Thermal Conductivity Measurement and Prediction from Geophysical Well Log Parameters with Borehole Application

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ABSTRACT

Problems related to thermal conductivity measurements of rocks were examined using the divided-bar method. [redacted]

relatively time consuming and expensive. The most common method for the determination of the thermal conductivity of earth materials is the divided-bar apparatus (Birch, 1950). [redacted]

Figure 1. An idea[illegible]

DIVIDED-BAR APPARATUS

[illegible]

study is shown in Figure 1. The design is an attempt to incorporate a short bar, having "constant" thermal resistance with a good insulation system capable of accepting a variable length sample. The theory for this design is [illegible]

into the following relationship

$$K = CX(\Delta T_1 + \Delta T_3)/\Delta T_2 \tag{2}$$

The calculation of the comparison factor C is based on the assumption that the thermal conductivity of the reference standard K_R^* is known and constant. However, C^* is found to be a function of pressure. Details of the effect of pressure on the thermal conductivity of reference materials will be published elsewhere (Goss and J. Combs, in preparation, 1975). Nevertheless, a few comments are appropriate.

Since the apparent pressure effect can be in opposite directions for different reference materials, it cannot be [illegible]

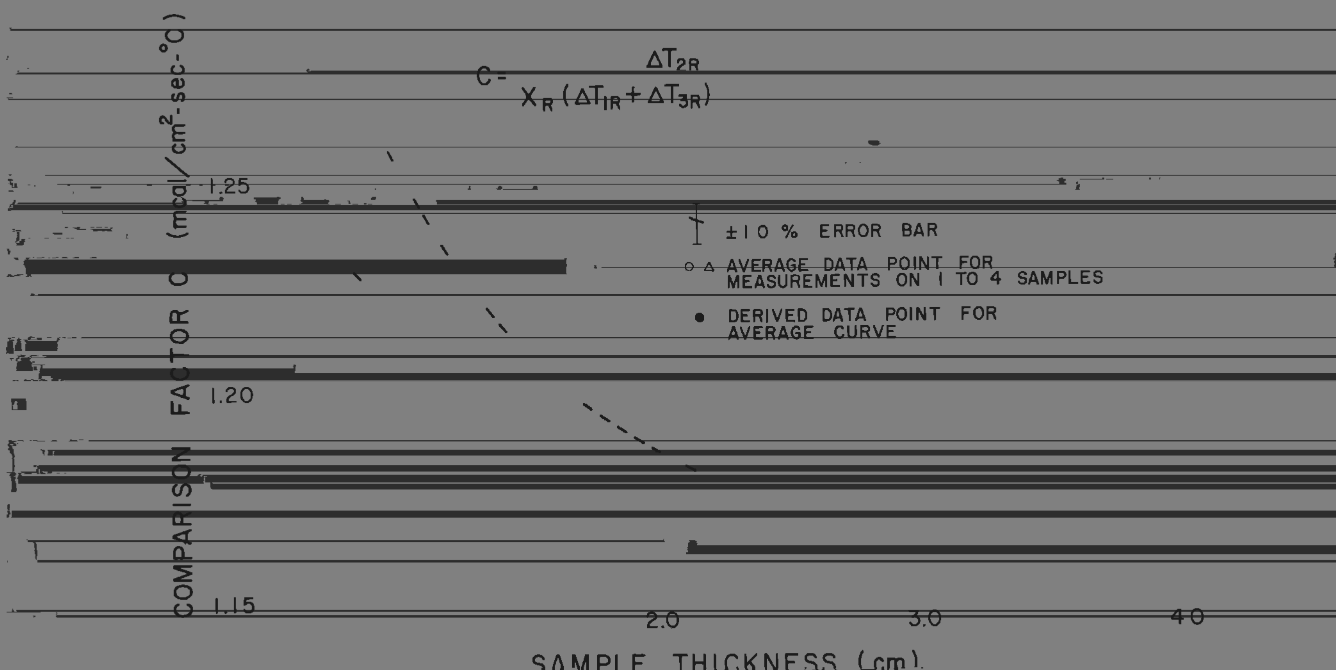
DERIVATION OF DIVIDED-BAR EQUATIONS

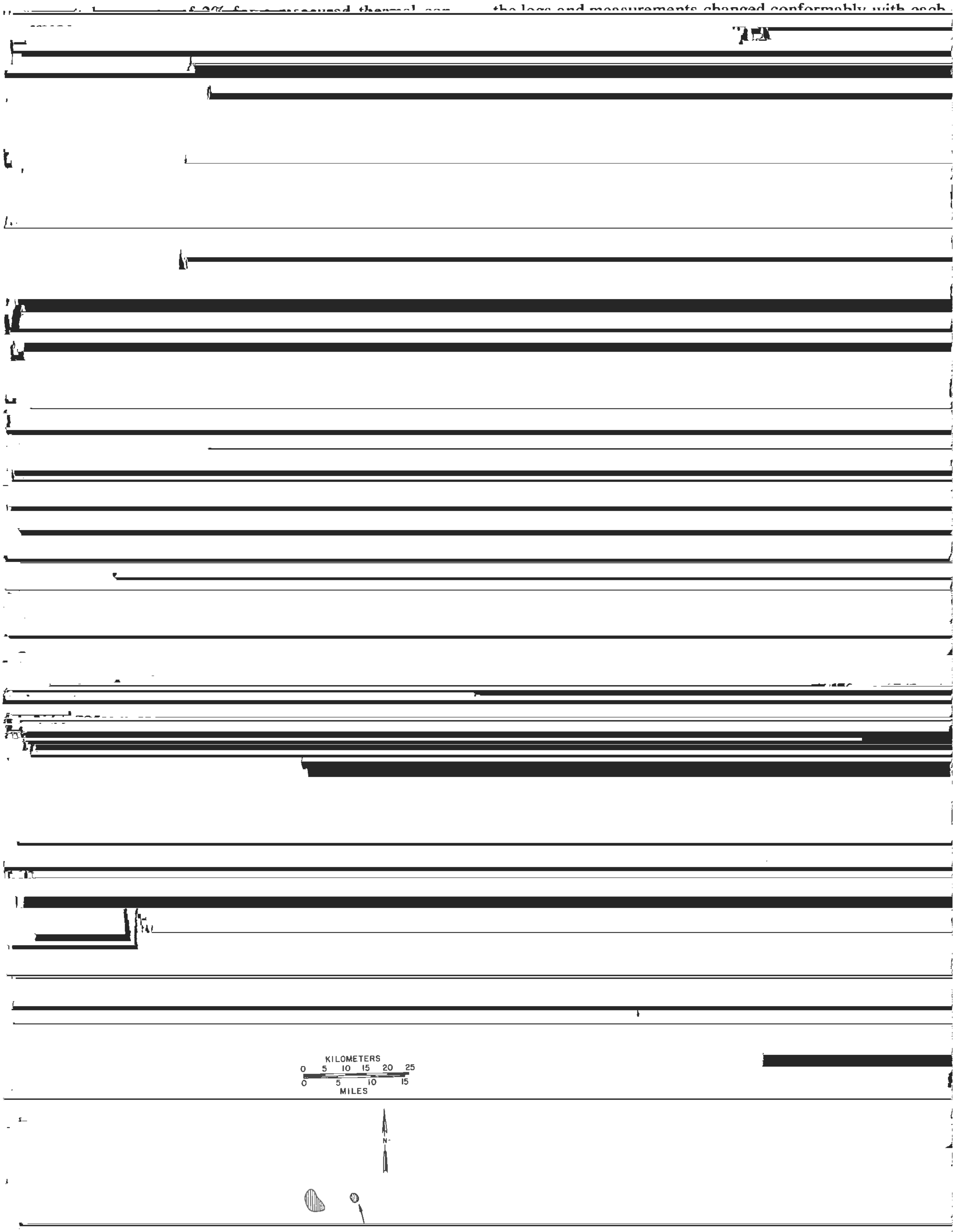
[illegible]

primarily an instrument effect. If it is assumed that all of the change is due to the effect of pressure on the reference thermal conductivity K_R^*, then use of the "true" reference conductivity which is a function of pressure, $K_R = f(P)$,

attempted here if all sample ends are similarly prepared and theoretical assumptions are verified.

The above method provides a reliable estimation of the slope for the pressure effects, but each curve (Fig. 3) must





For measurements on borehole grab samples of drill chips and unconsolidated sediments, a cell arrangement similar to that described by Sass, Lachenbruch, and Munroe (1971) was used. The cell device essentially constitutes a new of the U.S. Bureau of Reclamation (USBR) Mesa No. 5-1 geothermal well, and eight sets of values are from the shallow zone (200 to 800 m) of the USBR Mesa No. 6-1 well. These Mesa samples are representative of the unconsolidated

Table 1. Data from laboratory measurements of cores.

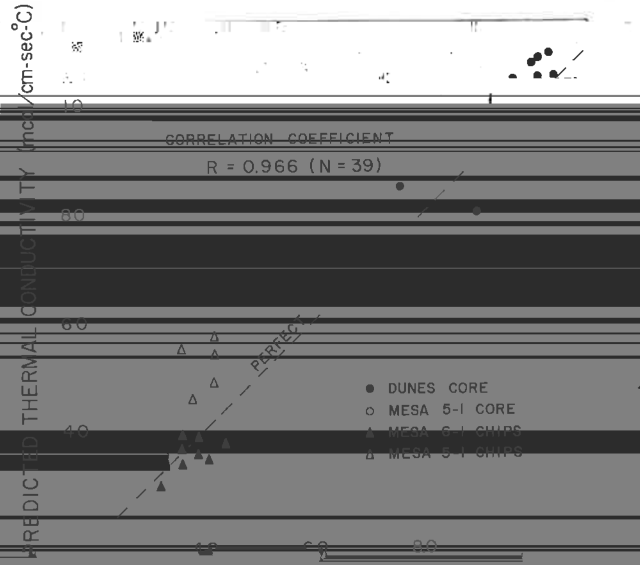
Identification	K $\left(\frac{\text{mcal}}{\text{cm·sec·°C}}\right)$	D_B $\left(\frac{\text{g}}{\text{cm}^3}\right)$	Φ (%)	k (mdarc)	ρ (ohm·m)	$\rightarrow F$ $\left(\frac{\rho}{0.05\ \text{ohm·m}}\right)$	σ $\left(\frac{\text{mmhos}}{\text{m}}\right)$	V_P $\left(\frac{\text{km}}{\text{sec}}\right)$	V_S $\left(\frac{\text{km}}{\text{sec}}\right)$	FFI (%)
Dunes DWR 1 core data from 100 to 300 meters										
UCR-1	10.0	2.47	9.56	0.76	16.7	334	59.9	5.09	3.17	8.33
UCR-2	10.0	2.49	8.62	0.50	23.6	472	42.4	5.07	3.23	6.52
UCR-3	7.60	2.35	12.9	350	3.25	65.0	308	4.63	2.60	11.1
UCR-4	9.99	2.46	10.4	15.0	8.04	161	124	5.03	3.13	8.61
UCR-5	8.45	2.40	13.1	470	3.24	64.8	309	4.91	2.87	10.0
[redacted]										
							170	4.33		
[redacted]										
							361	3.98		
							368	3.88		
UCR-7	9.00	2.43	12.4	1.3	5.88	118	5.18	5.54	2.57	9.12
[redacted]										
							63.3	4.94		
[redacted]										
							6.49	5.34		
							17.2	5.34		
UCR-9	8.13	2.36	16.3	14.0	2.77	55.4	11.1	5.38	2.22	4.11
UCR-10	8.16	2.36	16.5	39.0	2.72	54.4	[redacted]		2.15	11.2
UCR-11	10.1	2.56	3.93	0.01	193	3860			3.49	2.91
UCR-13	10.2	2.47	9.66	0.56	15.8	316	33.7	5.10	3.03	7.45
UCR-14	10.0	2.56	4.16	0.08	497	9940	34.9 2.01	5.35	3.52	3.53
UCR-15	10.3	2.55	3.14	0.02	445	8900	23.9	5.29	3.56	2.78
UCR-16	10.8	2.54	5.32	0.02	154	3080			3.49	4.21
UCR-17	10.0	2.53	5.90	0.02	58.2	1160		5.09	3.30 3.50	4.77
UCR-18	10.4	2.55	4.64	0.01	90.1	1800		5.25	3.36 3.32	3.23
UCR-19	10.0	2.51	7.64	0.16	23.8	476		5.31	3.17 3.73	5.97
UCR-20	10.5	2.53	6.74	0.02	29.7	594		5.31	3.17 3.56	4.60
UCR-21	10.1	2.53	6.44	0.38	31.7	634			3.32	5.07
UCR-22	10.6	2.53	6.35	0.08	41.8	836			3.31	4.92
UCR 115 core data, a few meters from Dunes hole							746	3.79	2.05	
[redacted]										
							227	3.94	2.08	
							392	4.65	2.64	
[redacted]										
							529	4.77	2.22	
[redacted]										
								3.81	2.03	
115-B	10.3	2.53	3.99	0.01	584	11700	1.71	4.75	2.42	3.21
115-C	9.67	2.53	4.13	0.03	402	8040	2.49	4.72	2.40	3.37
115-D	10.1	2.60	3.86	0.02	336	6720	2.98	6.98	3.76	2.87
[redacted]										

Drill cuttings and borehole logged measurements*

		D_B	Φ	"k" est. by SARABAND	ρ deep reading	$\rightarrow F$	σ		Temp (°C)	
[redacted]										
							140	3.30		
[redacted]										
							240	2.83		
							170	3.40		
							350			
[redacted]										
							630			
							940			
							770			

physical properties from the regression equations, special attention was given to the cancelling effect of obviously

[redacted]



[redacted]

ed since each offsets the effect of the other. Each velocity, when taken one at a time, was one of the most significant variables. During the present investigation, electrical resistivity ρ, and log ρ, electrical conductivity σ, formation factor F, $1/F$, and log F were all examined. The most significant functional forms were commonly ρ, σ and F. Therefore

[redacted]

$$K = 1.30 \exp (0.58\, D_D + 0.40\, S_w) \quad (12)$$

where S_w is the fractional water saturation and D_D is the bulk density in the dry state. Using core from a wide region of the Siberian lowlands, Moiseyenko and coworkers (1970) derived the relation

$$K = [1.17 + 0.83\,(3.42 - 0.55\,\Phi)]\, 10^{-3} \quad (13)$$

[redacted]

where the term in parentheses is for the dry conductivity,

D are the thermal conductivity, porosity, and density, respectively, with subscripts D, L, and G, for dry rock, saturating liquid, and gas (air), respectively; m, an empirical parameter, is the cementation factor of Archie's formula

$$F = A/\Phi^m \quad (19)$$

with A another empirical parameter.

Most of the relationships presented above are deficient

[redacted]

for the same samples; instead values from the literature

	F_{mea}/F_{est}	Measurement‡
6.6	42/15	9.6
6.6	52/18	9.7
4.9	11/11	6.7
4.0	7.8/8.7	4.9
2.4	9.1/9.1	2.9

*Requires assumed-dry density $D_D = D_B - 0.01\,\Phi$, saturation $S_w = 1.0$, and/or solid conductivity $K_S = 4.5$ Btu/ft·hr·°F if sample is predominately quartz and 3.5 if significant clay in sample. Values based on discussion of Somerton, Keese, and Chu, (1974). †Requires an assumption for gas conductivity

[redacted]

to give satisfactory results in the Imperial Valley geological environment. Therefore, we return to Equation (7), derived herein.

APPLICATION

Our ultimate goal is to determine thermal conductivity from common borehole logging parameters. Empirical rela-

ve made an initial attempt for the 300- to 700-m interval geothermal field. Casing at 310 m and a convective thermal regime below 670 m determine the limits of useful investigation. Equation (7)

the first measurement) with the differences of sampling

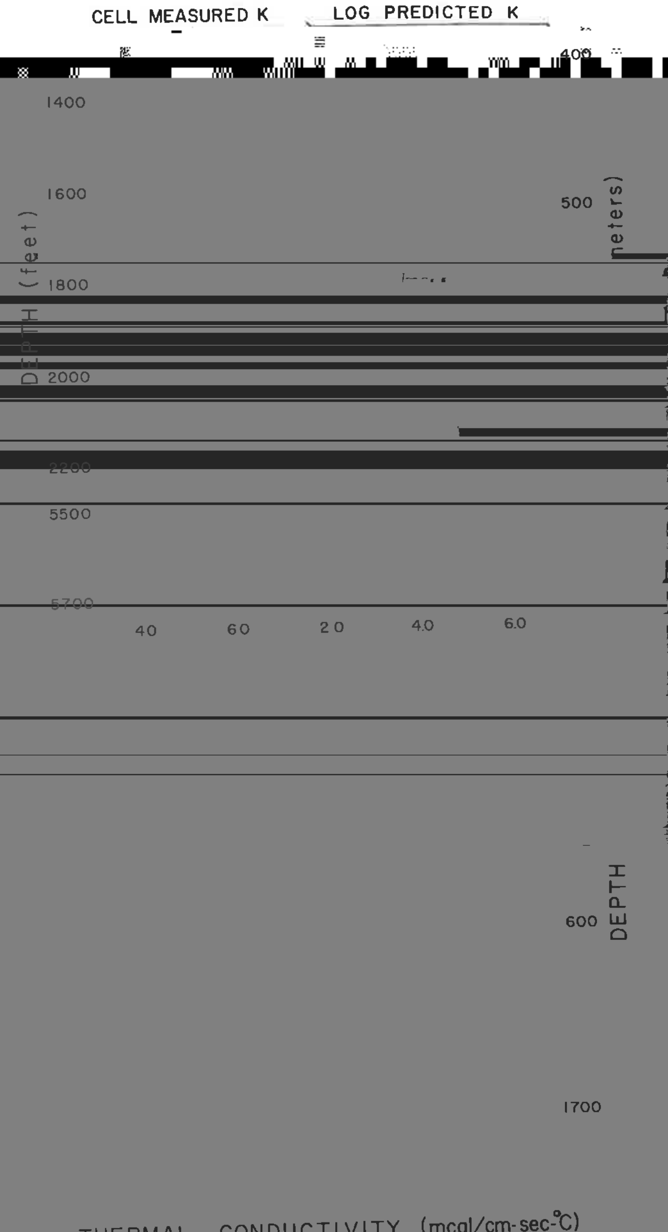


Figure 8. Thermal conductivities for the Mesa 5-1 geothermal well. Two cell data points at the same depth indicate repeated measurements. Log predictions are from Equation (7).

as the two phenomena—pressure effects and sample

New York, Wiley and Sons, 550 p.

thickness—are expected to clarify many subtle problems

Debye, P., 1914, Equation of state and quantum hypothesis