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APPENDIX 7

Core thermal conductivity reports

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Thermal Conductivity of Core Samples

Samples KEN001 - KEN020

Prepared for KUTh Energy Ltd.

10 April 2008, Final Report

Steven Sewell

Executive summary

KUTh Energy Ltd commissioned Hot Dry Rocks Pty Ltd (HDRPL) to measure the thermal conductivity of 20 core specimens delivered in mid February, 2008. Measurements were made on the 20 specimens using a steady state divided bar apparatus calibrated for the range 1.4–9.8 W/mK. Up to three samples were prepared from each specimen to investigate variation in thermal conductivity over short distance scales and to determine mean conductivity and uncertainty. All values were measured at a standard temperature of 30°C. The uncertainty for individual samples is $\pm 3.5\%$.

HDRPL considers the following points to be important:

- Thermal conductivities fall in the range 1.8–2.3 W/mK which is typical for dolerites.
- While the specimens were chosen to represent the cored geological sections from which they came, there is no guarantee that the sections themselves are typical of the overall geological formations.
- It is to be expected that the thermal conductivity of a given formation will vary from place to place if the porosity or degree of fracturing of the formation varies.
- Thermal conductivity of rocks is sensitive to temperature. This should be kept in mind when developing models of *in situ* thermal conductivity.

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1.0 Introduction

Thermal conductivity is the physical property that controls the rate at which heat energy flows through a material in a given thermal gradient. In the S.I. system of units, it is measured in watts per metre-kelvin (W/mK). In the earth, thermal conductivity controls the rate at which temperature increases with depth for a given heat flow. The thermal conductivity distribution within a section of crust must be known in order to calculate crustal heat flow from temperature gradient data, or to predict temperature distribution from a given heat flow. This report describes the results of laboratory thermal conductivity measurements on a series of drill core samples from KUTh Energy Ltd.

KUTh Energy Ltd commissioned Hot Dry Rocks Pty Ltd (HDRPL) to undertake this study. HDRPL took delivery of 20 core specimens[1] from the wells Lake Leake-1, Tooms-1, Snow-1 and Elizabeth-1 in February 2008 (Table 1). Thermal conductivity measurements were made on all of these specimens using a steady state divided bar apparatus calibrated for the range 1.4–9.8 W/mK. Thermal conductivity is sensitive to temperature, in general decreasing as temperature increases. The measurements contained in this report were made within ±2°C of 30°C.

Table 1. Specimens presented for thermal conductivity measurement.

Sample Ref	Well Name	Depth (m) top	Depth (m) base
KEN001	Lake Leake-1	158.67	158.77
KEN002	Lake Leake-1	171.3	171.4
KEN003	Lake Leake-1	228.4	228.5
KEN004	Lake Leake-1	267.4	267.5
KEN005	Lake Leake-1	290	290.1
KEN006	Tooms-1	154.5	154.6
KEN007	Tooms-1	180.61	180.75

[1] In this report the word "specimen" refers to a raw piece of rock delivered to HDRPL, while "sample" refers to part of a specimen prepared for conductivity measurement. In general, three samples are prepared from each specimen.

Sample Ref	Well Name	Depth (m) top	Depth (m) base
KEN008	Tooms-1	204.4	204.5
KEN009	Tooms-1	219.25	219.35
KEN010	Tooms-1	252.5	252.6
KEN011	Snow-1	168.2	168.31
KEN012	Snow-1	199	199.1
KEN013	Snow-1	221.4	221.5
KEN014	Snow-1	243.3	243.4
KEN015	Snow-1	267.45	267.55
KEN016	Elizabeth-1	156.7	156.85
KEN017	Elizabeth-1	171.7	171.81
KEN018	Elizabeth-1	202.35	202.37
KEN019	Elizabeth-1	252.7	252.8
KEN020	Elizabeth-1	283.72	283.81

2.0 Methodology

Hot Dry Rocks Pty Ltd selected samples of rock from each of the 20 cores, based on them being visually representative of the average lithological composition of the formation being sampled. The specimens were labelled, bagged and shipped to HDRPL's laboratory in South Yarra. Each specimen was prepared for thermal conductivity measurement in a divided bar apparatus[2]. Three cylindrical samples, each between 1 and 3 cm thick, were cut from each consolidated core to investigate variation in thermal conductivity over short distance scales and to determine mean conductivity (Figure1) and uncertainty. Each sample was ground flat and polished then evacuated via vacuum pump for a minimum of three hours. Samples were then submerged in water for an hour under

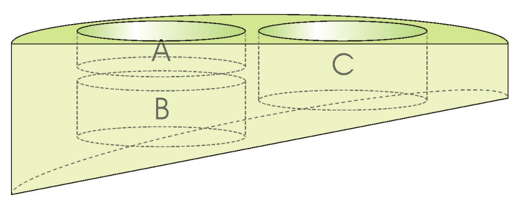

Figure 1. The average conductivity of samples in series (e.g. A and B) is found using the harmonic mean. The average conductivity of samples in parallel (e.g. A and C) is found using the arithmetic mean.

2 **Divided bar apparatus**: An instrument that places an unknown sample in series with a standard of known thermal conductivity, then imposes a constant thermal gradient across the combination in order to derive the conductivity of the unknown sample.

vacuum. Water saturation continued at atmospheric pressure for a minimum of three hours, until just prior to conductivity measurement. Values were measured at a standard temperature of 30°C (±2°C). Harmonic mean conductivity and uncertainty were calculated for each specimen. Results are presented in the next section.

3.0 Results

Table 2 displays the thermal conductivity for each individual sample, and the harmonic mean conductivity and standard deviation for each specimen. **All values are for a standard temperature of 30°C**. The uncertainty for individual samples is approximately ±3.5% (based on the instrument precision of the divided bar apparatus).

Table 1 - Thermal conductivity of samples at 30°C, and harmonic mean and uncertainty[3] for each specimen.

Well Name	Depth (m) top	Depth (m) base	Sample		Conductivity (W/mK)	
Lake Leake-1	158.67 m	158.77 m	KEN 001	A	2.201	2.18 ± 0.04
				B	2.121	
				C	2.192	
Lake Leake-1	171.3 m	171.4 m	KEN 002	A	1.973	1.99 ± 0.07
				B	2.071	
				C	1.936	
Lake Leake-1	228.4 m	228.5 m	KEN 003	A	2.020	2.02 ± 0.03
				B	1.989	
				C	2.055	
Lake Leake-1	267.4 m	267.5 m	KEN 004	A	1.941	1.96 ± 0.03
				B	1.949	
				C	1.990	

3 Uncertainty of the thermal conductivity for each specimen was derived from the uncertainty of the individual measurements for each sample.

Well Name	Depth (m) top	Depth (m) base	Sample		Conductivity (W/mK)	
Lake Leake-1	290 m	290.1 m	KEN 005	A	2.025	2.06 ± 0.06
				B	2.020	
				C	2.123	
Tooms-1	154.5 m	154.6 m	KEN 006	A	2.001	1.93 ± 0.12
				B	2.023	
				C	1.799	
Tooms-1	180.61 m	180.75 m	KEN 007	A	1.862	1.82 ± 0.13
				B	1.689	
				C	1.938	
Tooms-1	204.4 m	204.5 m	KEN 008	A	1.794	1.80 ± 0.06
				B	1.869	
				C	1.761	
Tooms-1	219.25 m	219.35 m	KEN 009	A	1.778	1.96 ± 0.18
				B	2.146	
				C	1.958	
Tooms-1	252.5 m	252.6 m	KEN 010	A	2.141	2.07 ± 0.10
				B	1.975	
				C	2.143	
Snow-1	168.2 m	168.31 m	KEN 011	A	1.855	1.99 ± 0.13
				B	2.103	
				C	2.032	

Well Name	Depth (m) top	Depth (m) base	Sample		Conductivity (W/mK)	
Snow-1	199 m	199.1 m	KEN 012	A	2.179	2.07 ± 0.19
				B	1.861	
				C	2.206	
Snow-1	221.4 m	221.5 m	KEN 013	A	1.986	2.04 ± 0.17
				B	2.237	
				C	1.923	
Snow-1	243.3 m	243.4 m	KEN 014	A	2.259	2.12 ± 0.12
				B	2.035	
				C	2.055	
Snow-1	267.45 m	267.55 m	KEN 015	A	2.345	2.25 ± 0.09
				B	2.256	
				C	2.160	
Elizabeth-1	156.7 m	156.85 m	KEN 016	A	2.029	1.99 ± 0.05
				B	1.932	
				C	2.003	
Elizabeth-1	171.7 m	171.81 m	KEN 017	A	1.940	2.01 ± 0.10
				B	2.136	
				C	1.977	
Elizabeth-1	202.35 m	202.37 m	KEN 018	A	2.444	2.27 ± 0.26
				B	2.047	
				C	2.440	

Well name	Depth (m) top	Depth (m) base	Sample		Conductivity (W/mK)	
Elizabeth-1	252.7 m	252.8 m	KEN 019	A	2.125	2.15 ± 0.03
				B	2.135	
				C	2.174	
Elizabeth-1	283.72 m	283.81 m	KEN 020	A	2.071	2.11 ± 0.03
				B	2.125	
				C	2.130	

4.0 Discussion and Conclusions

In all cases the measured values agree closely for samples taken from the same specimen. This implies that variation in thermal conductivity is not significant over the scale of centimetres for the specimens examined. Variation between specimens is also relatively small. The specimens varied by only 15% from the average conductivity for all specimens (about 2.05 W/mK).

The conductivities recorded from these specimens are in the normal range expected for dolerite samples. The results suggest that the formations assessed in this study could act as attractive thermal insulation for geothermal systems.

The following additional points must be considered if extrapolating the results in this report to *in situ* formations:

1. The samples upon which the thermal conductivity measurements were made are only several square centimetres in surface area. While the specimens were chosen to represent the geological sections from which they came, there is no guarantee that the sections themselves are typical of the overall geological formations. This is especially true for heterogeneous formations. This introduces an unquantifiable random error into the results.

2. Porosity exerts a primary influence on the thermal conductivity of a rock. Water is substantially less conductive than typical mineral grains[4], and water saturated pores act to reduce the bulk thermal conductivity of the rock. Gas-filled pores reduce the bulk conductivity even more dramatically. Results reported in this document are whole-rock measurements. No adjustments were made for porosity. It is to be expected that the thermal conductivity of a given formation will vary from place to place if the porosity of the formation varies (conductivity decreases with increasing porosity).

3. Thermal conductivity of rocks is sensitive to temperature[2]. This should be kept in mind when developing models of *in situ* thermal conductivity.

[4] **Beardsmore, G.R. and Cull, J.P.** (2001). *Crustal heat flow: A guide to measurement and modelling*. Cambridge University Press, Cambridge. 324pp.

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Thermal conductivity of core samples KEN021–KEN042

Prepared for KUTh Energy Limited

18 June 2008

Graeme Beardsmore

Executive summary

KUTh Energy Ltd commissioned Hot Dry Rocks Pty Ltd (HDRPL) to measure the thermal conductivity of twenty-one (21) core specimens collected on 13 May 2008. Measurements were made on the twenty-one specimens using a steady state divided bar apparatus calibrated for the range 1.4–9.8 W/mK. Up to five samples were prepared from each specimen to investigate variation in thermal conductivity over short distance scales and to determine mean conductivity and uncertainty. All values were measured at a standard temperature of 30°C. The uncertainty for individual samples is between ±4% and ±10%.

HDRPL considers the following points to be important:

- Results are relatively high for sedimentary material, owing largely to a strong, sub-vertical foliation and the silicified nature of many of the specimens.
- While the specimens were chosen to represent the cored geological sections from which they came, there is no guarantee that the sections themselves are typical of the overall geological formations.
- It is to be expected that the thermal conductivity of a given formation will vary from place to place if the porosity or orientation of the dominant foliation of the formation varies.
- Thermal conductivity of rocks is sensitive to temperature. This should be kept in mind when developing models of *in situ* thermal conductivity.

Table of Contents

1.0 Introduction

Thermal conductivity is the physical property that controls the rate at which heat energy flows through a material in a given thermal gradient. In the S.I. system of units, it is measured in watts per metre-kelvin (W/mK). In the Earth, thermal conductivity controls the rate at which temperature increases with depth for a given heat flow. The thermal conductivity distribution within a section of crust must be known in order to calculate crustal heat flow from temperature gradient data, or to predict temperature distribution from a given heat flow. This report describes the results of laboratory thermal conductivity measurements on a series of drill core samples from KUTh Energy Ltd (KEN).

KEN commissioned Hot Dry Rocks Pty Ltd (HDRPL) to undertake this study. HDRPL took delivery of twenty-one core specimens[1] from the wells Tower Hill 1, Temple Bar 1, Epping 1 and Ben Lomond 1 in May 2008 (Table 1). Thermal conductivity measurements were made on all of these specimens using a steady state divided bar apparatus calibrated for the range 1.4–9.8 W/mK.

Thermal conductivity is sensitive to temperature, in general decreasing as temperature increases. The measurements contained in this report were made within ±2°C of 30°C.

[1] In this report the word "specimen" refers to a raw piece of rock delivered to HDRPL, while "sample" refers to part of a specimen prepared for conductivity measurement. In general, three samples are prepared from each specimen.

Table 1. Specimens presented for thermal conductivity measurement.

Specimen	Well Name	Depth From	Depth To
KEN-021	Tower Hill 1	162.80 m	163.05 m
KEN-022	Tower Hill 1	174.85 m	175.10 m
KEN-023	Tower Hill 1	204.23 m	204.48 m
KEN-024	Tower Hill 1	218.85 m	219.10 m
KEN-025	Tower Hill 1	245.05 m	245.22 m
KEN-026	*Collected but not measured due to non-representative mineralogy*		
KEN-027	Temple Bar 1	153.50 m	153.68 m
KEN-028	Temple Bar 1	169.18 m	169.38 m
KEN-029	Temple Bar 1	220.00 m	220.18 m
KEN-030	Temple Bar 1	260.70 m	260.88 m
KEN-031	Temple Bar 1	284.77 m	284.95 m
KEN-032	Epping 1	147.70 m	147.90 m
KEN-033	Epping 1	185.15 m	184.35 m
KEN-034	Epping 1	198.00 m	198.20 m
KEN-035	Epping 1	240.20 m	240.40 m
KEN-036	Epping 1	267.70 m	267.88 m
KEN-037	Ben Lomond 1	135.55 m	135.80 m
KEN-038	Ben Lomond 1	150.33 m	150.55 m
KEN-039	Ben Lomond 1	176.37 m	176.56 m
KEN-040	Ben Lomond 1	210.25 m	210.49 m
KEN-041	Ben Lomond 1	247.55 m	247.80 m
KEN-042	Ben Lomond 1	265.10 m	265.30 m

2.0 Methodology

Hot Dry Rocks Pty Ltd selected samples of rock from each of twenty-one cores, based on them being visually representative of the average lithological composition of the formation being sampled. The specimens were labelled, bagged and shipped to HDRPL's laboratory in South Yarra.

Each specimen was prepared for thermal conductivity measurement in a divided bar apparatus[2]. Three to five disks, each approximately 1/3 to 1/2 the diameter of the core in thickness, were cut from each consolidated core to investigate variation in thermal conductivity over short distance scales and to determine mean conductivity and uncertainty. The samples were all of a circular/cylindrical shape. Each sample was ground flat and polished, then evacuated under >95% vacuum for a minimum of three hours. Samples were then submerged in water prior to returning to atmospheric pressure. Water saturation continued at atmospheric pressure for a minimum of three hours, and all samples remained in water until just prior to conductivity measurement.

Values were measured at a standard temperature of 30°C (±2°C). Harmonic mean conductivity (see Figure 1) and one standard deviation uncertainty were calculated for each specimen. Results are presented in the next section.

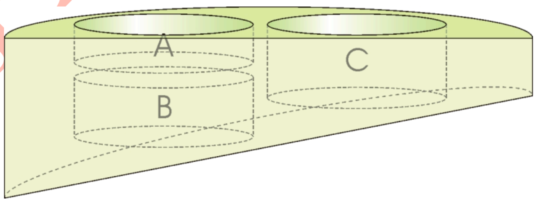

Figure 1. The average conductivity of samples in series (e.g. A and B) is found using the harmonic mean. The average conductivity of samples in parallel (e.g. A and C) is found using the arithmetic mean.

[2] Divided bar apparatus: An instrument that places an unknown sample in series with a standard of known thermal conductivity, then imposes a constant thermal gradient across the combination in order to derive the conductivity of the unknown sample.

3.0 Results

Table 2 displays the thermal conductivity for each individual sample, and the harmonic mean conductivity and standard deviation for each specimen. All values are for a standard temperature of 30°C. The uncertainty for individual samples is between ±4% and ±10% (based on the instrument precision of the divided bar apparatus).

Table 2. Thermal conductivity of samples at 30°C, and harmonic mean and uncertainty[3] for each specimen.

Well	Depth From	Depth To	Sample		Conductivity (W/mK)	
Tower Hill 1	162.8	163.05	KEN 021	A	5.21	5.23 ± 0.28
				B	4.97	
				C	5.53	
Tower Hill 1	174.85	175.1	KEN 022	A	4.31	4.26 ± 0.05
				B	4.27	
				C	4.21	
Tower Hill 1	204.23	204.48	KEN 023	A	5.30	5.18 ± 0.17
				B	4.98	
				C	5.26	
Tower Hill 1	218.85	219.1	KEN 024	A	4.84	4.76 ± 0.14
				B	4.82	
				C	4.85	
				D	4.55	
Tower Hill 1	245.05	245.22	KEN 025	A	4.05	4.06 ± 0.06
				B	4.01	
				C	4.13	
Temple Bar 1	153.5	153.68	KEN 027	A	2.53	2.48 ± 0.06
				B	2.42	
				C	2.49	
Temple Bar 1	169.18	169.38	KEN 028	A	2.39	2.49 ± 0.15
				B	2.43	
				C	2.66	
Temple Bar 1	220	220.18	KEN 029	A	2.52	2.49 ± 0.04
				B	2.50	
				C	2.44	

[3] Uncertainty of the thermal conductivity for each specimen is the standard deviation of the individual sample measurements.

Temple Bar 1	260.7	260.88	KEN 030	A	2.38	2.34 ± 0.05
				B	2.29	
				C	2.35	
Temple Bar 1	284.77	284.95	KEN 031	A	2.26	2.28 ± 0.02
				B	2.29	
				C	2.30	
Epping 1	147.7	147.9	KEN 032	A	2.09	2.09 ± 0.01
				B	2.09	
				C	2.10	
Epping 1	185.15	184.35	KEN 033	A	1.88	1.87 ± 0.05
				B	1.91	
				C	1.82	
Epping 1	198	198.2	KEN 034	A	1.94	1.97 ± 0.03
				B	1.96	
				C	2.01	
Epping 1	240.2	240.4	KEN 035	A	2.16	2.18 ± 0.03
				B	2.21	
				C	2.16	
Epping 1	267.7	267.88	KEN 036	A	2.10	2.10 ± 0.02
				B	2.08	
				C	2.12	
Ben Lomond 1	135.55	135.8	KEN 037	A	3.87	3.94 ± 0.11
				B	3.88	
				C	4.07	
Ben Lomond 1	150.33	150.55	KEN 038	A	4.28	4.24 ± 0.05
				B	4.23	
				C	4.19	
Ben Lomond 1	176.37	176.56	KEN 039	A	3.79	4.10 ± 0.30
				B	4.21	
				C	4.36	
Ben Lomond 1	210.25	210.49	KEN 040	A	3.88	3.87 ± 0.20
				B	3.68	
				C	4.08	
Ben Lomond 1	247.55	247.8	KEN 041	A	4.37	4.37 ± 0.06
				B	4.43	
				C	4.32	
Ben Lomond 1	265.1	265.3	KEN 042	A	4.21	4.41 ± 0.17
				B	4.51	
				C	4.25	
				D	4.54	
				E	4.56	

4.0 Discussion and conclusions

In most cases, the measured values agree closely for samples taken from the same specimen. This implies that variation in thermal conductivity is not significant over the scale of centimetres for the specimens examined.

The conductivities recorded from these specimens are relatively high for sedimentary units. Many of the units display a dominant foliation sub-parallel to the vertical axis of the core; generally greater than 70° to the horizontal. This alone could explain the relatively high values, as conductivity along a foliation is typically higher than across it. Formations with thermal conductivity >2.5 W/mK under surface conditions are unlikely to make adequate thermal insulation units for the purpose of geothermal energy exploration.

The following additional points must be considered if extrapolating the results in this report to *in situ* formations:

1. The samples upon which the thermal conductivity measurements were made are only several square centimetres in surface area. While the specimens were chosen to represent the geological sections from which they came, there is no guarantee that the sections themselves are typical of the overall geological formations. This is especially true for heterogeneous formations. This introduces an unquantifiable random error into the results.

2. Porosity exerts a primary influence on the thermal conductivity of a rock. Water is substantially less conductive than typical mineral grains[4], and water saturated pores act to reduce the bulk thermal conductivity of the rock. Gas-filled pores reduce the bulk conductivity even more dramatically. Results reported in this document are whole-rock measurements. No adjustments were made for porosity. It is to be expected that the thermal conductivity of a given formation will vary from place to place if the porosity of the formation varies (conductivity decreases with increasing porosity).

3. Foliations within the fabric of a rock also exert a dominant influence on thermal conductivity, with conductivity along the foliation typically significantly higher than

[4] **Beardsmore, G.R. and Cull, J.P.** (2001). *Crustal heat flow: A guide to measurement and modelling*. Cambridge University Press, Cambridge. 324pp.

across it. HDRPL intends to use some of the samples already collected to investigate the anisotropy in thermal conductivity of these units by preparing samples to measure conductivity across the foliation.

4. Thermal conductivity of rocks is sensitive to temperature, typically decreasing with increasing temperature. This should be kept in mind when developing models of *in situ* thermal conductivity.