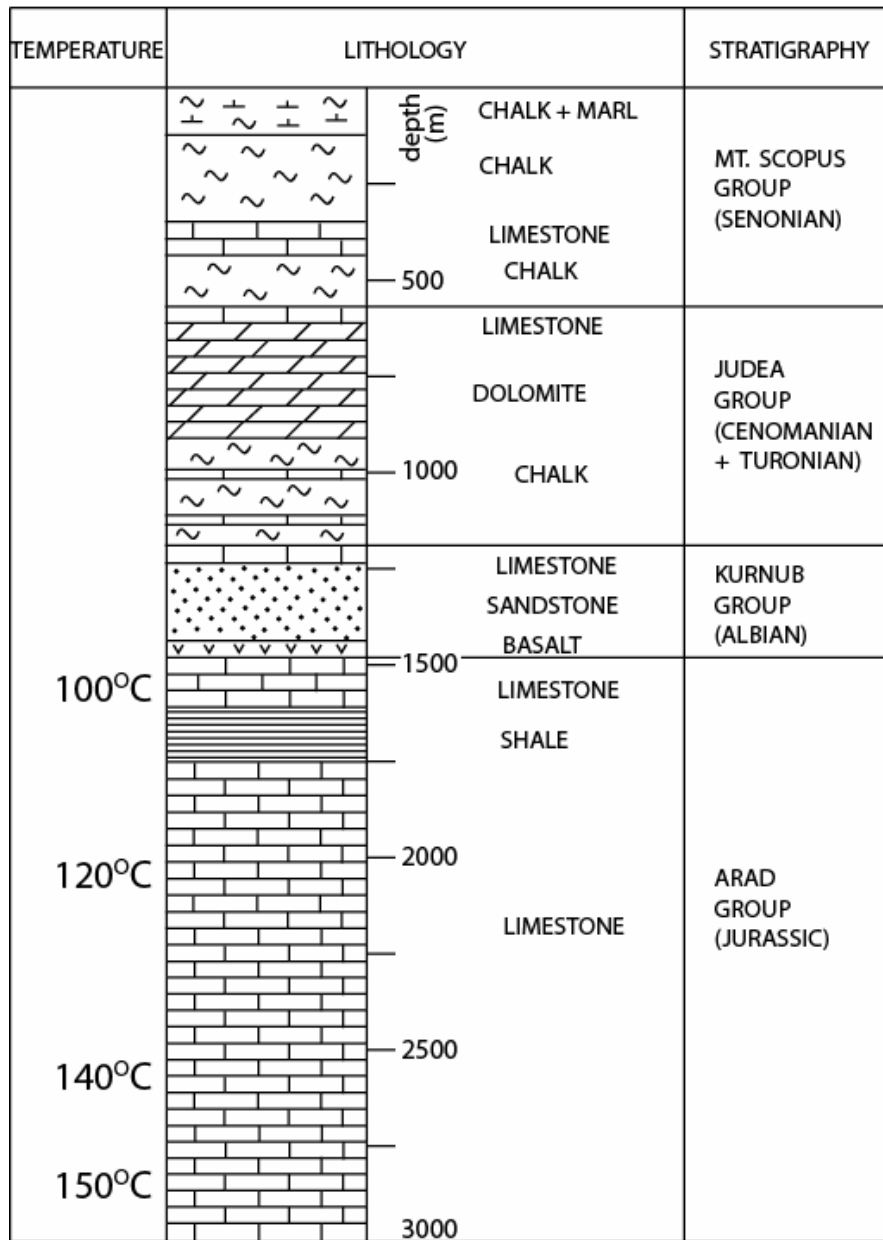


Figure 13: Predicted lithology and temperature depth profiles close to Mezar 2 borehole.

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