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Thermal properties of sediments in southern Israel: a comprehensive data set for heat flow and geothermal energy studies

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Abstract

To decipher the thermal structure of the sedimentary veneer in southern Israel, new values of thermal conductivity (TC) and porosity as well as of the radiogenic heat budget are provided.

TC is measured for lithotypes and scaled up for geological formations.

The new data are higher than most of the previously measured values, in particular for sandstones and siltstones, whose mean values are 5.0 and $2.9 \text{ W m}^{-1} \text{ K}^{-1}$. Mean values of the most abundant lithotypes, which are dolomites and limestones, are on the order of $4.1 \text{ W m}^{-1} \text{ K}^{-1}$ and $2.7 \text{ W m}^{-1} \text{ K}^{-1}$, respectively. The total radiogenic heat production (RHP) of the sedimentary cover varies slightly over southern Israel, due to variable lithology and total sediment thickness, yielding a maximum heat flow on the order of 4 mW m^{-2} , where the sedimentary section is thickest (about 7 km). A temperature prognosis was made by calculating temperature profiles to the top of the crystalline basement at five well locations applying the new thermal-conductivity data set and three scenarios of q_s ($50, 55, 60 \text{ mW m}^{-2}$). The calculated temperatures best match with measured drillstem-test temperatures by using heat-flow values close to the upper bound of range. Surface heat flow on the order of $55\text{--}60 \text{ mW m}^{-2}$ is supported by a reevaluation of an existing temperature log and the application of TC from this study. The temperature prediction for southern Israel shows values of $100\text{--}120^\circ\text{C}$ at $3500\text{--}4500 \text{ m}$ depth, indicating a geothermal potential that can be used for heating as well as electricity production.

1 Introduction

Studies on the thermal structure of sedimentary settings imply first a delineation of the vertical temperature-depth relations, which can be extended to 2-D or 3-D thermal models. If temperature-depth profiles from borehole logging are abundant, the thermal structure of a sedimentary basin can be shown by a series of temperature maps, which are generated simply by interpolating the data. On the contrary, if temperature data are scarce the thermal structure can be numerically calculated based on a geological model. This approach allows an apprehension of temperature changes that may occur if the geological structure is complex and if rocks of different thermal properties are involved. However, to use this approach in a heat conduction domain, knowledge of the q_s and the thermal rock properties (thermal conductivity (TC), radiogenic heat production (RHP)) is essential. Likewise, data of the thermal rock properties are a prerequisite for the determination of the heat-flow density at

borehole scale by combining the thermal properties with temperature data.

In this paper, the thermal properties of the sedimentary succession in southern Israel are investigated as part of the DESIRE project (<http://www.gfz-potsdam.de>) to form a basis on which an upcoming heat-flow study and thermal models will depend on. TC is measured of core and outcrop samples for different lithotypes and then scaled up to formation TC using information from well logs and litho-logs. RHP is determined for geological formations and scaled up for the entire sedimentary succession taking its lateral thickness change into account. Finally, the new data on thermal rock properties are used (I) exemplarily in conjunction with a temperature log (Eckstein and Simmons, 1978) to discuss the need for revising the q_s for southern Israel and (II) to provide geotherms for the sedimentary succession that can be used in exploration for geothermal energy.

2 Geological setting

Southern Israel, located at the western edge of the Arabo-Nubian Shield (ANS) is part of the southern Levantine Basin (Figure 1). The ANS was formed during the Pan-African Orogenic Cycle, about 1,000–530 Ma ago. The shield originated from the suturing of juvenile intra-oceanic arc terrains followed by magmatic thickening, giving rise to regional metamorphism and the generation of batholiths of predominantly granitic to granodioritic composition. Various structures of the ANS constitute fossil fragments of a Neoproterozoic Wilson cycle, representing opening and closure of an ocean basin that occurred between older crustal blocks of east and west Gondwanaland (Kröner et al., 1990; Stern, 1994). Volcanic and metamorphic rocks of late Precambrian age are exposed on outcrop only in the southernmost part of Israel, in the Timna Park, and the Eilat Complex.

From Cambrian to Paleogene times, the area was a stable platform owing to its position as a passive continental margin, and an extensive veneer of sediments was accumulated. The Levantine Basin has evolved through long and complicated processes which started in the late Triassic–early Jurassic times (Garfunkel and Derin, 1984; Ben-Avraham, 1989; Robertson et al., 1996). The platform history was interrupted by a period of faulting and magmatism related to shaping the Levant continental margin in the early Mesozoic, by intraplate magmatism in the early Cretaceous, and by mild folding and shearing in late Cretaceous to Miocene times (Garfunkel, 1988; and references therein).

During Miocene to Pliocene times, continental break up started with the extrusion of mafic

volcanic rocks related to the opening of the Red Sea at about 30 Ma and the activity of the Afar mantle plume (Wilson et al., 2000). The Dead Sea Transform (DST) was activated 14–18 Ma ago after the initiation of rifting along the Red Sea and is attributed to lithosphere thinning owing to asthenosphere upwelling, possibly involving a mantle-plume component (Camp and Roobol, 1992; Shaw et al., 2003; Krienitz et al., 2007; and references therein). Today the DST extends from the Red Sea spreading centre to the Zagros zone of plate convergence.

During the platform stage, several periods of major erosion interrupted the sediment deposition. The pre-Permian unconformity was the result of the ‘Helez’ uplift, which caused a substantial stack of Paleozoic sediments to be eroded. The Permian-Triassic disconformity, expressed by the hiatus of the lower part of the Triassic, separates the late Paleozoic Negev Group from the Triassic Ramon Group. The Triassic-Jurassic unconformity forms the boundary between the Ramon Group and the overlying Jurassic Arad Group (Hirsch, 2005a). The Jurassic paleotectonic setting is characterized by relative lows and highs, controlled by differential rates of subsidence. In the latest Jurassic and earliest Cretaceous times the area bordering the Eastern Mediterranean basin was affected by a phase of uplift and extensive erosion, therefore sediments of this age are missing (Gvirtzman and Garfunkel, 1998). During the Cretaceous, several regional events of erosion occurred resulting in unconformities which caused the separation of the Cretaceous into three stratigraphic groups: Kurnub, Judea and Mount Scopus Groups. With the beginning of the Alpidic faulting at the end of late Cretaceous, syntectonic deposition dominates until the end of the Paleogene. During late Oligocene regional uplift and erosion started contemporaneously with the opening of the Red Sea (Hirsch, 2005a).

Figure 1: Study area with the location of the Dead Sea Transform (DST) and of boreholes reported in this study. Wells with analyzed gamma-ray logs: Hz 1-Hazerim 1, Htz 2-Halutza 2, B 1-Beersheva 1, EO 1-EinOfarim 1, Plm 1-Palmahim 1, PT 2-Peta Tiqva 2, H 34-Helez 34, P 28-Paran 28. Well used for the heat budget calculation from gamma-ray logs: HD 1A-Helez Deep 1A. Well used for surface heat-flow calculation: D 1-Daya 1. Dotted lines show the position of the lithostratigraphic sections shown in Figure 3 and 4: Av 1-Avdar 1, R 1-Ramon 1, M 1-Meishar 1, Si 1-Sinai 1, ZD 8-Zohar Deep 8 wells.

3 Stratigraphy and lithology

In the following, the Permian to Paleogene sedimentary succession is described stratigraphically (Figure 2) and lithologically (Figure 3, 4) from the oldest to youngest groups. Sinai Group:

The Precambrian Zenifim Formation, building up the Sinai Group, consists of red to dark brown massive fine to coarse grained arkose. The arkose sequence is associated with extrusive igneous rocks (dolerite, rhyodacite and andesite) and it overlies the igneous basement (Weissbrod, 2005). In the Ramon 1 well (Figure 4) the formation is 2014 m thick which approximate the total thickness.

Figure 2: Chronostratigraphy of the Permian to Palaeogene in southern Israel (modified after Gvirtzman, 2004). R.B. is Ramon Basalt, n.d. is non deposition, a) Tamar, b) Avnon, c) En Yorqueam, d) Zafit.

Negev Group:

The Permian Sa'ad Formation overlaying the Precambrian Zenifim Formation forms the basis of the Negev Group. It is composed of fluviatile to deltaic sandstones. A few layers of limestone and dolomite interrupt the dominating fluviatile environment. The overlying Arqov Formation consists of alternating sandstone, shale and limestone. The Triassic Yamin Formation consists of dolomitic sandstone and limestone. The carbonate content in this formation varies largely across the Negev area. The overlying Zafir Formation is composed of calcareous and pyritic shales and sandy, glauconitic or dolomitic limestone (Weissbrod, 2005). The whole Negev Group is represented in the Zohar Deep 8 well (Figure 3).

Ramon Group:

The Triassic Ra'af Formation, making up the basis of the Ramon Group, is mainly composed of limestone and dolomite, rich in fossils, claystone and chalk.

The Gevanim Formation, overlying the Ra'af Formation, contains fluviatile sandstones, dark grey shale and limestone. The Saharonim Formation is a carbonate sequence with some shale, marlstone and evaporite intercalations. The Mohilla Formation at the top of the Ramon Group is mainly composed of dolomite and minor shale and gypsum (Benjamini et al., 2005). Towards the south the thickness of the Ramon increase to about 600 m (Ramon 1 well, Figure 4) farther south the Ramon Group is truncated by the base Cretaceous unconformity.

Arad Group:

The Mish'hor laterite constitutes the basis of the Jurassic Arad Group. The Mish'hor laterites are overlain by the Ardon Formation, which is composed of carbonates, shales and evaporates and thickens towards the Coastal Plain area to several hundred meters (Helez Deep 1A well, Figure 4). Fluviatile clastics characterize the overlying Inmar Formation. These are cross-bedded sandstones separated into two clastic units, the Lower and Upper Inmar intercalated by the marine Qeren Formation. The overlying Daya Formation contains carbonates and clastic rocks. Paralic clastic rocks and marlstone are typical for the Sherif Formation in southern Israel. These rocks are covered by a homogeneous sequence of limestones, shale and marlstone building up the Zohar Formation (Hirsch, 2005b). The Kidod Formation is predominantly composed of shale; its thickness increases progressively north-eastward. The Beersheva Formation and Haluza Formation consist primarily of limestone, dolomite, marlstone, shale and of subordinate sandstone. The Haluza Formation however is enriched in shale (Weinberger et al., 1991). In general, the Arad Group is of relatively homogeneous composition across southern Israel.

Figure 3: Lithostratigraphic E-W cross section of the Negev area based on boreholes shown in Figure 1. Numbers attached to columns indicate sampling depth for TC and porosity measurements on drill core and values of porosity (in %).

Kurnub Group:

The Kurnub Group, consisting mostly of terrestrial deposits and marine intercalations, includes all beds between the Jurassic marine Arad Group and the Middle Cretaceous marine Judea Group. In the southern part of the Negev, the Kurnub Group lies directly on the early Palaeozoic Nubian sandstone (Sinat 1 well, Figure 4). The Jurassic here is completely eroded. The composition of the formations building up the Kurnub Group changes from the southern Negev to the central and northern Negev and to the Coastal Plain area; therefore different stratigraphic nomenclatures are used. The Amir, Avrona and Samar Formations occur only in the southernmost part of the Negev. They consist of quartzarenite, sandstone and siltstone. The Hatira Formation composed of very fine to coarse-grained and moderately to well-sorted quartzarenite, cross-bedded on a large scale and in minor amounts argillaceous sandstone, conglomerate and bioturbated siltstone, occurs only in the southern Negev. It is subdivided into the Lower and Upper Hatira Formation separated by the Ramon basalt. In the northern Negev, the Lower Cretaceous section is subdivided into the marine intercalations Zeweira,

Dragot, Malhata and Uza. They consist of very fine to fine grained sandstone, siltstone and mudstone with limestone ledges, dolomite and marlstone (Lewy, 1990; Weissbrod, 1993). The Helez and Telamin Formations occurring in the Coastal Plain area are overlain by the carbonatic Yakhini Formation. The Helez Formation is mainly composed of interbedded limestone and shale and minor amounts of sandstone and dolomite. In contrast, the Telamin Formation is mainly sandy-calcareous and exhibits some coral-stromatopora-rudist-reefs (Rosenfeld and Hirsch, 2005b).

Figure 4: Lithostratigraphic N-S cross section of the Negev area based on boreholes shown in Figure 1. Numbers attached to columns indicate sampling depth for TC and porosity measurements on drill core and values of porosity (in %).

Judea Group:

The Judea Group is a rather homogeneous carbonate sequence due to the large thickness and good exposure over wide areas of Israel it is subdivided into several formations. The lowermost formation is the Hazera Formation, which is subdivided into five members: Hevion, En Yorqueam, Zafit, Avnon and Tamar (Hazerim 1 well, Figure 3). Glauconitic-dolomite, sandy dolomite and dolomite build up the Hevion Member in the basal parts

merging upwards into sandstone with dolomite. In the uppermost beds chert nodules occur. The En Yorqueam Member is composed of fossiliferous marlstone, argillaceous limestone and dolomite. The overlying Zafit Member mostly consists of limestone interbedded with marlstone (Rosenfeld and Hirsch, 2005b). The Avnon Member contains chalk, marlstone and nodular limestone and in the upper parts massive and bedded dolomite (Buchbinder et al., 2000). The Tamar Member forms a hard unit that consists of brown-yellow dolomite, dolomitic limestone and limestone alternating with marlstone.

In the Coastal Plain area, the Hazera Formation passes into the Yagur and Negba Formations. The Yagur Formation forms a sequence of dolomites at least 350 m thick, interbedded with limestone, sandstone, marlstone and chalk. The overlying Negba Formation can be subdivided into a lower member, comprising dolomite with marlstone intercalations and an upper member encompassing more marlstone interbedded with dolomite and limestone (Rosenfeld and Hirsch, 2005b).

In the southern Negev, the Hazera Formation is overlain by the Orashale, Gerofit and Zihor Formations (Sinaf 1 well, Figure 4). The Orashale Formation can be divided into a lower, mainly shaly member with numerous gypsum veins, a middle member containing limestone, argillaceous limestone, marlstone, shale and dolomite and an upper member composed of red and green shale, massive gypsum beds, glauconitic dolomite and sandstone. The Orashale Formation thins towards the north; north of the Ramon structure the upper part of the formation is missing. The Gerofit Formation is a sequence of massive well-bedded limestone and dolomite with oolites and fragmented fossils and minor amounts of shale and marlstone (Bartov et al., 1972, Rosenfeld and Hirsch, 2005b). Soft yellowish dolomite, marlstone, argillaceous and frequently fossiliferous limestone built up the overlying Zihor Formation in the south. In the north, the formation consists of chalky limestone and bioclastic limestone. The Derorim Formation overlying the Hazera in the northern Negev consists mainly of marlstone with some chalk and limestone. These rocks pass laterally into the limestones and calcarenites of the cliff-forming Shivta Formation (Braun and Hirsch, 1994). The Nezer Formation shows well-bedded hard limestone with quartz granules, crystals and chert concretions at the top of the formation. A few soft marlstone and chalk beds as well as dolomite beds occur. The equivalent of these three formations in the Coastal Plain area, the Bina Formation, is mainly composed of limestone. Only in the lower parts of the formation some dolomite and chert concretions occur (Rosenfeld and Hirsch, 2005b).

Mt. Scopus Group:

In the northern Negev, the mostly chalky and marly Mt. Scopus Group is subdivided into the Menuha, Mishash, Ghareb and Taqiye Formations (Beersheva 1 well, Figure 3). In the southern Negev, the Menuha and Mishash Formations are treated as one unit, the Say'yarim Formation. In the Coastal Plain area, the En Zetim Formation replaces the Menuha and Mishash Formations (Halutza 2 well, Figure 3) (Gvirtzman, 2004).

The Menuha Formation unconformably overlies the Judea Group. It consists of a marine, predominantly chalky sequence which is subdivided into two members. The lower one consists of limonitic chalk and the upper one of soft white chalk and marlstone, respectively. The transition to the Mishash Formation is characterized by the first occurrence of flint layers. The Mishash Formation is composed of calcareous, oolitic, phosphate layers alternating with phosphatic chalk, marlstone and limestone. The proportion of chert, as well as of phosphorites increases upwards, reaching its maximum in a laminated chert member. The En Zetim Formation contains white chalk and marly chalk and is sometimes bituminous. The Say'yarim Formation in the southern Negev consists of alternating soft chalks and harder units of sandstone, shale, dolomite, limestone and chert. The Ghareb Formation overlying the Mishash, En Zetim or Say'yarim Formations occurs over most of the Negev. It encompasses limonitic marly chalk with pyrite and phosphate nodules and in some areas black oil-shale and bituminous marlstone (Rosenfeld and Hirsch, 2005b). The Taqiye Formation covers the Ghareb Formation. Its base is defined by the first occurrence of green shales. The shales gradually pass upwards into argillaceous chalks and chalky limestone (Bartov, 1972).

Avedat Group:

The Adulam Formation forms the basis of the Avedat Group and is composed of chalk and silicified chalk with thin chert horizons and chert nodules (Halutza 2 well, Figure 3). The overlying Maresha Formation contains globigerinid chalks (Rosenfeld and Hirsch, 2005a).

Saqiye Group:

The Saqiye Group is extensively developed in the Coastal Plain area but is missing in the southern Negev. It consists of the Bet Guvrin Formation composed of chalky marlstone and limestone (Hirsch, 2005c) and the Yafo Formation which is mainly made up of clay (Helez Deep 1A, Figure 4).

4 Analysis

Sediment samples for laboratory measurements were obtained in the drill core archive of the Geological Survey of Israel. Most samples pertain to the Jurassic and Cretaceous (Aptian to Turonian) section. Minor samples were obtained from Paleozoic to Triassic and Precambrian formations and from formations of Paleocene to late Eocene age. The lithostratigraphic information of 9 of the 16 sampled wells is shown in Figure 3 and 4. To overcome the lack of core samples from the shallower formations, samples were also collected from outcrops, mostly from the Turonian to Paleocene section.

In total, 234 samples were obtained for TC and porosity measurements. With respect to rock type, 75 samples pertain to limestone, which also is the most frequent lithology in southern Israel, 46 samples pertain to sandstone, 32 samples to shale/claystone, 18 to siltstone, 16 to marlstone, 15 to dolomite, 14 to dolomitic limestone, 6 to igneous rocks, 5 to chalk, 3 to chert, 2 to gypsum, 1 to coal and to anhydrite, respectively.

TC was measured with the TC Scanning (TCS) apparatus (Lippmann and Rauen, GbR), which is based on high-resolution optical scanning (Popov et al., 1999). The error of determination is less than 3%. The samples were measured dry and, except for claystones, also water-saturated. The given water-saturated bulk thermal conductivity (BTC) values of claystone and shale were calculated using equation (2.1) and (2.2).

The effective porosity was quantified for all samples by the mass change between dry and water-saturated samples (Archimedes method). Because of clay swelling effects, these rocks were saturated with isooctane (density 0.69 g cm^{-3}) instead of water. In addition, porosity of selected shale samples was measured by Helium pycnometry.

In order to investigate the effect of mineral composition on measured BTC, the TC of the rock matrix was calculated for different lithotypes using the geometric mean model (Woodside and Messmer, 1961):

$$\lambda_{geo} = \lambda_m^{1-\phi} \cdot \lambda_p^\phi \quad (1)$$

$$\lambda_m = \left(\frac{\lambda_{sat}}{\lambda_p^\phi} \right)^{\frac{1}{1-\phi}} \quad (2)$$

where λ_{geo} is the TC according to the geometric mean; λ_m is the TC of the rock matrix; λ_p is the TC of the pore fluid, ϕ is porosity, and λ_{sat} is the saturated BTC.

For sandstones, the matrix thermal conductivity (MTC) obtained from measurements was

compared with respective values calculated from the major mineral constituents using the geometric, the arithmetic and the harmonic mean model (Voigt, 1928; Reuss, 1929; Horai and Simmons, 1969; Somerton, 1992). The arithmetic mean equation reproduced the measured values at best:

$$\lambda m_{ari} = \sum_{i=1}^n V_i \cdot \lambda_i \quad (3)$$

$$\lambda sat_{ari} = (1 - \phi) \cdot \lambda m_{ari} + \phi \cdot \lambda p \quad (4)$$

where λ_i is the TC, V_i is the volume fraction of the i -th mineral phase, λp is the TC of the pore fluid, and ϕ is porosity.

The modal mineralogy of sandstone samples was analyzed in thin sections by estimating the percentages of individual minerals.

TC was measured for lithotypes and then was upscaled to values for geologic formations by summing up the individual lithotype values multiplied by thickness. The proportions of lithotypes in each formation were obtained from lithological descriptions of cores available in the archives of the Geological Survey of Israel.

The radioactive heat generation in the sedimentary succession was determined from total gamma-ray logs, available from nine wells (Figure 1), using the equation of Bcker and Rybach (1996). The equation uses a linear relationship between natural total gamma-ray logs (GR) in API units and laboratory measured RHP A in μWm^{-3} .

$$A = 0.0158 (\text{GR}[\text{API}] - 0.8) \quad (5)$$

Heat production of stratigraphic units was calculated by averaging values over respective depth intervals. By multiplying the arithmetic mean with the thickness of the stratigraphic unit the heat flow produced in each unit was determined.

Surface heat flow q_s (mW m^{-2}) was recalculated for one borehole location (the Daya 1 well, Eckstein and Simmons, 1978, Figure 1) using the interval method (e.g., Powell et al., 1988) and the Fourier equation of heat conduction:

$$q_s = -\lambda \frac{\partial T}{\partial z} \quad (6)$$

where λ is the TC (in $\text{W m}^{-1} \text{K}^{-1}$) and $\partial T/\partial z$ is the temperature gradient (in $^\circ\text{C km}^{-1}$). The

intervals for the calculation were selected from a depth plot of interval temperature gradients calculated from a continuous temperature log. The Daya 1 temperature log has a temperature recording interval of 10 m; hence the temperature gradients were calculated over 10-m depth intervals. No exponential smoothing was applied to the data. The log shows no signs of temperature perturbation due to fluid flow thus reflecting heat conduction conditions.

5 Results

5.1 Thermal conductivity of lithotypes

The water-saturated BTC differs considerably between and within lithotypes (major lithotypes are listed in Table 1) as indicated by the range and mean of values. Highest TC is observed for chert ($5.1 \text{ W m}^{-1} \text{ K}^{-1}$), sandstone ($3.0\text{--}6.6 \text{ W m}^{-1} \text{ K}^{-1}$), anhydrite ($5.0 \text{ W m}^{-1} \text{ K}^{-1}$) and dolomite ($3.8\text{--}5.2 \text{ W m}^{-1} \text{ K}^{-1}$), moderate values for siltstone ($2.4\text{--}3.4 \text{ W m}^{-1} \text{ K}^{-1}$), igneous rocks ($2.3\text{--}3.2 \text{ W m}^{-1} \text{ K}^{-1}$), dolomitic limestone ($2.5\text{--}3.1 \text{ W m}^{-1} \text{ K}^{-1}$), limestone ($2.0\text{--}3.2 \text{ W m}^{-1} \text{ K}^{-1}$), and marlstone ($2.0\text{--}2.8 \text{ W m}^{-1} \text{ K}^{-1}$), and lowest values for claystone/shale ($1.6\text{--}2.2 \text{ W m}^{-1} \text{ K}^{-1}$), chalk ($1.2\text{--}2.0 \text{ W m}^{-1} \text{ K}^{-1}$), gypsum ($1.3 \text{ W m}^{-1} \text{ K}^{-1}$) and coal ($0.6 \text{ W m}^{-1} \text{ K}^{-1}$), respectively.

While the variability of TC is small for claystone and moderate for siltstone and carbonates, it is particularly large for sandstone. The smaller range of values for limestones can be explained with a relatively homogeneous composition of this lithotype. In general, the limestone values vary due to different amounts of dolomite, sand or argillaceous rock components. The effect of different porosity ($0.2\text{--}14.4\%$) is due to the low mean value of 6.0% less striking. The large diversity in saturated BTC observed for sandstones ($3.2\text{--}6.6$, mean $5.0 \text{ W m}^{-1} \text{ K}^{-1}$, Table 1) is, to a large extent, an expression of both variable modal mineralogy of the samples causing MTC values of $4.2\text{--}7.8 \text{ W m}^{-1} \text{ K}^{-1}$ (Table 2) and variable porosity. The effect of sandstone porosity ($3.7\text{--}23.0\%$) is larger than those of limestones indicated by a larger mean value (8.0%).

The sandstones can be classified either as quartzarenites and carbonatic sandstones or as argillaceous sandstones. The detrital component mainly consists of quartz and minor amounts of rock fragments and feldspar. Polycrystalline quartz and chert assemble the rock fragments. The grain-grain contacts of the lithics point to a magmatic origin. Calcite mainly constitutes the authigenic component. Dolomite, anhydrite, clay and gypsum are subordinate cement minerals, and quartz and iron oxide occur only sporadically.

For example, the Sinaf-1_04 and Sinaf-1_07 samples, relating to the Hatira Formation, (Table 2) are typical argillaceous sandstones with $31\text{--}37\%$ authigenic clay and quartz and feldspar as detrital component. Both the saturated as well as the MTC are accordingly low.

Table 1: Range and mean λ value ($\text{Wm}^{-1}\text{K}^{-1}$) of the measured TC of water-saturated rocks from

Lithology		Dolomite				Limestone				Dol Ls				Marlstone			
Gr.	Fm.	range	m	n	Φ	range	m	n	Φ	range	m	n	Φ	range	m	n	Φ
Mt. Scop.																	
C.Plain/ N./S. Negev	Taqiye																
	Ghareb													2.1–2.2	2.2	2	16
N./S. Negev	Mishash		4.9	1	3												
	Menuha																
Judea																	
C. Plain/ N. Negev	Negba					2.3–2.6	2.4	2	8								
	Yagur	3.8–4.3	4	3	4	2.5–3.1	2.8	9	5	2.9–3.1	3.0	2	3		2.8	1	7
N. Negev	Nezer					2.6–2.7	2.7	3	8								
	Shivta					2.8–3.1	2.9	3		2.8–3.1	2.9	3	3				
N./S. Negev	Tamar		4.6	1	1	2.1–3.2	2.9	5	8		2.9	1	1	2.0–2.6	2.4	3	5
	Avnon					3.0–3.1	3.0	2	8	3.0–3.1	3.1	2	6		2.3	1	8
	Zafit	4.0–5.2	4.7	3	6									2.3–2.8	2.5	3	13
	En Yorq.													2.3–2.4	2.3	2	9
S. Negev	Hevyon		3.8	1	10	2.0–3.2	2.6	3	10	2.8–3.2	3.0	2	14				
	Zihor					2.6–2.7	2.7	5	6								
	Gerofit						2.5	1	14						2.3	1	21
	Orashale						2.5	1	5								
Kurnub																	
C. Plain/ N. Negev	Yakhini					2.1–2.9	2.5	5	8	2.5–2.8	2.6	3	3		2.6	1	9
	Telamin					2.6–2.8	2.7	2	4								
N. Negev	Helez		3.7	1	5	2.1–3.2	2.8	7	7								
	Uza		4.0	1	5		2.7	1	2								
	Malhata																
	Dragot																
S. Negev	Zeweira																
	U. Hatira		3.6	1	7												
	L. Hatira																
	Samar																
Arad																	
C. Plain/ N. Negev	Haluza																
	B.–Sheva					2.6–2.7	2.7	2	6								
	Kidod														2.3	1	4
	Zohar					2.2–2.6	2.4	10	5								
N. Negev	Sherif	3.7–4.1	3.9	3	6	2.3–2.9	2.5	4	3		3.2	1	10				
	Daya					2.3–3.2	2.7	6	3								
	U. Inmar																
	Qeren																
	L. Inmar																
	Ardon					2.6–2.8	2.7	3	2								
Ramon																	
N. Negev	Mohilla																
	Saharonim																
	Gevanim						2.7	1	1								
	Raaf																
Negev																	
N. Negev	Zafir														1.9	1	1
	Yamin																
	Arqov																
	Saad																
Sinaf																	
	Zenifim																

mean λ 4.1 Φ 5 λ 2.7 Φ 5.9 λ 3.0 Φ 6 λ 2.4 Φ 9

m marks the mean and n the number of measured samples. The mean porosity (Φ) is given in %. No values are

the Sinaf, Negev, Ramon, Arad, Kurnub, Judea and Mt. Scopus Groups subdivided into lithotypes.

available for the Avedat Group and Sagiye Group. Outcrop samples are in italics. Dol Ls-dolomitic limestone.

The carbonatic sandstone (Zohar-1_5 sample, Zeweira Formation) displays 67% detrital components consisting mainly of quartz (95%) and of minor amounts of rock fragments (5%). Calcite constitutes basically the authigenic component besides minor iron-oxide and clay. The MTC is higher ($6.1 \text{ W m}^{-1} \text{ K}^{-1}$) than in the first samples. Also the saturated BTC is comparable high ($5.7 \text{ W m}^{-1} \text{ K}^{-1}$) due to a low porosity. The second carbonatic sandstone sample (Hltza-2_03, Zeweira Formation) shows comparable properties.

Table 2: Measured (saturated λ_{sat} and matrix λ_{m}) and calculated (from modal mineralogy) thermal conductivity of sandstones.

Table 2: Measured (saturated λ_{sat} and matrix λ_{m}) and calculated (from modal mineralogy) thermal conductivity of sandstones.

Stratigraphic Group	Fm.	Sample	Depth (m)	measured			modal mineralogy (volume fraction, V_i):										calculated	
				λ_{sat} ($\text{Wm}^{-1}\text{K}^{-1}$)	λ_{m} ($\text{Wm}^{-1}\text{K}^{-1}$)	ϕ (%)	qtz	fsp	cal	dol	hem	anh	gp	sme	org. m.		$\lambda_{\text{sat}_{\text{ari}}}$ ($\text{Wm}^{-1}\text{K}^{-1}$)	$\lambda_{\text{m}_{\text{ari}}}$ ($\text{Wm}^{-1}\text{K}^{-1}$)
Kurnu b	Hatira	Sinaf-1_04	447.7	3.5	4.2	10.3	0.47	0.22						0.31			4.3	4.7
	Hatira	Sinaf-1_07	494.6	4.2	4.8	6.5	0.53	0.10						0.37			4.7	5.0
	Zeweir a	Zohar-1_05	954.7	5.7	6.1	4.0	0.67		0.23		0.05			0.05			6.4	6.6
	Zeweira	Hltza-2_03	1431.2	5.1	6.5	10.1	0.68	0.02	0.18		0.12						6.6	7.3
Arad	Inmar	Daya-1_20	1639.8	6.6	7.2	3.7	0.70			0.09		0.15	0.06				6.4	6.6
	Upper Inmar	Daya-1_23	1736.5	5.0	7.8	17.7	0.95		0.05								6.3	7.5
	Inmar	Daya-1_27	1876.3	4.9	7.8	17.9	0.95			0.05							6.3	7.6
	Lower	Daya-1_28	1905.6	4.5	6.4	14.5	0.90		0.05		0.01				0.04		6.2	7.2

Thermal conductivity of minerals (λ_i) used in the calculation of bulk and matrix λ ($\lambda_{\text{sat}_{\text{ari}}}$; $\lambda_{\text{m}_{\text{ari}}}$): quartz $7.7 \text{ Wm}^{-1}\text{K}^{-1}$; feldspar $2.3 \text{ Wm}^{-1}\text{K}^{-1}$; calcite $3.6 \text{ Wm}^{-1}\text{K}^{-1}$; dolomite $4.7 \text{ Wm}^{-1}\text{K}^{-1}$; iron oxide (hematite) $11.3 \text{ Wm}^{-1}\text{K}^{-1}$; anhydrite $4.8 \text{ Wm}^{-1}\text{K}^{-1}$; gypsum $1.3 \text{ Wm}^{-1}\text{K}^{-1}$; smectite $1.9 \text{ Wm}^{-1}\text{K}^{-1}$; organic matter $0.3 \text{ Wm}^{-1}\text{K}^{-1}$ (Horai, 1971; Schön, 1996).

The Daya-1_20 sandstone sample (Upper Inmar Formation) displays the highest saturated BTC ($6.6 \text{ W m}^{-1} \text{ K}^{-1}$ at a porosity of 3.7%) as well as the highest MTC ($7.2 \text{ W m}^{-1} \text{ K}^{-1}$). The detrital component accounts for 70% of the rock matrix and is composed of quartz. The authigenic mineralogy is dominated by anhydrite; dolomite and gypsum are minor.

The pore filling minerals show a poikilitic texture (Figure 5a). Due to the presence of anhydrite and gypsum the sample can be characterized as evaporitic sandstone.

Typical quartzarenites are the Daya-1_23 (Upper Inmar Formation), Daya-1_27 and _28 samples (Lower Inmar Formation). In the Daya-1_28 sandstone sample the fine-grained detrital component makes up about 90% of the rock matrix. The major detrital component is quartz. Authigenic calcite can be identified, and black organic material is present along root channels. Although the quartz content is higher compared to the Daya-1_20 sample (Table 2), the saturated BTC and MTCs are lower. This can be explained by the presence of calcite cement, whose TC might be on the order of $3.6 \text{ Wm}^{-1}\text{K}^{-1}$ (Horai, 1971), and by the grain size of the detrital component, which here is smaller (Figure 5b) than in the Daya-1_20 sample. The Daya-1_27 sample comprises about 95% detrital component, basically consisting of

quartz (85%) and minor amounts of rock fragment (15%). Due to the occurrence of polycrystalline quartz, the sample is classified as a quartzarenite. It has a calcite cementation and the highest porosity of all analyzed samples (17.9%), which results in a relatively low saturated BTC ($4.9 \text{ W m}^{-1} \text{ K}^{-1}$) and a high MTC ($7.8 \text{ W m}^{-1} \text{ K}^{-1}$). The same applies to the fine-grained Daya-1_23 sandstone sample, which has a saturated BTC of $5.0 \text{ W m}^{-1} \text{ K}^{-1}$, and a high MTC of $7.8 \text{ W m}^{-1} \text{ K}^{-1}$. The detrital component of this sample consists of subrounded, moderately sorted quartz grains and lithics, probably from magmatic rocks. The authigenic component comprises two generations of cementation: first quartz overgrowth on the detrital grains and also as pore filling material and secondly calcite. In addition to the calcite matrix also idiomorphic calcite crystals appear. The detrital component covers 90% of the sample in which the lithics make up around 10%.

Figure 5: Thin section images of different sandstone types. (a) Sandstone with dolomite, anhydrite and gypsum cementation resulting in a TC of $6.6 \text{ W m}^{-1} \text{ K}^{-1}$; (b) sandstone with a calcareous cementation resulting in a TC of $4.6 \text{ W m}^{-1} \text{ K}^{-1}$.

To crosscheck the measured thermal conductivities, respective values were calculated based on the percentage of mineral constituents and porosity (Table 2, equation 3, 4). Comparison of measured and calculated saturated BTC shows a difference of $1.0 \text{ W m}^{-1} \text{ K}^{-1}$ on average with a range of $0.2\text{--}1.7 \text{ W m}^{-1} \text{ K}^{-1}$. Comparison of the MTCs reveals a smaller range ($0.2\text{--}0.8 \text{ W m}^{-1} \text{ K}^{-1}$) with an average value of $0.5 \text{ W m}^{-1} \text{ K}^{-1}$. The discrepancy is caused, on the one hand, by the determination of the percentage of mineral constituents and, on the other hand, by the choice of mineral TC from the literature. For example, there is large uncertainty in published quartz TC ranging from 6.5 to $13.0 \text{ W m}^{-1} \text{ K}^{-1}$ (Schön, 1996). MTC of $7.8 \text{ W m}^{-1} \text{ K}^{-1}$ measured on Daya-1_23 and Daya-1_27 sandstones, reflecting a multi-mineral

assemblage including also minerals with a TC lower than quartz, suggests that the quartz value ($7.7 \text{ W m}^{-1} \text{ K}^{-1}$; Horai, 1971) used in the calculation is too low to reproduce the measured MTC.

In summary, the mean measured MTC of quartzarenite is, as expected, the highest ($7.3 \text{ W m}^{-1} \text{ K}^{-1}$) followed by the carbonatic sandstone value ($6.3 \text{ W m}^{-1} \text{ K}^{-1}$) and the argillaceous sandstone value ($4.5 \text{ W m}^{-1} \text{ K}^{-1}$). Figure 6 shows for two lithotypes the impact of pore fluid (air versus water) on the measured BTC. The increase of ratio with increasing porosity indicates that the type of pore fill does influence the BTC especially at porosity values $>5\%$. The anisotropy between the TC measured parallel and perpendicular to bedding ($\lambda_{\parallel} / \lambda_{\perp}$) is in general nonexistent or small (<1.2). Most samples scatter around a ratio of 1.0.

Figure 6: Ratio of water-saturated and dry measured TC cross plotted versus porosity (in %). (a) sandstone samples, (b) limestone samples. $\circ$ Arad Group, $\blacksquare$ Kurnub Group, $*$ Judea Group.

5.2 Thermal conductivity of geological formations

The stratigraphic chart applied in this study for southern Israel is predominantly based upon chronostratigraphic and biostratigraphic information and to a minor extent upon the lithologic composition of the different units. Consequently, it needed to be investigated whether mean formation thermal conductivities for southern Israel, determined from the sampled rock, would represent the subsurface geology and could be universally applied in geothermal studies. For this purpose, 30 well sections (Figure 7) were analyzed with respect to variable formation lithology resulting from facies changes that occur from the western to the eastern Negev as well as on a small regional scale. Figure 8 shows, exemplarily for four formations, the change across the area of individual lithotypes making up the formation together with the resulting formation TC. The latter was calculated as a weighted mean on the basis of lithotype TC (Table 3) according to:

$$\bar{x} = \frac{\sum_{i=1}^n t_i \cdot \lambda_i}{\sum_{i=1}^n t_i} \quad (7)$$

where λ is the TC of the lithotype and t is the proportion of lithotype in (%).

Figure 7: Wells from which lithostratigraphic information was used to characterize changes in composition and thickness of the stratigraphic formations across southern Israel. a) Western Negev, b) Central Negev, c) Eastern Negev. Numbers denote well IDs as used in Figure 8.

All four formations show a remarkable change in mean TC across the studied area. TC of the Ardon Formation (Arad Group), composed of limestone, dolomite and shale, has a range of 2.7–4.1 W m⁻¹ K⁻¹ (mean 3.2 W m⁻¹ K⁻¹) and those of the Sherif Formation (Arad Group), mainly composed of limestone and shale, of 2.2–3.9 W m⁻¹ K⁻¹ (mean 2.9 W m⁻¹ K⁻¹). For the latter, values are highest in sections partly comprised of sandstone. The Zeweira Formation (Kurnub Group), made up of sandstone and shale, shows a TC of 2.8–5.3 W m⁻¹ K⁻¹ (mean 3.9 W m⁻¹ K⁻¹) depending on the dominating rock type.

Figure 8: Changes in lithology (in %) between wells exemplarily shown for the Ardon, Zeweira, Sherif and Hevyon Formations in the northern Negev. Numbers below the bars are the well IDs as used in Figure 7. The curve plotted across the bars shows the changes in formation thickness (in m). Numbers above the bars indicate the TC ($\text{Wm}^{-1}\text{K}^{-1}$) calculated from the percentages of the respective lithotypes in each well. argil. Ss-argillaceous Sandstone; limy Ss-limy Sandstone; no Inf.-no Information.

Table 3: The mean TC (m) of lithotypes determined in this study (saturated rocks) and as comparison determined by Eckstein and Simmons (1978, denoted with E & S).

λ this study			λ E & S study		
Lithology	n	m ($\text{Wm}^{-1}\text{K}^{-1}$)	Lithology	n	m ($\text{Wm}^{-1}\text{K}^{-1}$)
Dolomite	15	4.1	Dolomite	24	3.8
Limestone	75	2.7	Limestone	58	2.2
Dol Ls	14	3.0	Dol Ls	18	3.1
Marlstone	16	2.4	Limy Sh	2	1.3
Claystone	22	1.9	Shale	4	1.1
Shale	10	1.9	Marl and Chalk	4	1.8
Sandstone	16	5.6		12	1.3
carb. Ss	8	4.9	Ss and Siltstone	29	2.8
argil. Ss	11	3.6		27	2.2
Arkose	11	3.0			
Siltstone	18	2.9			
Chalk	5	1.8			
Gypsum	2	1.3			
Anhydrit	1	5.0			
Chert	3	5.1			
Coal	1	0.6			
Igneous	6	2.4			

Numbers in italics indicate measurements on cuttings. n is numbers of samples. Dol Ls-dolomitic limestone, Sh-shale, carb. Ss- carbonatic sandstone, argil. Ss- argillaceous sandstone, Igneous-igneous rock.

The Hevyon Formation (mostly carbonates, Judea Group) displays a TC of $2.5\text{--}3.6 \text{ W m}^{-1} \text{ K}^{-1}$ (mean $2.9 \text{ W m}^{-1} \text{ K}^{-1}$). The values are highest where the dolomite dominates over limestone. Altogether a highly variable TC is observed within the formations indicating that the application of a regionally undifferentiated average formation TC would cause a false quantification of this parameter.

5.3 Radiogenic heat production and heat budget of the sedimentary veneer

To get an overall understanding of the q_s in a sedimentary basin and the temperature gradient, the amount of heat generated by the sediments themselves is an important component, which needs to be quantified. Especially clastic sediments can provide a substantial proportion of the q_s where sediment basins are deep.

The gamma logs used for heat-production calculation cover stratigraphically the Jurassic and Cretaceous and, in the Coastal Plain area, also the Pliocene (Cenozoic). Table 4 lists the results for stratigraphic formations observed at 9 well locations. It is obvious that the mean values do not exceed $1.4 \mu\text{W m}^{-3}$ and that the majority of values is $<1.0 \mu\text{W m}^{-3}$. The lowest values are observed in carbonates as for example in the Shederot Formation (mostly

argillaceous limestone) and the Yaquim Formation (limestone). Slightly higher is the value in formations of mixed lithology, as for example the Malhata Formation (sandstone, shale and limestone) or the Kidod Formation (shale and marlstone). The highest values pertain to formations composed of bituminous shales and phosphate-rich sediments (e.g., formations of the Mt. Scopus Group). Mean values calculated for the main stratigraphic groups show only small differences. The Saqyie and Mt. Scopus Formations display values of $0.9 \mu\text{W m}^{-3}$, the Kurnub Formation of $0.7 \mu\text{W m}^{-3}$ and the Judea and Arad Formations of $0.5 \mu\text{W m}^{-3}$, respectively.

The RHP of Table 4 then was used to calculate the heat budget (heat flow) for each stratigraphic group and finally for the entire sedimentary section above the crystalline basement. For stratigraphic units older than the Jurassic, for which no well logs were available, lithotype values from the literature (Vila et al., 2010 and references therein) were applied as follows: carbonates $0.4 \mu\text{W m}^{-3}$, sandstone-wackestone $0.9 \mu\text{W m}^{-3}$, and mudrocks $1.4 \mu\text{W m}^{-3}$.

Table 4: RHP (range and mean value in $\mu\text{W m}^{-3}$) of stratigraphic formations from nine wells. The mean is

Well ID	PT 2	Plm 1		H 34	Htz 2		
Saqiye Gr.		mean 0.9 μWm^{-3}					
Yafo		0.6–1.7		1.3			
Afiq		0.4–1.5		1.1			
Mavqim		0.2–1.4		0.5			
B.–Guvrin		0.1–1.8		0.9			
Mt. Scopus Gr.		mean 0.9 μWm^{-3}					
Ghareb							
Mishash							
Menuha							
En Zetim					0.3–0.9		0.5
Judea Gr.		mean 0.5 μWm^{-3}					
Bina	0.1–0.5	0.3			0.2–0.4		0.3
Negba	0.0–1.6	0.4			0.2–0.7		0.3
Yagur	0.1–1.8	0.4		0.5–1.8	0.8	0.2–1.5	0.5
Talme-Yafe				0.7–1.2	0.9		
Zihor							
Nezer							
Shivta							
Gerofit							
Orashale							
Derorim							
Tamar							
Avnon							
Zafit							
Yorqeam							
Hevyon							
Kurnub Gr.		mean 0.7 μWm^{-3}					
Yakhini	0.0–1.3	0.4		0.7–1.0	0.8	0.2–1.4	0.7
Yaqum	0.4–0.9	0.5	0.1–1.9	0.6			
Uza							
Malhata							
Dragot							
Zeweira						0.4–1.2	0.8
Telamim	0.2–1.6	0.3	0.0–2.2	0.4	0.6–1.0	0.8	0.3–1.0
Zeweira							0.6
Arad Gr.		mean 0.5 μWm^{-3}					
Haluza							
Beersheva			0.0–2.4	0.4			
Kidod			0.1–1.8	0.9			
Nir'am	0.2–1.0	0.4					
Zohar	0.1–0.6	0.3	0.1–1.7	0.3			
Karmon	0.4–1.0	0.8	0.2–1.4	0.4			
Shederot	0.2–1.2	0.3	0.2–0.8	0.3			

calculated by averaging values over respective depth intervals. For location of wells see Figure .1.

Hz 1	B 1			Daya 1		EO 15		Paran 28	
0.9–2.2	1.4							0.2–2.6	1.3
0.5–1.1	0.6	0.8–1.3	1.1					0.4–2.6	1.2
0.3–0.7	0.5	0.6–1.0	0.7					0.4–2.5	1.1
0.1–0.4	0.2								
		0.0–0.9	0.3			0.2–1.0	0.3	0.2–0.7	0.4
						0.1–1.3	0.2		
								0.2–1.4	0.4
								0.2–1.4	0.7
						0.3–1.5	0.6		
0.3–0.9	0.5	0.8–0.1	0.5			0.4–1.6	0.8		
0.2–0.9	0.5			0.2–0.4	0.3	0.1–1.6	0.4	0.4–1.6	1.0
0.2–0.9	0.4	2.0–0.2	0.6	0.2–0.4	0.3	0.3–1.3	0.6	0.4–1.1	0.5
0.3–0.8	0.6			0.2–0.5	0.3	0.3–1.0	0.5		
0.2–1.9	0.6			0.2–1.1	0.5	0.2–1.7	0.6		
0.2–1.5	0.6			0.2–1.7	0.8				
0.3–1.9	0.9			0.2–1.7	0.9				
0.3–1.5	0.6			0.4–1.5	0.9				
0.1–1.7	0.8			0.2–1.7	0.6				
0.4–1.1	0.7								
0.2–1.9	0.7								
0.2–1.4	0.6								
				0.2–0.8	0.4				
				0.3–1.0	0.8				
				0.3–0.8	0.4

Figure 9: Generated heat (mW m^{-2}) of the stratigraphic groups contributes to q_s in the 5.8-km-thick sedimentary veneer of the Coastal Plain area. The thicknesses of stratigraphic groups are from the Helez Deep 1A well.

Figure 9 shows the results for the Helez Deep 1A well (Figure 1), which penetrates the whole sedimentary sequence down about 5800 m, which is close to the basement. The section generates a heat flow of 3.5 mW m^{-2} . However, it can be expected that the total heat production and hence the heat flow generated in the sediments varies slightly across southern Israel due to variable lithology and due to changes in total sediment thickness. For example, the sedimentary cover overlying

the crystalline basement thins towards the outcrops of basement rocks in the northern Gulf of Elat and the Timna area. To the north-west, the sedimentary cover thickens up to about 7 km (Rybakov and Segev, 2004) providing a maximum heat-flow component in the sediments of 4.2 mW m^{-2} , if geological data from the Helez Deep 1A well are extrapolated to the area.

6 Discussion

6.1 Implication for the determination of surface heat flow

As part of a reconnaissance heat-flow study conducted for Israel, TC of sedimentary rocks was measured with a divided bar apparatus on drill core samples and with a needle probe on cutting samples (Eckstein and Simmons, 1978). The data represent measurements under dry conditions only. If the Eckstein and Simmons data summarized for particular lithotypes (Table 3) are compared with the data of this study (also Table 3), it becomes obvious that the new data are higher than most previous values. This can be expected taking the different measuring conditions (dry versus saturated) into account. Only the values of dolomitic limestone are similar in the two data sets, probably because of the low porosity of this rock type and thus less difference between water-saturated and dry TC measurements. Some lithotype values in the two data sets are difficult to compare, because Eckstein and Simmons merged data of chalk and marlstone on the one hand and of sandstone and siltstone on the other hand to two single groups. However, the sandstone/siltstone group has values that are

lower than the sandstone values determined in this study. They rather represent values typical for siltstone.

The effect that the application of the new TC data has on calculated heat-flow density is exemplarily shown for the Daya 1 well location (Figure 10) reported by Eckstein and Simmons (1978). Table 5 lists depth intervals, interval temperature gradients, major lithology and interval TC used in the previous study in addition to TC from this work. The new thermal-conductivity values were applied taking into consideration the location of water table. Thus thermal conductivities for dry rocks were assigned to intervals above the water table and values for saturated rocks (Table 3) below the water table, respectively.

The resulting new interval heat-flow values are generally higher than previous values. The increase is especially large in the interval 350–440 m, for which an unrealistically high value on the order of 84 mW m^{-2} , opposed to 53 mW m^{-2} , would result, if the interval is considered as a pure sandstone interval and the saturated TC value is applied. Another outlier of the trend is the small subinterval 360–370 m selected by Eckstein and Simmons, for which the interval heat flow remains low (46 mW m^{-2}) even after applying the new TC data for siltstone. We interpret the low temperature gradient as arbitrary being an artifact of the large temperature recording interval (10 m). In a refined new approach, we modified the selection of depth intervals for heat flow by better honoring the lithological changes in the lithostratigraphic section (Figure 10). Consequently, the

three new intervals also honor better the temperature gradient pattern in the borehole. In addition, the new approach uses for each interval a TC that originates from the percentages of different sublithotypes making up the depth interval instead of using a single default lithotype TC (Table 5).

Figure 10: Heat flow determined in the Daya 1 well, based on a temperature log from Eckstein and Simmons (1978). Temperature and temperature gradient plots are shown together with a lithostratigraphic section. Blank intervals in the

section indicate no information. Lines in gradient plots mark intervals of gradient calculation. Numbers attached are the calculated interval temperature gradients ($^{\circ}\text{C km}^{-1}$). Black lines are the intervals used in this study; red lines mark the intervals used by Eckstein and Simmons (1978). Depth of water table (triangle) is shown.

The resulting heat-flow values again are consistently higher than the previous ones, varying from 52 to 62 mW m^{-2} (mean 57 mW m^{-2}). In addition, the values show less diversity than the previous interval values. The new mean heat flow is in contrast to the original mean value of 48 mW m^{-2} (Eckstein and Simmons, 1978) determined in the Daya 1 well. The new heat-flow value is even more in contrast to what is regarded by these authors as most reliable value for the site (about 37 mW m^{-2}).

Table 5: Geothermal data of the Daya 1 borehole.

Well Daya 1												
E and S study												
		this study					new approach					
Interval	Γ	Lith.	λ	q	λ	q	Interval	Γ	Lith.	λ	q	
(m)	($^{\circ}\text{C km}^{-1}$)		($\text{W m}^{-1}\text{K}^{-1}$)	(mW m^{-2})	($\text{W m}^{-1}\text{K}^{-1}$)	(mW m^{-2})	(m)	($^{\circ}\text{C km}^{-1}$)	(%)	($\text{W m}^{-1}\text{K}^{-1}$)	(mW m^{-2})	
200–250	21.8	Ls	2.1	46.7	2.4	52.3	250–330	21.6	Dol	24.5	2.4	51.8
250–260	26.6	M	1.3	34.6	2.1	55.9			Dol Ls	12.0		
260–330	21.8	Ls	2.1	46.7	2.4	52.3			Ls	33.0		
350–440	19.9	Ss	2.7	52.9	4.2	83.6			Sh	22.7		
360–370	16.0	Si	2.2	34.9	2.9	46.4			M	7.8		
							360–410	18.8	argil. Ss	31.8	3.3	61.9
									carb. Ss	6.3		
									Dol	23.8		
									M	14.3		
									Cl	14.3		
									Ls	7.1		
									Coal	2.4		
							430–440	20.0	argil. Ss	50.0	2.9	58.0
									Cl	50.0		
mean											57.3 $\pm$ 4	

Results from Eckstein and Simmons (1978, E and S) are compared with results from this study using the same depth intervals and interval temperature gradients (Γ), but different TC (λ) and with data from a new approach using different depth intervals of gradient and heat-flow calculation together with a more detailed lithology for λ of the interval. Heat-flow density (q , in bold) is the mean value with 1σ -standard deviation. Abbreviated lithology Dol-Dolomite, Ls-Limestone, Sh-Shale, M-Marl, Cl-Clay as in Table 4.

In general, a revisit of the q_s of southern Israel, reflecting crustal conductive heat flow, is desirable. Such a study, focused on an exclusion of hydrological perturbation of heat flow, could also investigate whether there is a regional trend of changes in q_s according to changes in crustal structure and composition.

6.2 Implication for the utilization of geothermal energy

The temperature and the hydraulic rock properties at depth are major parameters on which the type of utilization of geothermal energy depends. High porosity/permeability of geologic formations allow for a hydrothermal use of geothermal energy, whereas low porosity/permeability requires a conditioning of the target rocks to enhance its hydraulic performance. These so-called Engineered or Enhanced Geothermal Systems (EGS) would allow, if successfully generated, a universal heat mining not only including tight sedimentary formations but also igneous or magmatic rocks beneath a sedimentary basin.

The porosity data measured in this study in conjunction with TC show for southern Israel individual sedimentary formations of high porosity but yet unknown temperature range. It is therefore desirable to delineate on a regional scale the temperature conditions at depth. The new data on thermal rock properties and q_s presented in this study can be used to calculate temperature for depths beyond logging data and beyond temperature data available from drill-stem testing.

We followed this approach by calculating temperature (T) at depth (z) using the Fourier equation (2.6) as follows:

$$T_z = T_s + z \frac{q_s}{\lambda} \quad (8)$$

where T_s (°C) is the surface temperature, λ (W m⁻¹ K⁻¹) the TC, and q_s (mW m⁻²) the surface heat flow.

Considering the TC of stratigraphic formations, calculated by taking the proportion of different rock types into account, empirical temperature profiles are calculated for five well locations (shown in Figures 3 and 4), by summing the results of the incremental temperature calculations across individual layers of uniform conductivity:

$$T_z = T_s + \sum_i^n \left[(z_i \frac{q_s}{\lambda_i}) \right] \quad (9)$$

Where T_s (°C) and q_s (mW m⁻²) are the temperature and heat flow at the surface, z_i is the thickness of unit i and λ_i (W m⁻¹ K⁻¹) is the TC of unit i . An annual average surface temperature of 20 °C and three different values of q_s (50, 55, 60 mW m⁻²) are used.

The temperature profiles are calculated to the top of basement (Figure 11). Four of the

boreholes reach the basement between 1613 and 6093 m. The section of the 4019-m-deep Hazerim 1 well, which bottoms in the Ramon Group, is extended to the basement (at 4800 m depth) using the lithostratigraphic data from Gvirtzman (2004). In addition, temperatures from drill-stem tests obtained in the archives of the Geological Survey of Israel were plotted.

Figure 11: Geotherms calculated for three heat-flow scenarios ($50, 55, 60 \text{ mW m}^{-2}$) for wells reaching the basement. For the location of the wells see Figure 1.

It is obvious that the geotherms based on the 55 and 60 mW m^{-2} best approximate the measured individual temperature drill-stem-test data. All logs show some gradient breaks due to different TC and thickness changes of individual geological formations. Therefore, different temperatures are prognosed at a fixed depth. For example, at 3 km, the 60 mW m^{-2} geotherm shows highest temperature (94°C) at the Helez Deep 1A well location where the sedimentary cover above the basement is thickest, followed by the Hazerim 1 well (85°C) and the Zohar Deep 8 well (87°C). In the Ramon 1 well a temperature of 78°C is predicted. In the deepest parts of the sedimentary basin, in the Coastal Plain area, temperatures at the top of the basement at about 6 km are 160°C .

In summary, these first observations indicate temperatures in the sedimentary cover of

between 100 °C and 120 °C at a depth of 3500–4500 m, if a q_s at the upper bound of range is considered. From this estimate it can be concluded that a production of electric power in the sedimentary section would be possible, but only in the deepest parts of the basin. Temperature predictions for areas where the sedimentary cover is thin and energy production is envisioned in basement units require knowledge of the TC of the igneous and metamorphic rocks and the anisotropy tensor of TC of these rocks. For a concluding evaluation of the geothermal potential in Israel further exploration is needed targeted on petrophysical and hydrothermal properties of sediments and basement rocks as well as on the hydrological regime in aquifers that may overprint the thermal conditions by heat diffusion considered in this study.

7 Conclusions

TC and RHP are important thermal parameters in geothermal studies. This paper shows that the TC of the porous sediments of southern Israel strongly depends on whether it was measured on dry (air-filled pores) or water-saturated samples. The difference in values becomes higher the higher the rock porosity. In addition to porosity, TC is most sensitive to the mineral assemblage of a rock and in turn to facies changes in the sedimentary veneer. Thus, if no understanding is developed for depositional and diagenetic processes giving rise to the present-day characteristics of geological formations, an extrapolation of TC from one location to another seems conflicted with large errors.

Without sufficient measurements of TC, a proper evaluation of conductive q_s (equalized as terrestrial heat flow) in boreholes is hampered, even if the measured temperature log is of high quality and not afflicted by thermal perturbations due to fluid flow. On the other hand, careful interpretation of temperature logs and hence interval temperature gradients calculated from the log can assist in the evaluation of thermal properties in the sedimentary cover as the gradients reflect first order the lithology of a section.

The paper exemplarily showed in the case of the Daya 1 well, how different approaches and data affect the interpretation of an available temperature log for the determination of heat flow. The large range of suggested values (37 mW m⁻²; Eckstein and Simmons, 1978 and 57 mW m⁻²; this study) are of profound evidence for the need in investing in laboratory measurements of TC and in lithological characterization of the measured borehole section. As the RHP of the sedimentary cover in southern Israel, comprising mostly carbonates, is relatively low (max. 4 mW m⁻²), the basement heat flow practically equals the q_s in the error range of determination.

The range of surface heat-flow values previously reported for southern Israel is broad (31–85 mW m⁻², Eckstein and Simmons, 1978) and can hardly be explained by variable thermal properties of the upper crust or by different geodynamic settings. It is assumed that part of this deviation is related to the aforementioned complexities in the determination of heat flow. However, the careful inspection of the logging results and the use of TC, honouring lithological changes in the section, allow for high-quality and thus reliable values of conductive heat flow.

Interestingly, the new q_s of 57 mW m⁻² reported for the Daya 1 in this study is similar to the value determined in a cluster of five boreholes located farther east in southern Jordan (Förster et al., 2007). Further heat-flow data need to substantiate whether this value is typical for southern Israel.

The new data of TC constitute an important database for the modeling of the deep thermal field beyond the depth of measured temperature data. Together with data on hydraulic transport properties (effective porosity and permeability) the prognosed temperatures allow a delineation of the type of geothermal use. Calculated temperature profiles for southern Israel showed that hydrothermal resources maybe used where the sedimentary cover is thick. For the use of higher temperature the basement must be considered and therewith an EGS concept. Further studies on the values and the pattern of conductive heat flow across Israel can substantially add knowledge not only to lithosphere geothermics but also for the utilization of geothermal resources.

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