

The surface heat flow of the Arabian Shield in Jordan

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Received 25 January 2006; received in revised form 7 August 2006; accepted 11 September 2006

Abstract

Surface heat flow in southern Jordan (western part of the Arabian Plate) was determined in a dense cluster of five, up to 900-m-deep boreholes that have encountered sedimentary rocks of Paleozoic (Ordovician and Silurian) age. These rocks are underlain by an igneous and metamorphic basement, which has been studied for its radiogenic heat production, along the eastern margin of the Dead Sea Transform (DST) fault system. The heat flow, calculated from continuous temperature logs and laboratory-measured thermal conductivity of drillcores and surface samples, averages to $60.3 \pm 3.4 \text{ mW m}^{-2}$ and contrasts the common view of the late Proterozoic-consolidated Arabian Shield constituting a low heat-flow province of $\leq 45 \text{ mW m}^{-2}$. Although only characterizing an area of about 300 km^2 , this average is unlikely representing a positive local anomaly caused by voluminous HHP granites/rhyolites at shallow depths. Instead, a heat flow of 60 mW m^{-2} is considered a robust estimate of the Phanerozoic conductive surface heat flow not only for Jordan, but for the Arabian Shield in areas unaffected by younger reactivation. The large variation in conductive heat flow ($36\text{--}88 \text{ mW m}^{-2}$) previously observed in Jordan, southern Syria, and Saudi Arabia is irreconcilable with their broad similarity in lithosphere structure and composition and rather reflects a combination of factors including low-quality temperature data and insufficient knowledge on thermal rock properties. © 2006 Elsevier Ltd. All rights reserved.

Keywords: Heat flow; Thermal conductivity; Radiogenic heat production; Jordan; Arabian Shield

1. Introduction

The conductive surface heat flow is essential for understanding the thermal structure, composition, and seismicity of lithosphere sections. One of the major tectonic units, for which the heat-flow pattern is only poorly constrained, is the Arabian Plate (Fig. 1a). The Arabian Plate consists of the late Proterozoic Arabian Shield bounded to the east by a Phanerozoic platform. The shield formed principally during the Pan-African orogeny ($\sim 900\text{--}530 \text{ Ma}$) by suturing of juvenile arc terrains (e.g., Stoeser and Camp, 1985; Jarrar et al., 2003; Stein, 2003). It occupies the western part of the plate and mainly encompasses the exposed Pan-African basement region. Parts of the shield are unconform-

ably overlain by platform sediments, such as in Jordan (e.g., Stoeser and Frost, 2006). The shield remained a stable continent for most of its history until the opening of the Red Sea rift at about 30 Ma (Bohannon et al., 1989) and the formation of the DST starting at about 17–20 Ma (Freund et al., 1970; Bartov et al., 1980; Sobolev et al., 2005). Thermal effects associated with these young geodynamic processes have not yet reached the surface owing to the time/length scale of thermal diffusion through the lithosphere (e.g., Turcotte and Schubert, 2002).

The few previous data on conductive surface heat flow in the Arabian Shield and its immediate vicinity range between 36 and 88 mW m^{-2} (Gettings, 1982; Gettings and Showail, 1982; Galanis et al., 1986; Matviyenko et al., 1993; Milner, 1998). They mainly originated from shallow temperature data measured for a geothermal reconnaissance or constitute by-products of well logging

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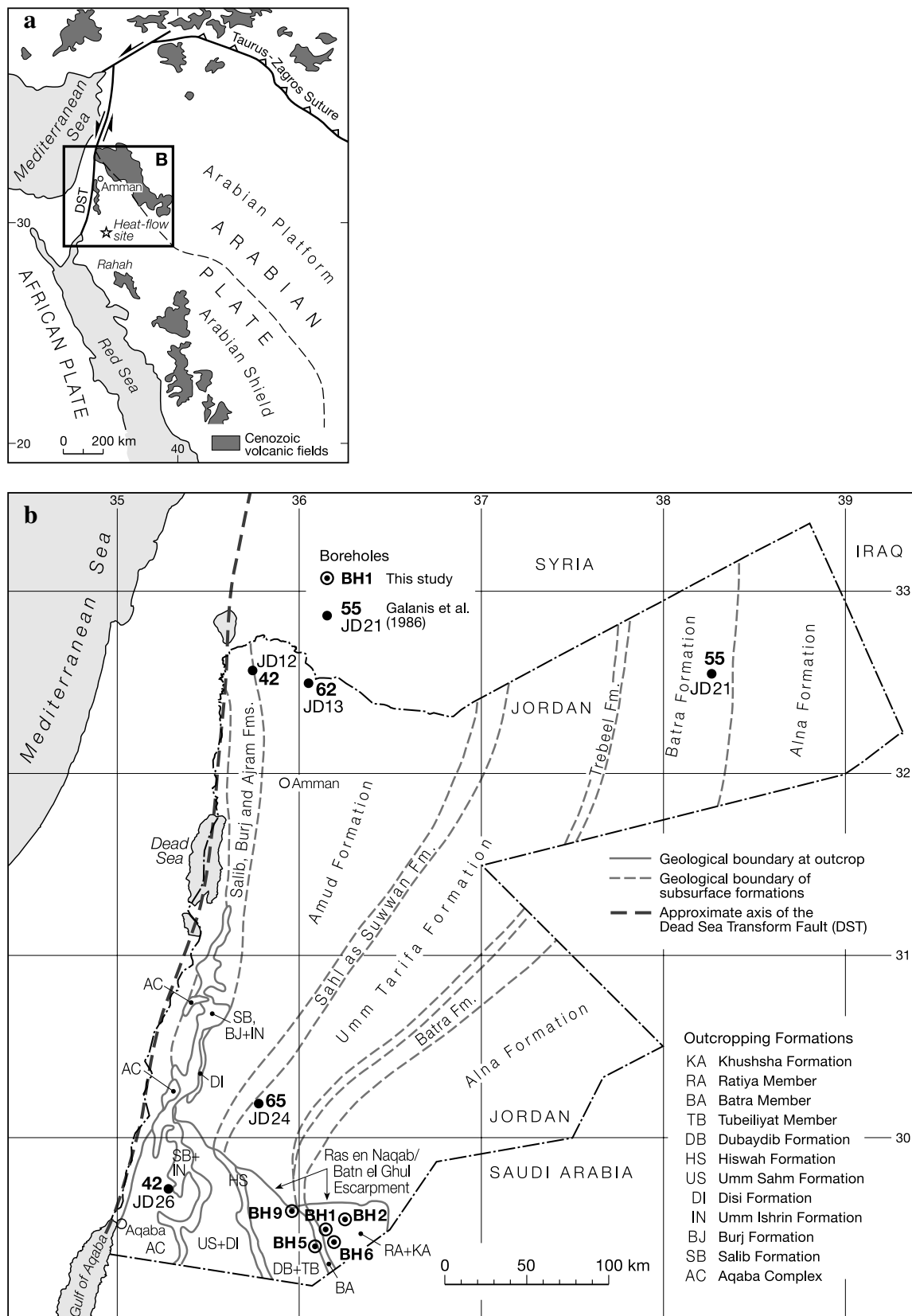


Fig. 1. (a) A simplified map showing the main tectonic features of the western part of the Arabian Plate; (b) regional map of Jordan showing the distribution of the Lower Paleozoic surface and subsurface formations (modified after Andrews, 1991) and the approximate position of the DST fault system. Location of boreholes (BH1–BH9, this study; JD12–JD26, Galanis et al., 1986) is marked. Bold numbers adjacent to borehole location denote heat flow in mW m^{-2} . Stratigraphic description is according to Table 1.

in hydrocarbon exploration, both not targeted explicitly for the determination of heat flow characterizing lithosphere regimes.

In this paper, new data on surface heat flow are reported that are based on thermal measurements in a tight cluster of five deep boreholes penetrating consolidated Paleozoic sediments in southern Jordan (Fig. 1b). This research was conducted in the frame of the multidisciplinary project DESERT, which required an in-depth knowledge of the thermal conditions on both sides of the DST (DESERT Group, 2004; Sobolev et al., 2005; Petrulin and Sobolev, 2006). Inferences on the deep thermal field of the Arabian Shield (Förster et al., 2004a) form the subject of a companion paper (Förster et al., 2007).

2. Geological setting

The five boreholes available for heat-flow determination are located south of the Ras en Naqab/Batn el Ghul Escarpment, in the Southern Mountainous Province (Bender, 1974), between 90 and 120 km east of the axis of the DST (Fig. 1b). The area is characterized by a relatively flat land surface, which makes a correction of heat

flow for topographic effects unnecessary. In this region, also named the Southern Desert, sedimentary rocks of the Lower Paleozoic are exposed, gently dipping towards the north and northeast. These sediments unconformably overlie the Pan-African magmatic–metamorphic basement outcropping in southwest Jordan.

Three subdivision schemes of the Paleozoic sedimentary formations in Jordan are in use. Because the thermal conductivity was determined on both outcrop rocks and subsurface (drillcore) samples, this paper considers the surface stratigraphy specifically established for the Southern Desert outcrop area and the Natural Resources Authority's subsurface-division nomenclature (Table 1). In the following discussion, the lithology of the Paleozoic sediments, from which samples were taken in this study, is briefly described from the youngest to the oldest formation (after Andrews, 1991):

2.1. Khushsha Sandstone Formation

Khushsha Sandstone Formation consists of a thick-bedded micaceous siltstone and fine-grained sandstone. In general, the subsurface equivalent, the Alna Formation,

Table 1
Stratigraphy of Lower Paleozoic sediments in Jordan (modified from Masri, 1988; Powell, 1989)

Age			Group	Surface Formations	Surface Members	Subsurface Formations (Petroleum Division Nomencl.)	Subsurface Formations (Subsurface Division Nomencl.)
PALEOZOIC	SILURIAN	Llandovery	KHAYIM	Khushsha Sandstone		Khushsha Sandstone	Alna
					Ratiya Sandstone		
	ORDOVICIAN	Caradoc-Ashgill		Mudawwara Sandstone	Batra Mudstone	Mudawwara Clay	Batra (Hot Shale)
					Tubeiliyat Sandstone		Risha
		Llandeilo		Dubaydib Sandstone	Upper (DB 3)	Dubaydib Sandstone	Umm Tarifa
					Middle (DB 2)		
					Lower (DB 1)		
		Llanvirn		Hiswah Sandstone	Upper (HS 2)	Hiswah Clay	Sahl As Suwwan
					Lower (HS 1)		
	CAMBRIAN	Tremadoc-Arenig	RAM	Umm Sahm Sandstone		Umm Sahm Sandstone	Amud
				Disi Sandstone		Disi Sandstone	
		Upper		Umm Ishrin Sandstone		Umm Ishrin Sandstone	Ajram
		Middle		Burj Dolomite-Shale		Burj Dolomite-Shale	Burj
		Lower		Salib Arkosic Sandstone		Salib Arkosic Sandstone	Salib

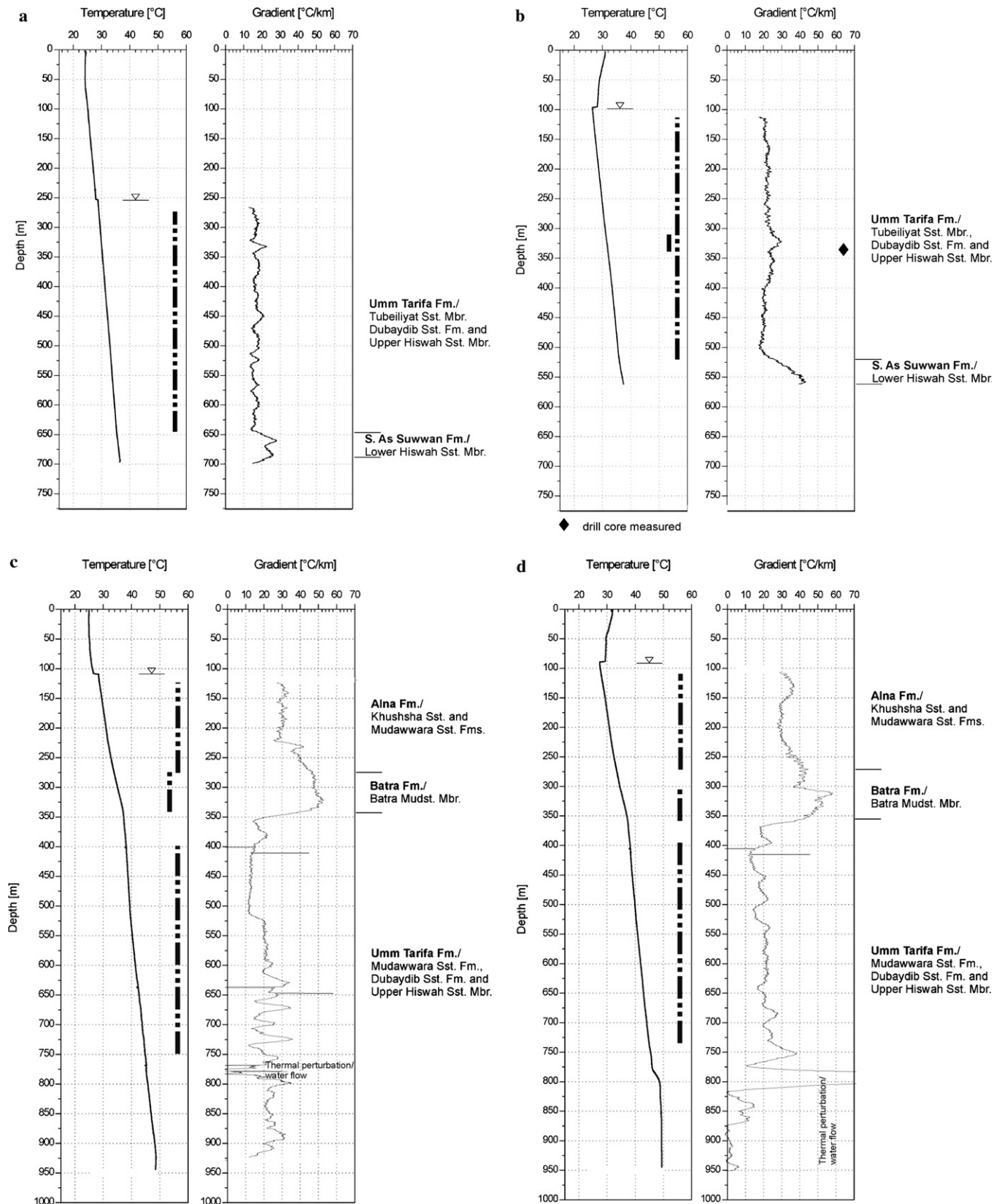


Fig. 2. Well-logging data used for heat-flow determination. (a) BH9 borehole, (b) BH5 borehole, (c) BH1 borehole, (d) BH6 borehole, and (e) BH2 borehole. Note the strong resemblance of temperature-gradient pattern and gamma-ray values in (e). The change in gamma-ray response at 849 m indicates the depth of borehole casing. Temperature values were smoothed by a 1-m-running average; the temperature gradients were processed with an 11-point-mean filter. Depths of water table (triangle) and depth intervals of heat-flow determination (stippled lines) are shown in the temperature plot. Subsurface stratigraphy (bold) and surface stratigraphy are denoted.

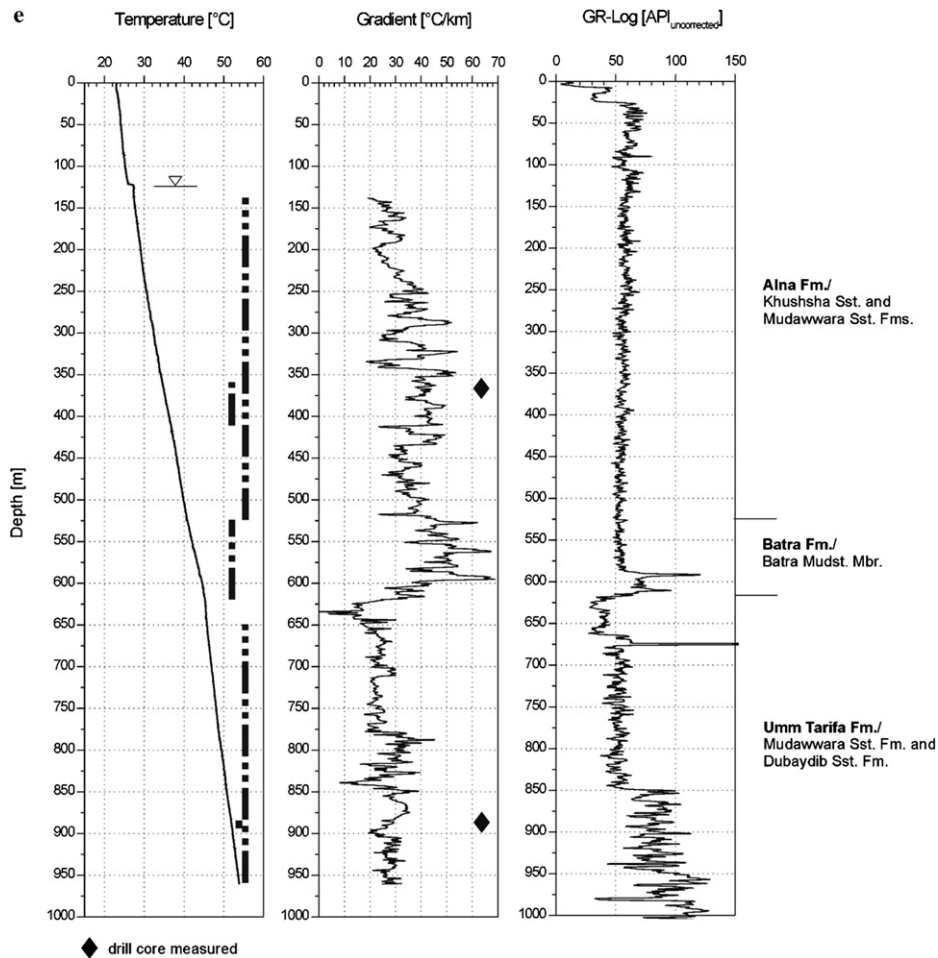


Fig. 2 (continued)

is more fine-grained resembling a siltstone interbedded with claystone. Typically, the Alna Formation has a high gamma-log response similar to that of the Batra Formation. The boundary of the Alna Formation with the underlying Batra Formation is gradational, from interbedded siltstones and claystones to shale.

2.2. Mudawwara Sandstone Formation

Mudawwara Sandstone Formation comprises three members. The lower member, the Tubeiliyat Sandstone (~24% porosity), consists of hummocky, cross-bedded sandstones interbedded with shales and equals lithologically the Upper Dubaydib Sandstone. The middle member is the Batra Mudstone. In boreholes, the laterally equivalent Batra Formation can be divided into two units: a thin, basal, euxinic shale (not developed everywhere), and a claystone, which grades up into the interbedded sandstone/claystone lithology of the overlying Alna Formation. The shale of the lower unit is black, fissile, highly radioactive, and carbonaceous. This shale bed has a distinctive high gamma-log response (Fig. 2e), which contrasts the low-gamma sandstones below and the normal-gamma shales above. The upper member of the Mudawwara Sandstone Formation, the Ratiya Sand-

stone (21–26% porosity), observed at outcrop, consists of finely laminated, micaceous sandstone interbedded with micaceous siltstone and silty mudstone. It is lithologically similar to the overlying Khushsha Sandstone Formation.

2.3. Dubaydib Sandstone Formation

In outcrops, the Lower Dubaydib Sandstone Formation consists of interbedded fine-grained micaceous sandstone and siltstones. The Middle Dubaydib Sandstone Formation is comprised of channel sandstones and micaceous siltstone, the Upper Dubaydib Sandstone Formation consists of hummocky, cross-bedded sandstones interbedded with shales. Sandstone porosity is in the order of 17–24%. In subsurface, the equivalents of the surface Dubaydib Sandstone Formation, the Upper Hiswah Sandstone Formation, and the Tubeiliyat Sandstone Member are collectively referred to as Umm Tarifa Formation.

2.4. Hiswah Sandstone Formation

Hiswah Sandstone Formation consists mainly of a thin-bedded micaceous siltstone interbedded with fine-grained micaceous sandstones and silty claystones/shales. The

Table 2
Laboratory-measured thermal conductivity of Lower Paleozoic surface and subsurface sedimentary formations

Surface Formation	<i>n</i>	<i>n_T</i>	λ_D (W m ⁻¹ K ⁻¹)	SD	λ_D^* (W m ⁻¹ K ⁻¹)	SD	$\lambda_{S/meas}$ (W m ⁻¹ K ⁻¹)	SD	$\lambda_{S/calc}$ (W m ⁻¹ K ⁻¹)	ϕ (%)	λ_S^* (W m ⁻¹ K ⁻¹)	SD
Khushsha Sandstone	2	5	2.48	1.00	2.17	0.59	8	3.94	0.91		3.71	0.59
Ratiya Sandstone	3	8	1.97	0.59			5	3.49	0.03			
Batra Mudstone	1	7	1.03						1.21	5		
Tubeliyat Sandstone	3	11	2.10	0.20			4	3.88	0.36			
Dubaydib Sandstone	4	12	2.66	0.53	2.43	0.29	8	4.00	0.52		3.88	0.12
Upper Hiswah Sandstone	4	13	2.55	0.15			13	3.76	0.33			
Lower Hiswah Sandstone	1	4	1.66				3	1.82				
Umm Sahm Sandstone	3	16	3.89	0.67	3.02	0.92	4	5.20	0.42	15	4.40	0.96
Disi Sandstone	4	9	2.38	0.32			6	4.93	0.24			
Umm Ishrin Sandstone	4	10	2.33	0.36			3	5.25	0.89			
Salib Arkosic Sandstone	2	6	2.88	0.62					3.81			
Subsurface Formation	<i>n</i>	<i>n_T</i>	λ_D (W m ⁻¹ K ⁻¹)	SD	λ_D^* (W m ⁻¹ K ⁻¹)	SD	$\lambda_{S/meas}$ (W m ⁻¹ K ⁻¹)	SD	$\lambda_{S/calc}$ (W m ⁻¹ K ⁻¹)	ϕ (%)	λ_S^* (W m ⁻¹ K ⁻¹)	SD
Alna	2	6	1.58	0.19			4	1.70	0.11			
Batra	1	4	1.46				1	1.55				
Umm Tarifa	2		1.88	0.05			8	2.46	0.54			
Amud	2	5	3.78	0.07			8	5.67	0.12			

n – number of samples; *n_T* – number of tracks measured; λ – thermal conductivity; subscripts D, S, meas, and calc – dry, saturated, measured, and calculated; λ^* – thermal conductivity averaged from different formations of similar rock type; ϕ – porosity used if λ was calculated; SD – 1 σ standard deviation.

Upper Hiswah Sandstone Formation is comprised of interbedded fine-grained sandstones and siltstones (similar to the overlying Lower Dubaydib Sandstone Formation). The lower-half of the Hiswah Sandstone Formation exposed in outcrop corresponds with the subsurface Sahl As Suwwan Formation, which mostly consists of shales intercalated with silty claystones and siltstones or siltstone interbedded with shale. Porosities of surface samples vary between 10% and 24%.

2.5. Umm Sahm Sandstone Formation and Disi Sandstone Formation

Umm Sahm Sandstone Formation and Disi Sandstone Formation are differentiated in outcrop mainly on the basis of weathering features, which are criteria impractical for use in subsurface geology. Therefore, the two formations are often considered as one unit, termed Amud Formation, in subsurface studies. Both formations dominantly are made up of medium- to coarse-grained quartz arenites. The sandstone of the Disi Formation is massive, while the sandstone of the Umm Sahm Formation is thick-bedded and intercalated with micaceous siltstone, sandstone, and claystone. Porosities measured on outcrop samples range between 12% and 26%, the porosity of subsurface samples is in the order of 14%.

2.6. Umm Ishrin Sandstone Formation

Umm Ishrin Sandstone Formation consists predominantly of a medium- to coarse-grained quartz arenite, sub-arkosic in part, intercalated locally with thin beds of micaceous siltstone/shale. Porosities are similar to that of the Salib Arkosic Sandstone Formation. In contrast to outcrop exposures, this formation is very fine-to fine-grained (occasionally medium-grained) in the subsurface, where it is named Ajram Formation.

2.7. Salib Arkosic Sandstone Formation

Salib Arkosic Sandstone Formation consists of a poorly consolidated, medium- to very coarse-grained, arkosic and sub-arkosic sandstone of variable porosity (12–19%).

3. New heat-flow data

The selection of the study area was dependent on the availability of open wells drilled in the exploration of hydrocarbons or groundwater. Wells formerly used in geothermal studies in Jordan were abandoned or utilized for water supply and thus, could not be re-investigated for confirmation or disconfirmation of previous heat-flow data.

Typically, the drillcore recovery from those “industrial” boreholes is minor relative to “scientific” drill holes. To get a sufficiently large, representative number of thermal-conductivity data, outcrop samples were additionally collected (e.g., Fig. 1b). Sampling and measurement involved almost

all Paleozoic formations and thus, provides for the first time a more or less complete record of the thermal conductivity of the major Paleozoic formations in Jordan (Table 2). In contrast to this study, former determinations of heat flow in Jordan are based on temperature measurements in shallow boreholes in Cretaceous rocks (sandstones and limestones), the thermal conductivity of which was measured on drill cuttings or surface samples collected in west-central Jordan (Galanis et al., 1986).

3.1. Borehole temperatures

Temperature logs were recorded in spring 2002 and spring 2003. All wells were drilled for water exploration in the early 1990's ensuring that thermal re-equilibration after the drilling process has long been attained. For the logging, an analogue, electric-line system was deployed, which consists of a 28-mm-diameter sensor (max. temperature 80 °C, max. pressure 300 bar) and a 1000-m-long cable (Vektor-Schlumberger-Kabel 1-10P 1/10"). The system allows temperature recordings to a precision of 0.01 °C, at a limiting accuracy of ~ 0.1 °C. The recording interval was 0.1 m. The downward logging speed of ~ 7 m min⁻¹ was sufficient that the actual subsurface temperature could be recorded in the liquid-filled part of the

boreholes without having to deconvolve the records afterwards. The logs of the air-filled parts of the wells above the water table are not used.

All logs show a continuous, semi-linear temperature increase with depth indicating that heat conduction dominates the heat transfer (Fig. 2). Thus, the breaks in the temperature logs are related to changes in lithology. Irregularities at about 800 m depth in the logs from the BH1 and BH6 boreholes are attributed to local water flow not affecting the thermal conditions in the depth intervals above.

3.2. Thermal conductivity

Rock samples were measured dry and, except for the shales and some sandstones, water-saturated using the high-resolution optical scanning method (Popov et al., 1999). This transient method is based on a no-contact scanning of a sample surface with a focused, mobile, and continuously operated constant heat source in combination with a temperature sensor. The heat source and the sensor move with the same speed relative to the sample and at a constant distance to each other. The temperature sensor displays the value of the maximum temperature rise along

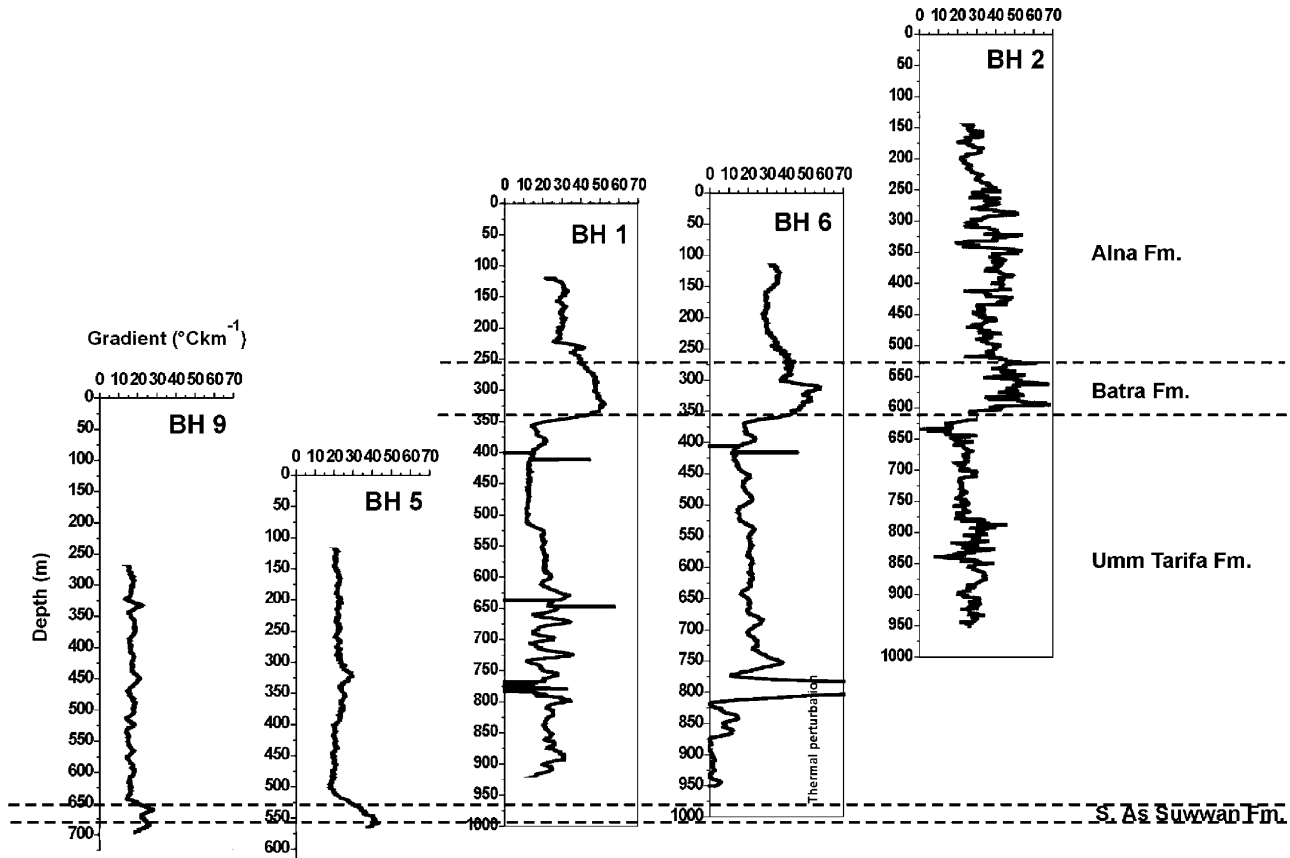


Fig. 3. Correlation of temperature gradients in the five wells reported in this study. For the location of wells see Fig. 1b. Subsurface stratigraphy is denoted.

Table 3
Geothermal data for heat-flow sites in southern Jordan

Borehole ID	Depth interval (m)	Temperature gradient (°C km ⁻¹)	λ (Wm ⁻¹ K ⁻¹)	Error	Q (mW m ⁻²)	Average $Q \pm$ Error (mW m ⁻²)	FM	Average Q /borehole (mW m ⁻²)
BH2	139~525	36.0	1.70	0.2 = 12%	61.2 $\pm$ 7.3	64.7 $\pm$ 5.5	Alna	65.7 $\pm$ 4.5
	360–410	42.1	1.62 ^a	0.2 = 12%	68.2 $\pm$ 8.2		Batra	
	525–617	48.7	1.35 ^b	0.1 = 7%	65.7 $\pm$ 4.6	66.8 $\pm$ 9.4	Umm Tarifa	
	650–961	26.6	2.46	0.5 = 20%	65.4 $\pm$ 13.1			
	885–890	24.0	2.84 ^a	0.5 = 20%	68.2 $\pm$ 13.6			
BH6	110–270	32.0	1.70	0.2 = 12%	54.4 $\pm$ 6.5	57.1 $\pm$ 4.2	Alna	57.1 $\pm$ 4.2
	305–355	49.8	1.35	0.1 = 7%	67.2 $\pm$ 4.7		Batra	
	390–735	20.2	2.46	0.5 = 20%	49.7 $\pm$ 9.9		Umm Tarifa	
BH1	125–275	32.9	1.70	0.2 = 12%	55.9 $\pm$ 6.7	57.4 $\pm$ 4.3	Alna	57.4 $\pm$ 4.3
	276–340	49.6	1.35	0.1 = 7%	67.0 $\pm$ 4.7		Batra	
	400–750	20.1	2.46	0.5 = 20%	49.4 $\pm$ 9.9		Umm Tarifa	
BH5	120–520	22.7	2.46	0.5 = 20%	55.8 $\pm$ 11.2	55.7 $\pm$ 7.9	Umm Tarifa	55.6
	310–340	26.7	2.08 ^a	0.5 = 20%	55.5 $\pm$ 11.1			
BH9	275–645	16.9	3.88 ^c	0.5 = 20%	65.6 $\pm$ 13.1		Umm Tarifa	65.6
								60.3 $\pm$ 3.4

λ – thermal conductivity, Q – heat flow, FM – geological formation (see Table 1).

^a Value determined on drill-core material from this borehole.

^b Value averaged from surface and subsurface formation values.

^c Value from surface formation counterpart.

the heating line behind the source. The maximum temperature rise, Θ , is determined by the relationship

$$\Theta = \frac{Q}{2\pi \cdot x \cdot \lambda}, \quad (1)$$

where Q is the source power, x the distance between source and sensor, and λ is the thermal conductivity. The measured sample(s) and a reference standard with known thermal conductivity, λ_R , are aligned along the scanning direction. The thermal conductivity of each sample then can be determined from λ_R and the ratio of Θ and Θ_R or, in actual application, from the ratio of electrical signals U and U_R , which are proportional to

$$\lambda = \lambda_R \cdot \left(\frac{\Theta_R}{\Theta} \right) = \lambda_R \cdot \left(\frac{U_R}{U} \right). \quad (2)$$

The measurements were performed on plain (sawed) samples, on which a 7–12-mm-wide strip of black enamel (25–40- μ m-thick) was painted along the scanning line. Thermal conductivity was measured perpendicular to the bedding of the samples, which is the direction of regional heat flow. Accuracy and precision of measurement are 3% (for a confidence probability of 0.95). Sample length and thickness were >4 cm and >3 cm, respectively.

For samples not measured at saturated conditions, the thermal conductivity determined on the dry sample was corrected for water saturation using a porosity estimate derived from petrophysical well-logs.

Care was taken that interbedded formations on outcrop were sampled for their end-member lithologies. Thermal conductivity of the siltstones and sandstones varies between 3.5 and 5.7 W m⁻¹ K⁻¹ (Table 2). The poorly cemented, feldspar- and quartz-rich Umm Sahm and Disi sandstones (subsurface Amud Formation) and the Salib arkosic sandstones are at the upper end of this range. Claystones and shales (Batra Mudstone Formation and Lower Hiswah Sandstone Formation) show a lower thermal conductivity, in the order of 1.2–1.8 W m⁻¹ K⁻¹, which is similar to the value obtained from the subsurface Batra Formation (1.5 W m⁻¹ K⁻¹). These values of shales are in the range of thermal conductivity typical for this type of rock, e.g., in the American Midcontinent (0.9–1.4 W m⁻¹ K⁻¹; Sass and Galanis, 1983; Blackwell and Steele, 1988; Gosnold, 1990) and in the Northern Sacramento Basin of California (1.4 W m⁻¹ K⁻¹; Blackwell et al., 1999).

A formation thermal conductivity of 1.35 W m⁻¹ K⁻¹ is calculated for the shaly/clayey Batra Formation, which is lithologically quasi-homogeneous on outcrop and in the subsurface. Also largely homogeneous in composition is the subsurface Alna formation (mostly claystone with some siltstone), with a thermal conductivity of 1.7 W m⁻¹ K⁻¹ (Table 2). The value of 3.7 W m⁻¹ K⁻¹, determined for its surface equivalents (Khushsha and Ratiya Sandstone Formations), is relevant to mature sandstones that do not occur in the boreholes. Differences in lithology also relate to the Umm Tarifa Formation. Its thermal conductivity of

2.5 W m⁻¹ K⁻¹ is lower than the average value of 3.9 W m⁻¹ K⁻¹ of its shallow equivalents, the Tubeiliyat, Dubaydib, and Upper Hiswah Sandstone Formations.

3.3. Heat-flow determination

Heat-flow q was determined using the interval method. It is given by the Fourier's law of heat conduction as

$$q = \lambda dt/dz \quad (3)$$

where dt/dz is the temperature gradient and λ is the thermal conductivity of the rock, in which the gradient is measured. In the interval method, q is calculated using Eq. (3) for discrete depth intervals and then averaged over the length of the borehole. The depth intervals were selected from a plot of temperature gradients calculated for 1-m depth intervals (Fig. 2).

The assignment of the lithostratigraphy to each borehole section was guided by the pattern observable in a composite plot of temperature gradients (Fig. 3), geological maps, and the subsurface lithostratigraphic data of Andrews (1991). The data from the BH2 borehole served as a standard profile, because of the availability of a gamma-log (Fig. 2e).

Table 3 lists the depth intervals for which average temperature gradients and heat-flow values are determined. In deeper boreholes (BH1, BH2, and BH6), heat flow is first calculated in three intervals and then averaged. In the two shallower boreholes (BH5 and BH9), heat flow is calculated for one interval only. The error attributed to the average values mainly originates from the lithological complexity and the therewith-related uncertainties in calculation of the formation thermal conductivity.

Temperature gradients in the Alna Formation show overall gradients in a small range of 32–36 °C km⁻¹, with a slightly higher gradient of 42 °C km⁻¹ in a limited depth interval in the BH2 borehole. The range of gradients testifies to minor lithological heterogeneity in this formation. Heat flow ranges between 54 and 68 mW m⁻². Values at the lower end of this range relate to the BH6 and BH1 boreholes (southwest of the BH2 borehole) situated in the marginal part of the sedimentary basin. It is likely that in these wells the formation contains a higher percentage of siltstone than at greater depth in the BH2 borehole, where mudstones, from which the thermal-conductivity data were obtained, predominate.

The lithologically homogeneous Batra Formation shows near-identical gradients (49–50 °C km⁻¹) in three boreholes, resulting in heat-flow values of 65–67 mW m⁻².

The Umm Tarifa Formation (mostly sandstones and siltstones) has gradients in the range of 20–27 °C km⁻¹, attesting to minor sedimentological heterogeneity laterally in the basin. Again, all boreholes west and southwest of the BH2 borehole show somewhat lower overall gradients, which may be attributed to a larger amount of sandstone in the formation near the outcrop area. This would also

Table 4

Density (ρ), composition (U, Th, K₂O), and heat production (A) of Pan-African metamorphic and magmatic upper crustal rocks from Jordan

Rock	ρ kg m ⁻³	U ppm	Th ppm	K ₂ O wt%	A μ W m ⁻³
Volcanic rocks					
Al Bayda AR	2610	3.71	14.6	4.81	2.26
Qusayb AR	2630	5.53	15.2	7.64	2.99
	2620	4.61	15.8	6.27	2.69
Qusayb TR	2660	3.63	11.0	4.90	2.04
Ahaimyr TR	2600	4.05	12.0	3.92	2.10
	2640	2.97	8.90	4.36	1.68
Quraynifat AR	2630	7.69	36.5	4.90	4.75
Quraynifat TC	2650	3.08	9.88	4.18	1.77
Ghuwayr TB	2900	1.13	3.49	1.98	0.74
Alkali-feldspar granites					
Feddan	2580	3.15	26.0	5.23	2.88
Humrat	2570	4.77	15.2	4.52	2.50
	2560	6.14	22.2	4.32	3.27
Ar Rashidiya	2570	13.9	31.1	4.27	5.76
	2580	10.4	41.1	5.17	5.69
Sabil (aplite)	2580	9.49	29.1	3.97	4.55
	2580	10.3	46.3	4.75	5.94
Mishar	2590	4.74	22.2	4.51	2.98
Marsad	2580	5.49	21.8	4.78	3.14
Qara	2600	14.8	41.5	4.89	6.79
	2640	5.27	24.0	4.87	3.32
Kharawi (xen)	2610	5.38	28.0	5.48	3.62
Marsod (alt)	2600	2.27	9.94	6.48	1.71
Granites					
Abu Jedda	2620	3.00	11.6	4.16	1.84
	2570	1.77	12.3	4.90	1.61
Imran	2590	1.79	8.53	4.43	1.34
Barraq	2610	2.05	4.32	3.52	1.06
Rubeig	2600	3.35	10.5	4.03	1.83
Hunayk	2610	3.03	15.2	4.01	2.07
Mulgan	2600	3.06	17.4	3.78	2.20
Muheirid	2590	2.41	10.7	3.93	1.60
Abyad	2590	1.65	6.64	3.56	1.11
Filk	2590	1.40	8.02	3.27	1.12
Ishaar	2600	3.03	12.6	3.63	1.86
Humrat	2650	4.81	13.2	4.48	2.45
Huwar	2590	1.55	5.28	3.48	0.99
Abu Radmar	2640	1.04	4.24	2.65	0.75
Um Sayyala	2590	1.89	10.1	4.53	1.47
Taba	2600	0.82	4.03	3.79	0.76
Turban	2600	0.69	2.85	2.86	0.58
Nab'a	2620	1.21	5.38	4.56	1.01
qtz monzonites/granodiorites					
Sahaqi QMZ	2660	3.08	9.92	3.83	1.75
	2670	3.06	8.38	3.03	1.58
	2700	1.84	6.96	2.73	1.17
Hubayra GD	2740	3.86	13.9	3.32	2.24
Sabil QMZ	2690	2.64	13.1	3.35	1.84
Sabil GD	2720	3.55	14.8	2.77	2.17
Waara GD	2670	1.98	10.1	3.17	1.44
Abu Radmar QMZ	2690	1.46	7.50	2.82	1.11
Es Sadre GD	2650	1.03	3.49	1.81	0.64
qtz monzodiorites/monzogabbros					
Um Rachel	2720	1.44	4.12	2.30	0.84
	2770	1.62	4.52	2.26	0.93
Muhtadi	2770	1.72	5.37	2.48	1.03
Thaur	2780	2.15	6.34	2.41	1.21
	2830	1.42	4.05	1.96	0.84
Marsod	2820	1.36	3.34	1.70	0.74

Table 4 (continued)

Rock	ρ kg m ⁻³	U ppm	Th ppm	K ₂ O wt%	A μ W m ⁻³
Gneisses					
Abu Barqa PG	2740	1.72	6.54	2.46	1.10
	2790	1.97	5.35	3.25	1.17
	2750	1.75	4.65	1.99	0.94
	2730	1.61	7.86	2.37	1.16
Abu Barqa OG	2670	2.25	6.43	3.14	1.25
Busaynat OG	2630	1.10	16.0	2.04	1.51
Duheila QMD	2750	1.06	4.12	1.85	0.71

AR – alkali rhyolite; TR – trachyrhyolite, TC – trachydacite, TB – trachybasalt, xen – xenolith in Neogene basalt, alt – altered, QMZ – quartz monzonite, GD – granodiorite, PG – paragneiss, OG – orthogneiss, QMD – quartz monzodiorite.

$A = \rho(9.52U + 2.56Th + 3.48K)10^{-5}$, with ρ in kg m⁻³, U and Th in ppm, and K in wt%.

explain the very low gradient of 17 °C km⁻¹ in the westernmost BH9 borehole which, in combination with a thermal conductivity of 3.9 W m⁻¹ K⁻¹ (from surface samples, honouring the larger amount of sandstone in the sequence), yields a heat-flow value of 66 mW m⁻², similar to the value in the BH2 borehole.

For each site, the interval heat-flow values were finally converted into a heat-flow average, which ranges from 56 to 66 mW m⁻². The smallest error in these data is observed for the BH2 borehole; the largest error for the BH9 borehole located near formation outcrop. The overall average for the five boreholes is 60.3 ± 3.4 mW m⁻², which we consider a robust estimate for the heat-flow in southern Jordan.

4. Discussion

The conductive surface heat flow from this study (56–66 mW m⁻²) is at the upper end of range previously measured in Jordan (42–65 mW m⁻²; Galanis et al., 1986, Fig. 1b), but significantly deviates from that of the Saudi Arabian part of the shield (36–45 mW m⁻²; Gettings, 1982; Gettings and Showail, 1982). It is within the range of values reported for southern Syria (50–88 mW m⁻²; Matviyenko et al., 1993). In total, the entire range in surface heat flow reported for the Arabian Shield and its immediate platform surrounding is broad (36–88 mW m⁻²). Moreover, all these data refer to areas in which the upper crust is virtually unaffected by thermal perturbations related to Cenozoic geodynamic processes. These processes include the Red Sea rifting starting in the Oligocene (e.g., McGuire and Bohannon, 1989), the eruption and emplacement of basaltic lava flows of Oligocene and younger age (e.g., Shaw et al., 2003), and the formation of the Dead Sea Transform fault system starting in the Miocene (e.g., Sobolev et al., 2005).

Although the regions under consideration are not identical geologically and have slightly different thicknesses and compositions of the crust, their crustal structure and lithosphere composition (e.g., Gettings et al., 1986; Mechie et al., 1986; Nasir and Safarjalani, 2000) are too similar to account for heat-flow variations in the order of 50 mW m⁻². It is this broad similarity in lithosphere struc-

ture and composition that leads us 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 younger geodynamic reactivation.

Opponents of the regional significance of the heat flow average from this study may argue that it represents a small-scale positive anomaly caused by local heat sources in the shallow metamorphic/magmatic basement underlying the sedimentary cover at depths between 2 and 3 km. Table 4 shows a compilation of heat-production values measured on a representative suite of magmatic and metamorphic, Pan-African upper-crustal basement rocks that are in outcrop along the DST in Jordan. Widespread and most voluminous rock types such as monzogranites and monzonites/granodiorites typically display rather normal heat-production values, between 1 and 2 μ W m⁻³. Rocks of increased heat production, between 2 and 4 μ W m⁻³, are rhyolites and alkali-feldspar granites of generally low occurrence and small volume. High heat-production (HHP) rates, in the range 4–6.8 μ W m⁻³, are confined to rhyolites and alkali-feldspar granites that form dikes, aplites, or minor intrusions of small thickness, between a few decimetres and a few hundred of meters. Therefore, it is unlikely that the study area, encompassing about 300 km², is fully underlain by HHP granites/rhyolites in a volume that has severely increased the heat flow in the sedimentary cover.

In all probability, temperature disturbances related to young volcanic activities next to the Red Sea Rift and the Dead Sea Transform can be excluded for our heat-flow site. The site is located some 100 km south of the southernmost basalt field spatially associated with the DST and about 150 km north of the nearest alkali-basalt field associated with the Red Sea rift, the Harat Rahah (see Fig. 1a). Moreover, no geophysical evidence exists for hidden young igneous activity in the greater area of the heat-flow site (Götze et al., 2006).

The supposedly minor impact of geology and geodynamic setting directs the attention to problems, with which earlier heat-flow determinations in the Arabian Shield might have been confronted. In the previous study on Jordan heat flow (Galanis et al., 1986), thermal conductivity was determined on drill cuttings and surface samples, but not on drill cores. Potential uncertainties mainly arise from

the difficulty of relating the cuttings to depth and to the formations encountered by the boreholes. Another limitation is the small depth interval used for determining the interval temperature gradient in some boreholes: 30–91 m in JD26 borehole, 174–247 m in JD21 borehole, and 314–384 m in JD12 borehole (cf., Fig. 1b). Interestingly, the two sites yielding heat-flow values in the order of this study (65 mW m^{-2} and 62 mW m^{-2}), relate to boreholes considering larger depth intervals (61–201 m in the JD24 borehole; 299–500 and 500–917 m in the JD13 borehole).

An additional source of error is the annual climatic effect that temperatures at shallow (<100 m) depths experience. The heat flow in inland southwestern Saudi Arabia (Gettings, 1982; Gettings and Showail, 1982) was determined in ≤ 70 -m-deep boreholes drilled as shot holes for a seismic transect, with the heat-flow determination interval sometimes being smaller. In addition to this limitation, questions arise about the validity of the thermal-conductivity values that were assigned to the interval temperature gradients. For example, the heat-flow value (39 mW m^{-2}) determined for the seismic shot point 1 (Gettings and Showail, 1982) resulted from a temperature gradient of $14.7^\circ\text{C km}^{-1}$, which is uncommonly low for a shale unit, and a supposed thermal conductivity of $2.6 \text{ W m}^{-1} \text{ K}^{-1}$, which is atypically high for a shale (see also Jessop and Vigrass, 1989). The heat-flow value determined at shot point 2 (36 mW m^{-2} , with a temperature gradient of $8.2^\circ\text{C km}^{-1}$) is based on a thermal-conductivity value of $4.6 \text{ W m}^{-1} \text{ K}^{-1}$ calculated from the individual conductivities of the different mineral components making up the granodiorite. However, laboratory-measured thermal conductivities of granodiorites of similar composition, modal mineralogy, and age from Jordan yielded substantially lower values, averaging to $2.4 \text{ W m}^{-1} \text{ K}^{-1}$. The same discrepancy is noted for alkali-feldspar granites, where the thermal-conductivity values (3.5 – $3.6 \text{ W m}^{-1} \text{ K}^{-1}$) calculated by Gettings and Showail (1982) for the shot points 3 and 4 differ from those measured on equivalent rocks in Jordan (2.6 – $2.9 \text{ W m}^{-1} \text{ K}^{-1}$). If the thermal-conductivity values of the Jordanian rocks would be combined with the temperature gradients, unrealistically low surface heat-flows between 20 and 36 mW m^{-2} would be the outcome for shot points 1–4. Altogether, the low heat-flow in the Saudi-Arabian boreholes probably is the result of erroneously low temperature gradients reflecting unaccounted perturbed shallow thermal conditions.

Heat-flow determinations in Syria, made as a side product of a geothermal reconnaissance study, also are afflicted with a number of shortcomings. The use of single-temperature readings (bottom-hole temperatures, BHTs) and the lack of measured thermal conductivities constitute the most problematic limitations. Considering the general quality of BHTs, true subsurface temperatures may remain underestimated by 8 – 10°C , at a large standard deviation of 8°C (1σ), even if a correction method is applied (Hermanrud et al., 1990; Förster, 2001). Furthermore, calculation of an average temperature gradient, using BHTs and the sur-

face temperature as only constraints, may be erroneous, especially in the situation of geological formations with different thermal conductivities (Blackwell and Steele, 1988). Therefore, the heat-flow values determined in Syria have to be regarded as poor estimates, and any resemblance with the Jordan average of 60 mW m^{-2} may be purely coincidental.

The bulk of previously reported heat-flow values (e.g., 36 – 45 mW m^{-2} , Gettings, 1982; Gettings and Showail, 1982; 42 mW m^{-2} , Galanis et al., 1986) aided to the widely accepted concept of the Arabian Shield being a province of low heat flow (e.g., McGuire, 1988; Stein et al., 1993; Medaris and Syada, 1998). These former values matched the low heat flow of Archean-consolidated terranes ($41 \pm 11 \text{ mW m}^{-2}$; Rudnick et al., 1998) attributed to a great lithosphere thickness (200 – 250 km) combined with a low crustal heat production (Nyblade, 1999; and references therein). Neither factor applies to the late Proterozoic, Arabian Shield. Its lithospheric thickness is significantly lower and assumed to increase from the DST in the west (about 90 km ; Sobolev et al., 2005) towards Saudi Arabia in the east (110 – 180 km ; McGuire and Bohannon, 1989). A lithosphere section constructed for the heat-flow area from this study yields a bulk crustal heat production of $0.83 \mu\text{W m}^{-3}$ (Förster et al., 2004b), which is slightly higher than the heat production of the Archean bulk crust ($\sim 0.65 \mu\text{W m}^{-3}$, McLennan et al., 2005). These circumstances lend support for our heat-flow estimate for the Arabian Shield being in accordance with that of stable Proterozoic provinces far away from Archean cratons ($55 \pm 17 \text{ mW m}^{-2}$; Rudnick et al., 1998; see also Nyblade and Pollack, 1993). A past underestimation of the surface heat flow may not only be relevant for the shield area outside of the DST, but may also hold for the DST itself. Here, the result of a 3-D thermomechanical modelling of the formation of the Dead Sea basin also supports a surface heat flow of $\sim 60 \text{ mW m}^{-2}$ (Petrunin and Sobolev, 2006) and contrasts the bulk of previous estimates maximizing to 40 mW m^{-2} (e.g., Ben-Avraham et al., 1978; Aldersons et al., 2003). However, exhaustive and high-precision heat-flow studies are needed to get a sufficiently substantiated insight into the scale of surface heat-flow variations in the Arabian Shield.

Acknowledgements

We particularly wish to thank J. Schrötter and M. Pöser (GeoForschungsZentrum Potsdam, GFZ), who have performed the temperature logging in Jordan. R. Naumann and P. Dulski (GFZ) conducted the XRF and ICP-MS analyses. Constructive reviews by D.D. Blackwell (SMU, Dallas) and an anonymous referee helped to strengthen the paper. The National Resources Authority (Amman) is thanked for providing invaluable logistic support during the field campaigns. HJF was funded via a grant (We 1457/8-5) from the Deutsche Forschungsgemeinschaft.

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