Present Heat Flow and Paleo-Geothermal Anomalies in the Southern Golan Heights, Israel

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Abstract While present heat flow (HF) throughout Israel and the Dead Sea Transform (DST) area is considered low, a thermal anomaly exists near the Yarmuk valley at the southern tip of the Golan Heights. New temperature measurements in the southern Golan Heights show that the distribution of the thermal anomaly is significantly wider than previously thought. The new data conforms to either a local and shallow magmatic chamber, which is in thermal steady state with the surrounding rocks, or to a transient heat front associated with localized Pleistocene magmatic intrusions in the Yarmuk. An alternative mechanism suggests that the present HF intensity is higher than the HF value calculated based on the apparent borehole temperatures due to heat removal by deep aquifer flow. A paleothermal analysis was performed using high-resolution organic matter maturation profiles on the Late Cretaceous source rocks, across the southern Golan basin. The maturation data show remarkably similar values throughout the basin, indicating that a single thermal event led to the source rock maturation. Constraints given by geological considerations have associated the paleo-thermal event with Pliocene volcanic eruptions, which has allowed the calculation of the basin paleo-heat flows, and indicated on a basin wide heat source, such as a crustal heat source. The paleothermal event is sharply bounded by a DST branching fault. This observation is suggested to be related to either strike-slip movement associated with the DST or to heat removal and modulation by a deep hydrological system.

1. Introduction

The regional present-day heat flow (HF) throughout Israel (Figure 1) and the Arabian shield is low with average values between 40 and 45 mW m$^{-2}$ (Eckstein & Simmons, 1977; Gettings & Showail, 1982; Shalev et al., 2013). While HF$s$ are usually elevated within rift basins due to lithospheric thinning and rising mantle plumes (Ruppel, 1995), the HF$s$ along the Dead Sea Transform (DST) are generally low (Ben-Avraham et al., 1978). This excludes the Red Sea and the Sea of Galilee (Yarmuk) regions that show elevated HF$s$. The main observations for elevated HF near the Yarmuk river are the geothermal springs of Hammat Gader and Mokhaha (discharging 45 × 10$^3$ m$^3$ yr$^{-1}$ with temperatures reaching up to 50°C) (Baijjali et al., 1978; Levitte et al., 1978; Mazor et al., 1973; Starinsky et al., 1979), elevated thermal gradients in the Ein Said well (subhydrostatic) and the high water temperature in some artesian wells in the area (Arad & Bein, 1986; Michelson, 1981). While there are indications that the elevated HF at the Red Sea is associated with extension tectonics (spreading rate of 10–16 mm yr$^{-1}$ [Chu & Gordon, 1998]), and opening of the crust, the source for elevated HF near the Sea of Galilee and the Yarmuk valley is not straightforward as the transform in this area shifts to a strike slip fault with a predominant shear component (slip rate of 1–10 mm yr$^{-1}$ [Ben-Avraham et al., 2005]). Since the tectonic setting associated with the DST cannot easily explain the source of the elevated HF, the mechanism responsible for the thermal anomaly has been the focus of many studies. The heat source in the area was previously associated with a shallow seismogenic zone (Aldersons et al., 2003; Ben-Avraham et al., 1978; Davies & Davies, 2010; Shalev et al., 2013; Shamir, 2006), magmatic activity of the southern Golan Heights (Ben-Avraham, 2014; Stein et al., 1993; Weinstein & Garfunkel, 2014), thermally driven rising plume (Goretzki et al., 2016), groundwater convection systems (Gvirtzman et al., 1982) as well as ascending hot water from deep hydrological systems, which discharge into the springs of the Yarmuk valley (Arad & Bein, 1986; Roded et al., 2013). It is important to note that some of these suggested mechanisms and explanations, can be indirectly associated with the nearby plate boundary and therefore the activity of the transform throughout the geological history is likely to have played a key role in the generation of the thermal anomaly.
Further evidence for elevated HF in the Yarmuk area through geologic time is the presence of hydrocarbons which were detected in relatively shallow source rock deposits in the Ein Said well (Michelson, 1981). These hydrocarbons, mostly bituminous in nature, are considered as indicative of early thermal maturation triggered by a thermal event (Tannenbaum & Aizenshtat, 1984). Since the 1980s, no additional wells were drilled in the area and therefore, the extent, spatial distribution and mechanism of the thermal event has remained unclear.

In this paper, temperature data from six new wells is presented which allows to delineate the magnitude and spatial extention of the present HF anomaly. Furthermore, for the same wells, high-resolution maturation data of thick Late Cretaceous source rock is provided as a function of depth, allowing the derivation of paleo HF by applying a forward basin model approach as previously performed by Feinstein (1987), Horkowitz et al. (1989), Majorowicz et al. (1983), McKenzie (1981), Shaaban et al. (2006), Tagiyev et al. (1997), and Tissot et al. (1987). The current HF are then compared with the modeled paleo-HF derived from source rock maturation data, in attempt to better understand the various possible mechanisms and scenarios for the heat source and thermal history of the region.

2. Geological Background

The Golan Heights is an elevated plateau covered by an extensive basalt flows and located at the edge of the massive Harrat Ash Shaam volcanic field (~50,000 km²) which extends into Syria, Jordan, and Saudi-Arabia (Figure 1). The Golan basin is a large synclinal structure, considered as part of the Syrian Arc fold system (Figure 2). This basin hosts a thick Late Cretaceous organic rich sequence of chalk, cherts, and phosphate deposits of the Har-Hatzofim Group (Menuha, Mishash, and Ghareb formations). The thick organic source rock (>400 m) is composed of Type IIS kerogen that was deposited in many basins of Syrian Arc system due to upwelling circulation in the Late Cretaceous Tethys Sea (Almogi-Labin et al., 1993). Overlying the source rocks are marine deposits of ages ranging from the Paleocene (Taqiye formation) up to the middle Eocene (Adulam and Maresha formations) (Michelson, 1972). These marine
sediments also point to a syn-depositional tectonic activity with thick deposits in the basin center and erosion and onlaps toward the basin margins.

During the Neogene, mostly terrestrial deposits (Hordos and Gesher formations) punctuated by short-lived marine ingressions (Bira formation) filled and flattened the basin (Michelson, 1972; Rozenbaum et al., 2016). The shift from a marine environment to a terrestrial one occurred in response to the major tectonic event of the DST, which split the African and Arabian Plates (Garfunkel et al., 1981) and bounded the Golan basin from the west. In the northern part of the syncline, a branching fault of the DST (Sheik Ali fault, SAF) that trends to the northeast displaced the basin by more than 900 m, while hosting a thick Neogene section of a different sedimentary fill from the southern Golan basin (Figure 2).

Since Miocene times, several volcanic events occurred in the northeastern part of Israel. These events believed to be associated with lower lithospheric melts that produced basaltic flows differentiated by location and composition (Stein et al., 1993; Weinstein et al., 2006). These volcanic events were attributed to the tectonic activity of the DST (Heimann et al., 1996; Joffe & Garfunkel, 1987; Weinstein, 2012). Eruptions and lava flows in the region were discontinuous in time with volcanic quiescence in between eruption episodes. The main volcanic events in northern Israel are (Figure 1): (a) Lower Basalt of late Oligocene to early Miocene times, mostly found west of the DST; (b) Cover Basalt of early Pliocene, which overlays most of the southern Golan basin, with additional eruptions in the late Pliocene north to the SAF; (c) Young Basalts, which occur at the center and northern Golan of late Pliocene and Pleistocene times, and locally in the Yarmuk and Raqqad valleys of Pleistocene age (Mor, 1993).

3. Methods

3.1. Downhole Temperature Measurements

Fluid temperature measurements were performed as a function of depth along the fluid column in all six boreholes examined in the study, using a conventional EC/T probe capable of measuring temperatures up to 80°C ± 0.1°C, at logging speeds of 4 m/min (Robertson Geologging). The measurements were performed on the first downhole logging trip following a minimal period of months (Ness 02, 03, 05, 12) up to years (Ness 10, ES) after the finalization of drilling and completion operations, in order to allow thermal equilibration between the wellbore, near wellbore environment and reservoir temperatures. In addition, the derived temperature log-based thermal gradients were extrapolated and compared to continuous downhole temperature gauge readings (Spartek Systems) during shut-in periods of drill stem tests, which targeted eight separate 15 m intervals, yielding an average difference of 1°C (Figure 3). The log-based wireline temperatures were also verified using maximum temperature registering thermometers (Kessler thermometer) which recorded the bottom-hole temperatures (BHT) yielding differences of less than 1°C.

3.2. Source Rock Maturation

Throughout the drilling phase of the source rocks, cuttings were collected at a resolution of 3–5 m. A few grams of each sample from the target layer were ground using a mortar and pestle. A subsample of ~100 mg was taken from the ground sample to perform a source rock thermal maturation analysis using the RockEval 6 (Vinci technologies). During the analysis, the sample is heated rapidly and steadily (between 200°C and 650°C) in the absence of oxygen, leading to thermal cracking of the kerogen (pyrolysis), into liquid and gaseous hydrocarbons. The temperatures at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis (often designated as $T_{\text{max}}$) is used as a maturation index and a proxy for thermal maturation of the sample. For the purpose of basin modeling, the $T_{\text{max}}$ values measured on the cutting material from the wellbores were converted to transformation ratio (TR). TR is defined as the ratio of the generated petroleum from the kerogen to the total amount of HC that the kerogen is capable of generating (Schwartz et al., 1980). In terms of RockEval properties, TR is defined according to RockEval S2 peak as: $1 - \frac{S_2(i)}{S_2(\text{immature})}$, where $S_2(i)$ and $S_2$ (immature) are $S_2$ measurement of a given sample and of an immature sample, respectively (Tissot & Welte, 1984). The conversion of $T_{\text{max}}$ to TR was performed using a
calibration curve from an artificial maturation laboratory experiment performed on an analogous immature type IIS deposit of the same formation (Amrani et al., 2005; Rosenberg et al., 2021). The laboratory experiment allowed to define the oil and gas windows, specifically for the type IIS deposit, in terms of TR values as follows: 0–0.10: Immature, 0.10–0.25: Bitumen generation, 0.25–0.75: Oil window, 0.75–1.00: Gas window. A detailed discussion of the calibration experiment, Golan basin source rock richness, composition and maturation state can be found in Rosenberg et al. (2021).

3.3. Basin Modeling

A forward basin model (BasinMod-1D, January 2017 Release, Platte River Associates, Inc.) was constructed taking into account the stratigraphy, formation ages and known hiatuses, lithology, organic matter type and modern-day HF. Using these inputs, the burial history was reconstructed while simulating compaction. Comparison between well-log derived porosity (averaged per strata) and the forward-model calculated porosity based on compaction curves of a given lithology, validated the model calculation and allowed to rely on the subsequent effect on the thermal conductivity of the rocks.

By applying HF levels through time, the model calculates temperatures as a function of depth and time, which allows the calculation of the kerogen TR. The independent thermal history of each well is iterated until the modeled TR the measured values. It should be noted, that fitting the model to the TR data may be attained by multiple solutions, as the increase in maturation is proportional to the product of time and temperature (Lopatin, 1971; Waples, 1980). As will be discussed below, the geological history of the basin provides constraints to the timing of and duration of the elevated HF which allows to narrow the range of possibilities.

Figure 3. Temperature profiles (lines) and drill stem test data (solid circles) as recorded in ES, Ness 02, 03, 05, 12, and 10 wells. Thermal gradient lines, in the range of 2°C–5°C/100 m, were added for reference purposes. Linearity depends on time allowed for thermal equilibrium, loss of drilling fluids and perforated intervals. Inset: Measured geothermal gradient as derived from the temperature profiles a function of distance from the Yarmouk valley.
4. Results

Maturation and thermal data from six new boreholes between the Yarmuk and Yehudiya valleys (∼30 km apart), is presented. Depending of the topography, basin structure, thickness of the Har-Hatzofim Group (Menuha, Mishash, and Ghareb formations) and displacement along faults, the source rock depth ranges from ∼500 to 2,250 m below ground level (mBGL) enabling to examine a wide range of thermal conditions. The data from the wells consists of information on stratigraphy, lithology, and temperature logs as well as Rock-Eval measurements on the source rock drill-cuttings. The depositional history was integrated with the organic maturation data in order to reconstruct the thermal history of the region.

4.1. Present Thermal State

Thermal gradients calculated based on the temperature logs and drill stem test data, vary by a factor of 2 and range from 5.15°C/100 m at Ein Said well to 2.5°C/100 m in Ness 10 (Figure 3). A clear exponential decrease is noticed from south to north along cross section A-A’ (Figure 1) showing that the center of the thermal anomaly is located near the Yarmuk valley and extends by more than 15 km to the north (Figure 3, inset). The geothermal gradients were converted to HF (mW m$^{-2}$) using the thermal conductivities calculated based on a high resolution stratigraphic and lithologic record. The calculated HF ranges from 45 to 85 mW m$^{-2}$ increasing from north to south (Figure 4a). The newly estimated spatial coverage of the elevated HF extends northwards and covers a significantly larger area (∼150 km$^2$) than previously reported (Figure 4a).

The temperatures at the base of the Late Cretaceous source rocks, which depend on the combination between the local HF and burial depths, range from 63°C to 67°C in most parts of the basin. Despite the fact that the lowest present thermal gradients in the basin were found in Ness 10 (2.5°C/100 m or 45 mW m$^{-2}$), the temperatures at the base of the source rocks are the highest (77°C) due to the significantly deeper burial in the downthrown block of the SAF.

4.2. Source Rock Maturation

Due to the uniquely thick Late Cretaceous source rocks (>350 m), it was possible to track the maturation increase as a function of depth. For example, values in Ness 03, start at the top of the Ghareb formation at a TR value of <0.05, and increase logarithmically with depth up to a maximal value of 0.45 at the base of the Menuha formation (Figure 5). The maximum measured TR value per well range from 0.32 to 0.44 across the basin (excluding Ness 10). The maturation trends in the basin are disrupted in the downthrown block.
of the SAF (Ness 10), which shows distinctly low TRs of <0.15 (immature), despite the fact that the source rock found in this well was buried ∼900 m deeper than the rest of the basin.

4.3. Forward Basin Model

The purpose of modeling the TR values in each well was to identify the limits on the HF and the duration of a paleothermal event in order to reach the measured maturation levels. The burial history of 10 key horizons (Bina-Cover basalt) were constructed according to the detailed lithological logs of each well (see Ness 03 example, Figure 6). Once the burial history constraints were taken into account, various HF scenarios were modeled. Figure 7 provides an example for Ness 02 well, where a Pliocene paleothermal event was defined between 5.3 and 3.5 My. The HF was adjusted in order for the modeled TR (solid lines in Figure 5) to best fit the measured TR data (solid circles in Figure 5).

5. Discussion

The data from the boreholes of the Golan Heights show that the present Yarmuk valley thermal anomaly extends further north than previously reported (Shalev et al., 2013), gradually decreasing northward (Figure 4a). Despite the fact that the present thermal gradients or HF are anomalously high, the temperatures (65°C–70°C) at the base of the Late Cretaceous source rocks are insufficient to transform the kerogen to the measured TR levels. Furthermore, the TR of the source rocks show remarkably uniform TR values with
almost no spatial variance across the basin, extending far past the present thermal anomaly coverage area (Figure 4b). This leads to the conclusion that the southern Golan basin has been subjected to higher HF and temperatures in the past. These observations raise several questions, which will be addressed below: What is basin’s heat source, timing and duration? What is the relationship between the current thermal anomaly and the paleothermal event? Is the current thermal anomaly a continuation of the paleothermal event (i.e., similar source with an extended duration) or are these heating events separate?

5.1. Present Thermal State

Two optional first order estimates for heat sources are evaluated below using the new thermal data in the southern Golan basin.

5.2. Localized Magmatic Heat Source

The first source assumes the presence of a small and localized subsurface magma chamber near the Yarmuk valley where the geothermal gradients are the highest. Such a magma chamber can be described by assuming a hot spherical body at a constant temperature, radius and depth which diffuses heat according to the following equation, at steady state (Carslaw & Jaeger, 1959):

\[ T(r) = T_2 + \left(T_{\text{chamber}} - T_2\right) \frac{R_0}{\sqrt{x^2 + z^2}} \]

where: \( T_2 \) are the background temperatures (estimated as the temperature at given depths of 0.5–2 km at a distance of 25 km), \( T_{\text{chamber}} \) and \( R_0 \) are temperature and radius of the intrusion, respectively, both of which are mathematically indistinguishable from one another; \( x \) and \( z \) are the horizontal and vertical distance from the heat source to the measured temperature location.

Fitting Equation 1 to the measured temperatures (at reference depths of 0.5, 1, 1.5, and 2 km) while constraining \( T_2 \) and \( x \), yield the solution presented in Figure 8. Two parameters were extracted from the fitting exercise: (a) the product of \( (T_{\text{chamber}} - T_2) \) and \( R_0 \) (70 m °C), which enables the derivation the intrusion temperature as a function of the radius of the magma chamber by examining the interplay between parameters. (b) The depth of the suggested magma chamber (z) of 3.5 km.

While it is hard to ascertain at this point whether a relatively shallow magmatic chamber reside beneath the nearby Yarmuk valley as there is a lack of seismic, gravimetric or magnetic data, it is not unlikely that

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Figure 7. HF curve at Ness 02 well. Heating event was constrained to 5.3–3.5 m.y ago. The amplitude of the thermal event was adjusted by numerical iterations, in order to attain a fit between measured TR data (solid circles, Figure 5) and the basin model (solid lines, Figure 5).
the current temperature field is influenced from the younger and localized volcanic events associated with the Yarmuk basalts (0.8–0.6 m.y) and/or Raqqad basalts (0.2–0.1 m.y). In order to examine this possibility, the following point source transient solution for Green's function (Carslaw & Jaeger, 1959) was used to calculate the timescales required for a heat pulse to radially diffuse and propagate via thermal conduction in an infinite medium:

\[
T(r, t) = T_2 + (T_{\text{invasion}} - T_2) \frac{4}{3} \pi r_0^3 \frac{1}{4 \pi \alpha t} e^{-\frac{r^2}{4\alpha t}}
\]

where: \(\alpha\) is thermal diffusivity, which is defined as \(\frac{k}{\rho C_p}\) (41 and 83 km²/m.y, for the Ghareb and Mishash formations, respectively), \(k\) is thermal conductivity (2.2 and 4.9 J/(m·k·s) for the Ghareb and Mishash, respectively, [Schütz et al., 2012]), \(\rho\) is bulk densities of the rocks (1,800–2,100 kg/m³, for the Ghareb and Mishash, respectively, [Shitrit et al., 2016]), \(C_p\) is specific heat capacity (900 J/(kg·k) for both the Ghareb and Mishash formations) and \(t\) is time, m.y.

The results, presented in Figure 9, indicate that the timescales required for of a transient heat front to reach the measured temperatures in the boreholes is in the order of several hundreds of thousands of years, depending on the exact location of the point source. These timescales conform with the Pleistocene volcanic events, suggesting that the current anomaly could be related to localized Yarmuk or Raqqad eruptions within the Yarmuk valley (Figure 1). This implies that the present temperature field could be explained by a local and short Pleistocene heat pulse associated with magmatic intrusions which have lost most of their heat to the surrounding rocks via thermal conduction. The solution of Equation 2 provides an alternative explanation to the heat source. It indicates that the postulated hot magma chamber at a depth of 3.5 km, as implied by the steady state model in Equation 1 is not a unique solution. While evidence for massive and shallow Pliocene and middle-late Miocene magmatic gabbro deposits were found in the nearby Zemach well (Marcus & Slager, 1985; Segev, 2017) (Figure 1), no indication for magmatic intrusions associated with the Pleistocene eruptions is yet to be provided, as this region lacks deep boreholes and geophysical data.
5.3. Regional Heat Source

An alternative scenario, follows Roded et al., (2013) who numerically modeled groundwater flow and heat transfer in the Golan Heights by applying an energy balance approach. The model suggests a relatively high basal HF of 100 mW m$^{-2}$, a value higher by a factor of 2.5 than the estimated mean basal HF in the region. Such elevated HF values indicate according to Roded et al., (2013) deep crust conditions (exceptional source of geothermal heat) or magmatic origin. Furthermore, this elevated basal HF is reduced by deep groundwater flow, which is recharged from the northern most part of the basin in Mt. Hermon and flows southwards to the Hammat Gader and Mokhaba as geothermal springs (Yarmuk springs). Therefore, the groundwater temperatures gradually increase through their flow path southward which leads to less heat removal and higher geothermal gradients in the south, which is consistent with the new temperature measurements reported in this paper. The fact that the current basal HF is estimated to be 100 mW m$^{-2}$ is especially interesting since similar HF values were derived for paleo conditions based on the source rock maturation data and basin modeling. This explanation implies that the basal HF has barely changed since the Pliocene, while the hydrologic system has gradually developed through time, leading to currently lower apparent HF values. This model will be further discussed below in relation to paleo thermal conditions.

5.4. Paleo Thermal Event

Three observations point to the fact that a paleo thermal event has occurred in the geological past: (a) the present temperature regime at the base of the Late Cretaceous source rocks is insufficient to mature the source rock to its measured level. (b) The area that has undergone thermal maturation is significantly larger than the spatial distribution of the present thermal anomaly. (c) When observing the TR trends as a function of depth from the surface (mBGL), a large variance between wells is exhibited (Figure 5a). However, when using a structural datum for calculating the depth of the source rocks, such as depth below sea level (mBSL), the TR data with depth converge and show remarkably similar values throughout the southern Golan basin, except for Ness 10 (Figure 5b). The usage of a constant datum removes the post Pliocene topographic features (young basalts flows and incising rivers) and serves as a proxy to the basin structure prior to the heat pulse that matured the source rocks (Figure 2). This indicates that the southern basin has undergone
a similar thermal history throughout the basin and that the thermal event occurred prior to the end of the Pliocene.

Since the regional HF in the Arabian plate has been low through the Cenozoic (Eckstein, 1979; Stein et al., 1993), the heating event which led to maturation of the Senonian source rocks in the basin had to be local and therefore, likely to correspond in time with the volcanic history of the Golan Heights. Out of the three main volcanic events that have been identified in the area (Early and Late Pliocene and Pleistocene, Figure 1), the only sufficiently large event that overlies the entire thermally matured rocks in the southern Golan basin, is the late Pliocene Cover Basalt volcanic event dated to 5.3–3.5 Ma. Over this time period, we assumed a constant HF for each well (Wangen et al., 2007). The HF intensity (Figure 7) was adjusted, in order to individually fit the Basin model TR values to the measured data (Figures 8 and 5a). The HF calculated for the thermal event show little variation across the basin (100–112 mW m$^{-2}$), suggesting a uniform heat source that extended over an area of at least 450 km$^2$ (Figure 4b). It is important to note that a sensitivity test which assumed a baseline HF up to 80 mW m$^{-2}$ (instead of 40 mW m$^{-2}$) prior to the Pliocene, did not prompt additional maturation of the source rocks, due to their shallow burial depth at the time.

Such long term and uniform HF distribution on a basin wide scale suggests a different heat source than the one suggested for the present thermal state, most probably a deep magma chamber or a crustal heating source.

The spatial coverage of the paleo heating event overlaps the present thermal anomaly and extends northward. The intensity of the widespread paleo thermal event was significantly higher than the spatially limited present thermal event with HF of 45–85 mW m$^{-2}$. At this point, it is impossible to determine if the paleo and present HF anomalies are genetically tied or not. The following options are brought forward: (a) the paleo and present thermal events are separate and discreet. The paleo heat source has completely decayed since the Pliocene. The new heat source located near the Yarmuk, points to either an active hot shallow magmatic chamber (3.5 km depth) or a local Pleistocene intrusion associated with the younger basalt eruptions. (b) The present thermal anomaly is a relic of the paleothermal event which decayed due to volcanic eruptions, DST plate tectonics related effects, or heat removal by groundwater flow. (c) The Pliocene thermal anomaly, of the order of 100 mW m$^{-2}$, has remained relatively constant through time. According to energy balance approach of Roded et al. (2013), the lower (apparent) HF measured north of the Yarmuk (45–85 mW m$^{-2}$) is explained by deep groundwater flow, removing some of the basal heat. To this end, this value is practically similar (or perhaps slightly lower, indicating some cooling of the heat source through time) to the paleothermal HF modeled based on source rock transformation ratios (100–112 mW m$^{-2}$). This implies that the deep hydrogeological system has been gradually developing with time, allowing groundwater flow from the northern to the southern Golan while gradually cooling the overlying strata and inhibiting further source rock maturation.

### 5.5. The SAF Anomaly

In the downthrown block, north of the SAF, the source rock is buried 900 m deeper than the rest of the basin (Figure 2). According to the basin model, if this block would have been exposed to a similar heat pulse as in the southern block, the source rocks would have over matured. However, despite the deeper burial, the kerogen did not undergo almost any transformation (TR < 0.15, Figure 5). Two main options can explain this observation. Tectonics associated with the DST plate boundary (Bartov et al., 1980; Girdler & Styles, 1978) and the strike slip component on the SAF (Rotstein et al., 1992; Sneh et al., 1998) could have shifted the block over a distance of a few km away from its current position, from an area that was not influenced by the elevated HF of the magmatic chamber (Figure 5b). Alternatively, the SAF served as a hydraulic barrier which separated the northern and southern blocks, leading to different heat regimes: North of the fault, the energy conducted from deep was removed by a deep hydrological system that flowed in an underling aquifer. These hydrological systems did not pass through the fault zone, thereby allowing coeval maturation south of the SAF. Over time, with the continuous throw of the SAF and the placement of permeable layers from both sides of the fault, the hydrological system could have developed across the fault southward, allowing the southern basin to cool, as described above.
6. Conclusions

The present temperature field, as measured in the new boreholes, indicates that the thermal anomaly around the Yarmuk is wider than previously thought. The present temperature field points to local heat sources (maggmatic chamber or magmatic intrusions) or a regional (crustal) basal heat source, which is modulated by deep groundwater flow. During the Pliocene, a regional (crustal) scale thermal source has led to strikingly similar degrees of maturation of Late Cretaceous source rocks across the basin. Further thermal modeling of both the present and paleo thermal anomalies is required in order to determine the heat source origin, heating mechanism, timing and duration. Additionally, further study is needed in order to determine whether the present and paleo thermal anomalies can be considered separate and discrete events with potentially different heat sources or whether these events are genetically tied.

Data Availability Statement

Global Heat Flow Database of the International Heat Flow Commission; re3data.org – Registry of Research Data Repositories. http://doi.org/10.17616/R3G305.

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