x 3

B.C. HYDRO AND POWER AUTHORITY

Report on

THERMAL CONDUCTIVITY AND HEAT FLOW IN DIAMOND DRILL HOLES, MEAGER CREEK GEOTHERMAL AREA, SOUTHWESTERN BRITISH COLUMBIA

June 1, 1983

NEVIN | SADLIER-BROWN | GOODBRAND | LTD

B.C. HYDRO AND POWER AUTHORITY

Report on

THERMAL CONDUCTIVITY AND HEAT FLOW IN DIAMOND DRILL HOLES, MEAGER CREEK GEOTHERMAL AREA, SOUTHWESTERN BRITISH COLUMBIA

by

John F. Reader, P.Eng.

NEVIN SADLIER-BROWN GOODBRAND LTD.

June 1, 1983

TABLE OF CONTENTS

1. Summary

A total of 166 thermal conductivity measurements from core from fifteen exploration gradient holes at the Meager Creek project are analyzed. Heat flow determinations show a convectively disturbed high flux area in the South Reservoir with distinct boundaries to the south and east and remaining open to the west and north. Background values are low and consistent. North Reservoir background values are nearly twice the magnitude of those in the south, the difference attributed to a combination of higher thermal conductivity and heat productivity and a possible unseen thermal anomaly of considerable size. Heat flow measurements have proven to be useful in the development and verification of models of the geothermal system.

2. Terms of Reference

As part of the 1982 exploration program at the Meager Creek Geothermal Project, numerous samples of drill core were measured for thermal conductivity so that heat flow determinations could be made. This work was carried out under B.C. Hydro and Power Authority Purchase Order #247 693, in early 1983.

3. Theory

Temperature gradients in geothermal exploration drill holes provide valuable information about the nature of thermal anomalies in the crust. Gradients display the actual rock temperatures, as well as the existence and nature of fluid convection.

Due to variations in the thermal conductivity of the rock however, gradients may vary locally in a given hole or throughout the field when in fact the heat flow is constant. Topography, erosion, sediment deposition, past climatic variations and sediment wedges can all serve to locally concentrate or dissipate the heat flow and create a misleading geometry for the geothermal system if gradients are used as the only interpretation tool.

In this study, a rigorous analysis of the corrections that are commonly made for the listed effects has not been undertaken. Analytical methods for determining the corrections apply only to homogeneous half-spaces where no thermal anomalies exist. Clearly this does not apply at Meager Creek. Where variations of heat flow might be expected due to physiographic and geologic parameters, a sense of the correction (positive or negative) has been put forth. Some expected results are summarized here:

- heat flow is generally higher near the bottom of steep valleys

- conversely, heat flow is lower on the tops of mountains

- heat flow is low beneath thicknesses of poorly conductive sediments due to refraction (typically in valley bottoms).

4. Database

Sixty-one core samples from Meager Creek had been measured for thermal conductivity prior to this study. These samples have been incorporated into this work which includes an additional 105 for a total of 166 measurements. A summary of all values is included in Appendix A. The divided bar method as described in Goss and Combs (1976) was used to determine thermal conductivity.

During a core volume reduction program undertaken in spring 1983, core samples were taken from all holes at a nominal 15 metre spacing for future thermal conductivity measurements. The 105 determinations in this study originate from these samples. The sampling density is considered a minimum for proper statistical estimation of the average thermal conductivity of each hole. Should additional work be required the remaining samples are held in storage.

Fifteen holes were deemed suitable in gradient character for heat flow calculation. Gradients were estimated from bottom hole temperatures through the application of a least-squares regression analysis. Temperatures were taken from straight portions of the temperature profile, usually in the lower half of the hole remote from surficial disturbances. Exceptions are holes L1-78D, M6-79D and M7-79D where gradients were estimated by eye due to the high level of convective disturbance observed.

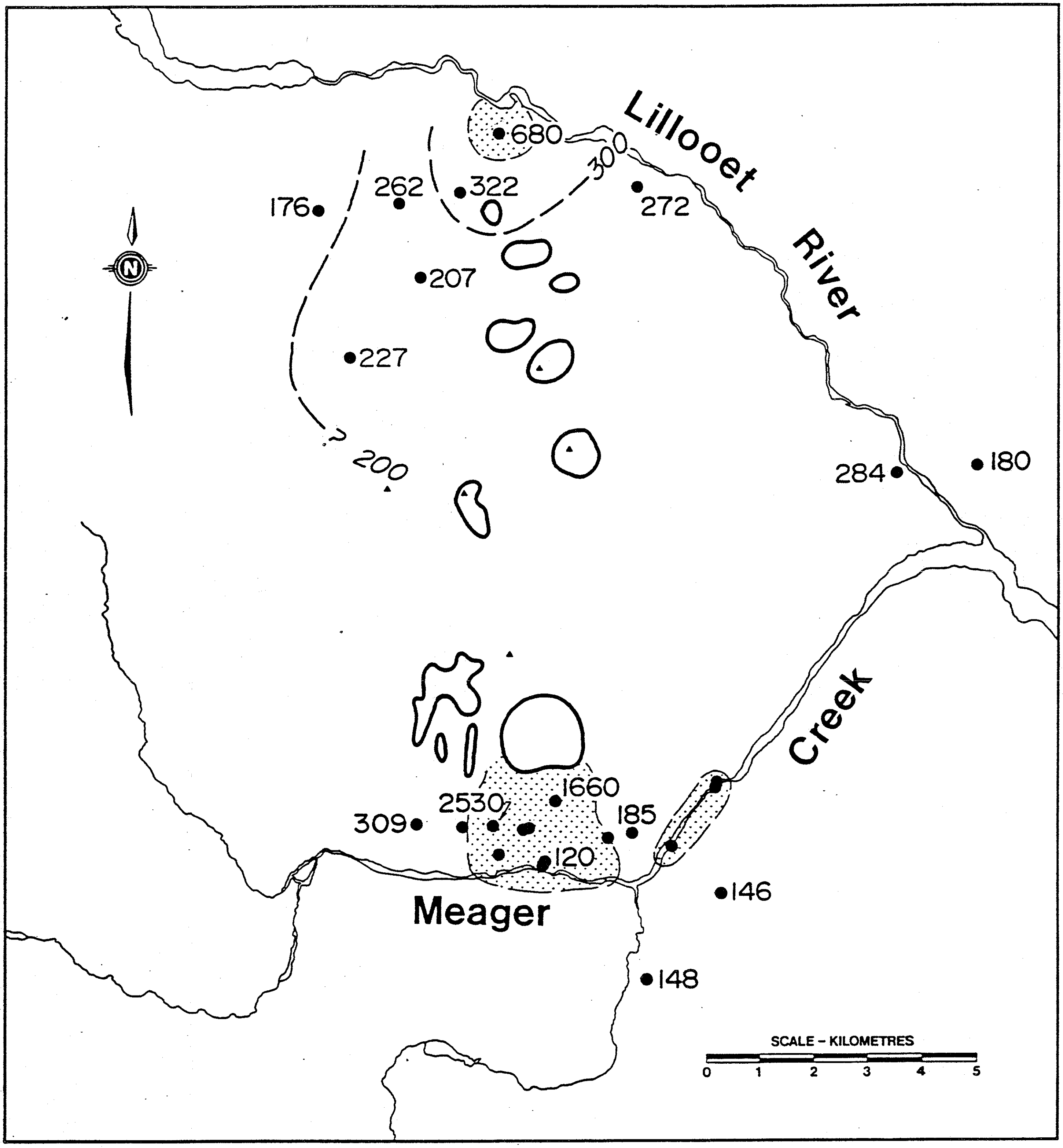
5. Data Presentation

The gradient, conductivity and heat flow data is

TABLE 1

Summary of Heat Flow Data

Hole	Gradient (°C/Km)	Average Thermal Conductivity (W/m-K)	Heat Flow (mW/m^2)
South Reservoir			
M6	733.0	2.26	1660
M7	1230.0	2.06	2530
M8	123.1	2.51	309
M9	52.4	2.30	120
M11	73.0	2.54	185
M12	61.0	2.42	148
M14	60.9	2.40	146
North Reservoir			
L2	80.5	3.26	262
L3	104.5	3.08	322
L4	86.6	2.39	207
L5	85.6	3.18	272
L6	61.1	4.64	284
L7	89.5	2.54	227
L8	72.0	2.45	176



LEGEND

Volcanic centres

146 Drill holes with heat flow in mW/m²

Contour line

Convective zone

FIGURE 1

MEAGER CREEK HEAT FLOW

TABLE 2: Variation of Thermal Conductivity with Rock Type

Area	Rock Type	Number of Samples	Average (mW/m^2)	Standard Deviation
South Reservoir	Quartz Diorite and Gneiss	50	2.38	0.31
	Metamorphic Rocks	10	2.00	0.47
North Reservoir	Quartz Monzonite	30	3.19	0.15
	Metamorphic Rocks (all except samples ⊥ to foliation)	43	2.94	0.88
	parallel to foliation	12	2.51	0.29
	perpendicular to foliation	4	1.91	0.05
	L6-81D	16	3.73	0.91
Entire Project Area	Volcanic Dykes (miscellaneous)	10	2.24	0.59

summarized in Table 1. Figure 1 is a map showing heat flow values and drillholes. The stippled area displays the zones which are highly disturbed by convecting fluids.

Table 2 shows the distribution of conductivity values with rock-type. The data has been divided into categories to show major differences between data subsets. Of note are the distinctly higher conductivities of the North Reservoir rocks versus the South Reservoir values, the much higher values of the L6-82D measurements, and the high variability of the volcanic dyke samples. Finally, the difference in thermal conductivity with respect to foliation direction implies significant inhomogeniety and further complicates interpretation of the results. The effects of inhomogeniety are not addressed in this study due to lack of sample density and uncertain geometry of geologic rock units.

6. Interpretation

6.1 South Reservoir

The South Reservoir is dominated by a large convective flow system. Holes M5, M6, M7, M10, M13, MC1, MC2 and MC3 all display convective signatures typified by both non-linear and/or isothermal temperature profiles. Beyond this disturbed zone, shown in stipples on Figure 1, measured gradients are essentially conductive at depth with occasional minor lateral warm and cold flows overprinted.

High temperatures in convectively disturbed holes, increase to the west towards No Good Creek and are augmented by a high conductive heat flow value at M8-79D. This suggests that although M8 is not penetrating a convective cell, it overlies a thermally active zone at depth. The high heat flow suggests the continuation of the convection system to the west, a potentially significant finding regarding future deep exploration hole targeting.

Elsewhere the gradients are remarkably consistent, implying an eastern and southern cut off to main geothermal activity. Drill hole M9-80D is unusual in that despite its proximity to the main system it produces a below background heat flow value. This can be explained by the fact that the hole penetrates the Meager Creek fault zone which appears to be one of the major fluid-controlling structures. In the area of M9-79D the convective system is not active below this fault. Enhancing the low heat flow value is the refraction effect of the water-saturated and poorly-conducting sediments in the valley bottom.

6.2 <u>North Reservoir</u>

Heat flow magnitude in the North Reservoir is about twice that observed to the south. Several factors are probably contributing to this feature. Of primary importance is the distinctly higher average thermal conductivity of the quartz monzonites and metamorphic rocks in this area (see Figure 2). For an identical heat source and identical gradients, a higher conductivity will result in a higher heat flow.

Heat production by radioactive decay is observed in the Tertiary quartz monzonite of the Affliction Creek Stock (see Appendix B). It is unlikely, however, that more than 10mW/m^2 heat flow can be attributed to the average heat productivity of 2.46 uW/m^3.

Of the North Reservoir drill holes, L1-78D is distinguished by evidence of considerable fluid flow and an approximate heat flow of 680mW/m^2. Heat flux can be contoured around this anomalous hole suggesting that the measured conductive gradients are affected by a convective system the magnitude and location of which is clear.

The heat flow value of L7-82D is relatively high considering its collar elevation of 6000 feet. The location of the hole near a ridge top should serve to suppress the value (not observed) and indicates that the thermal anomaly extends to this area.

Near the confluence of Meager Creek and the Lillooet River, different heat flows are measured in adjacent holes L6-81D (284mW/m^2) and Energy, Mines and Resources hole 303-1 (180mW/m^2, Lewis and Jessop, 1981). These holes are probably in the same thermal regime on the fringes of the Meager anomaly, with their differences reflecting the variation in thermal conductivity between the metamorphic rock in L6 and the quartz diorite in 303-1. The possibility of fluid flow enhancing the high value in L6 cannot, however, be ruled out.

6.3 Overview of the Project Area

Considering on a larger scale the Meager Creek Volcanic Complex, the heat flow data presents a model consistent with a north-south trending hot zone related to the observed volcanic centres. Whereas no latent heat originating from the explosive activity dating around 1.9 mya in the south is to be expected, it appears that fracturing in the rock, accompanied by some major structural discontinuities has allowed the development of a mature convection system which produces locally higher heat flow. To the north, evidence for an active convective system is limited primarily to one hole. An overall area of high heat flows may be due to a combination of rock properties and/or an undiscovered geothermal system of considerable size. A continuous hot zone connecting the South and North Reservoirs cannot be ruled out with the present data. Such a zone would considerably enhance the magnitude of the thermal anomaly.

7. Discussion of Heat Flow as an Exploration Tool

Determination of heat flow in areas where conductive gradients are evident is an essential part of analyzing gradient data. Without thermal conductivity measurements, the significant difference between North and South Reservoirs at Meager Creek is not evident. Where rock conductivity varies considerably and gradients are identical, heat flow differences can be significant and the gradient information alone does not give an accurate picture of the potential geothermal system.

The technique must be used with caution due to the effects of convective fluid flow. Unseen deep convective systems can produce elevated heat flows which are difficult to interpret. The use of heat flow is most useful for modeling features of a system on a scale that describes the entire thermal anomaly, as opposed to defining local drill targets.

8.0 References

Goss, R. and Combs, J., 1976. Thermal Conductivity Measurement and Prediction from Geophysical Well Log Parameters with Borehole Application, 2nd UN Geothermal Symposium. Volume 2, p 1019-1027.

Lewis, J.F. and Jessop, A.M., 1981. Heat Flow in the Garibaldi Volcanic Belt, A Possible Canadian Geothermal Energy Resource Area. Can. J. Earth Sci., 18, p 366-375.

Nevin Sadlier-Brown Goodbrand Ltd. reports to B.C. Hydro and Power Authority, 1974 - Present.

APPENDIX A

L2-80D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
49.8	QUARTZ MONZONITE	3.03
51.0	" "	3.32
150.2	" "	3.36
201.2	RHYODACITE	2.96
206.3	"	3.24
290.0	QUARTZ MONZONITE	3.30
335.0	" "	3.29
349.6	" "	3.41
411.0	" "	3.31
442.0	" "	3.08
488.0	PORPHYRITIC ANDESITE	1.85
518.0	QUARTZ MONZONITE	3.29
549.0	" "	3.26
579.0	" "	3.22
	Average (All)	3.14
	SD	0.39
	Average QM Only	3.26
	SD	0.11

ELEVATION: 896m

TOTAL DEPTH: 595.4m

TEMP. GRADIENT: 80.5°C/km (304.8 - 586.7m depth interval)

Heat flow (uncorrected)

- using QM average: 262 mW/m^2

L3-80D

SAMPLE DEPTH(m)	**ROCK TYPE**	**K (W/m-K)**	
405	LEUCOGRANITE	3.22	(Fall Creek Pluton)
495	"	3.13	
540	"	3.22	
600	"	3.29	
645	"	3.10	
705	"	2.92	
750	PORPHYRITIC ANDESITE	2.70	
765	LEUCOGRANITE	2.65	
810	"	3.11	
855	"	3.39	
915	"	3.13	
975	"	3.15	
	Average	3.08	
	SD	0.22	

ELEVATION: 972m

TOTAL DEPTH: 1010m

TEMP. GRADIENT: 104.5°C/Km (649.0 - 1000.0m depth interval)

Heat flow (uncorrected): 322 mW/m^2

L4-81D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)	
108.0	PHYLLITE (strongly foliated)	2.24	to foliation
208.0	" " "	2.20	"
208.0	" " "	1.94	Perp. to foliation
316.5	" " "	2.33	to foliation
316.5	" " "	1.85	Perp. to foliation
395.0	AMPHIBOLITE (streaky)	3.21	to foliation
395.0	" "	1.89*	Perp. to foliation
426.0	" "	1.96	Perp. to foliation
426.5	" "	2.68	to foliation
495.0	PHYLLITE (strongly foliated)	2.41	" " "
650.0	" " "	2.54	" " "
855.0	" " "	2.36	" " "
1005.0	" " "	2.88	" " "
1110.0	MIGMATITE (mixed phyllite/ quartz diorite)	2.48	" " "
1170.0	PHYLLITE (strongly foliated)	2.47	" " "
1245.0	" " "	2.35	

Average 2.39
SD 0.36

* Sample not flat on ends - one side cracked in divided-bar -apparatus-value may be low.

ELEVATION: 1097m

TOTAL DEPTH: 1279m

TEMP. GRADIENT: 86.6°C/Km (814.5 - 1279.0m depth interval)

Heat flow (uncorrected): 207 mW/m^2

L5-81D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
285	RHYODACITE	1.66
315	"	0.77*
360	LEUCOGRANITE	3.13 (Fall Creek Stock)
465	"	3.12
495	"	3.16
525	"	3.18
555	"	3.17
585	"	3.17
615	"	3.19
660	"	3.29

Average (without 285m)
3.18
SD 0.05

ELEVATION: 774m

TOTAL DEPTH: 660m

TEMP. GRADIENT: 85.57°C/Km (445.2 - 660.0m depth interval)

Heat flow (uncorrected): 272 mW/m^2

* Sample ran at less than standard pressure.

L6-81D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)	
27.8	METAVOLCANICS	2.78	to foliation
69.7	"	2.30	to foliation
133.5	"	2.77	to foliation
180.0	"	3.10	
195.0	"	3.51	
255.0	"	3.36	
270.0	"	3.43	
300.0	"	2.52	
315.0	"	3.48	
345.0	"	4.67	
375.0	"	4.93	
405.0	"	4.50	
450.0	"	4.85	
495.0	METASEDIMENTS (strongly foliated)	4.48	
540.0	METASEDIMENTS	4.96	
555.0	METAVOLCANICS	4.10	

Average for last 7 samples
4.64
SD 0.31

ELEVATION: 535m

TOTAL DEPTH: 579.2m

TEMP. GRADIENT: 61.1°C/Km (400.0 - 579.0m depth interval)

Heat flow (uncorrected): 284 mW/m^2

- taking only conductivities from bottom of hole

L7-82D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
60	QUARTZ DIORITE (Homogeneous)	2.81
105	" "	2.68
135	" "	2.73
165	" "	2.78
180	" "	2.70
225	" "	2.63
240	" "	2.70
270	QUARTZ DIORITE (Heterogeneous)	2.44
300	ANDESITE	1.80
303	DACITE	2.09
350	QUARTZ DIORITE (Heterogeneous)	2.29
393	" "	2.84
	Average:	2.54
	SD	0.32

ELEVATION: 1808m

TOTAL DEPTH: 420.7m

TEMP. GRADIENT: 89.5°C/Km (250m - bottom)

Heat flow (uncorrected): 227 mW/m^2

L8-82D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
45	AMPHIBOLITE (Mod to strongly foliated)	2.12
105	"	2.03
150	ANDESITE DYKE	2.39
165	AMPHIBOLITE (Mod to strongly foliated)	2.16
210	"	2.44
240	"	2.22
255	"	2.15
285	"	2.18
300	"	2.38
345	AMPHIBOLITE (Altered + some intense fracturing)	2.18
360	"	2.13
375	"	2.74
405	AMPHIBOLITE (Mod to strongly foliated)	2.65
420	AMPHIBOLITE (Altered/fractured)	3.24
435	AMPHIBOLITE (Mod to strongly foliated)	3.69
	Average:	2.45
	SD	0.47

ELEVATION: 960m

TOTAL DEPTH: 475.5m

TEMP. GRADIENT: 72.0°C/Km (362.0 - 472.0m depth interval)

Heat flow (uncorrected): 176 mW/m^2

M6-79D

SAMPLE DEPTH(m)	**ROCK TYPE**	**K (W/m-K)**
83.5	GNEISS	2.13
138.0	AMPHIBOLITE	2.74
135.5	GNEISS	1.77
196.0	AMPHIBOLITE	2.31
215.5	GNEISS	1.99
283.5	AMPHIBOLITE	2.64
	Average:	2.26
	SD	0.38

ELEVATION: 885m

TOTAL DEPTH: 321m

TEMP. GRADIENT: 733°C/Km (approx. from 72 - 143m)

Heat flow (uncorrected): 1660 mW/m^2

M7-79D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
133.5	VOLCANIC PORPHYRY	2.26
174.0	QUARTZ DIORITE	1.90
201.0	" "	2.08
210.0	" "	2.12
322.0	" "	1.99
340.0	" "	1.99
	Average:	2.06
	SD	0.13

ELEVATION: 900m

TOTAL DEPTH: 367m

TEMP. GRADIENT: 1230°C/Km (150 - 240m)

Heat Flow (uncorrected): 2.53 W/m^2

M8-79D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
57	GNEISS	2.15
135	AMPHIBOLITE	1.69
156	"	1.79
172	GNEISS	2.41
195.8	GNEISS	2.43
234	AMPHIBOLITE	2.06
285	GNEISS	3.13
345	QUARTZ DIORITE	2.81
390	" "	2.23
435	GNEISS	2.64
495	GNEISS	2.37

Average:	2.34	175m+	2.51
SD	0.42	SD	0.34

ELEVATION: 875m

TOTAL DEPTH: 497m

TEMP. GRADIENT: 123.1°C/Km (700m - bottom)

Heat flow (uncorrected): 309 mW/m^2

M9-80D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
163.0	QUARTZ DIORITE	2.08
413.0	" "	2.20
795.0	" "	2.50
855.0	" "	2.77
905.2	" "	2.41
930.0	" "	2.54
975.0	" "	2.11
1054.8	AMPHIBOLITE & METAVOLCANICS	2.13
1091.0	AMPHIBOLITE	1.92
	Average:	2.30
	SD	0.27

ELEVATION: 765m

TOTAL DEPTH: 1142m

TEMP. GRADIENT: 52.4°C/Km (650m - bottom)

Heat flow (uncorrected): 120 mW/m^2

M11-80D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
19.7	GREENSTONE (Massive)	1.28
64.0	HORNFELS	1.47
159.2	GNEISS (Med. grained)	2.09
287.3	QUARTZ DIORITE	2.76
305.0	" "	2.64
335.0	" "	3.04
340.3	" "	2.64
380.0	GNEISS (Med. grained)	2.51
403.0	"	2.66
425.0	"	2.07
475.2	"	2.41

Average: 2.54 (below 100m)
SD 0.31

ELEVATION: 791m

TOTAL DEPTH: 559.4m

TEMP. GRADIENT: 73.0°C/Km (350m - bottom)

Heat flow (uncorrected): 185 mW/m^2

M12-80D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
101.5	QUARTZ DIORITE	2.14
194.5	PORPHYRITIC ANDESITE	1.40
210.0	QUARTZ DIORITE	2.38
240.0	" "	2.57
286.0	" "	2.17
315.0	" "	2.49
375.0	" "	2.58
450.0	" "	2.33
510.0	" "	2.50
550.0	" "	2.51
600.0	" "	2.57
	(without andesite) Average:	2.42
	SD	0.16

ELEVATION: 792.5m

TOTAL DEPTH: 605.0m

TEMP. GRADIENT: 61.0°C/Km (350m - bottom)

Heat flow (uncorrected): 148 mW/m^2

M14-80D

SAMPLE DEPTH(m)	ROCK TYPE	K (W/m-K)
360	GNEISS	2.40
405	"	2.66
435	"	1.89
450	"	2.26
480	"	2.15
525	"	2.49
555	QUARTZ DIORITE	2.22
570	" "	3.12
	Average:	2.40
	SD	0.37

ELEVATION: 861m

TOTAL DEPTH: 578.5m

TEMP. GRADIENT: 60.9°C/Km (225m - bottom)

Heat flow (uncorrected): 146 mW/m^2

APPENDIX B

Heat Productivity Values - Meager North Core Samples

Sample	U(ppm)	Th(ppm)	K(%)	Heat Prod (μWm^3)**	% Counting Error	Th/U
L1-1288'	4.54	9.93	3.71	2.21	1.2	2.2
L1-1504'	3.83	10.5	3.94	2.09	3.4	2.7
L1-1712'	5.21	9.97	4.02	2.41	1.9	1.9
L2-1092'	4.58	12.4	4.18	2.43	3.4	2.7
L2-1110'	6.07	13.6	4.32	2.92	1.8	2.3
L2-1200'	4.47	11.5	3.97	2.32	3.4	2.6
L2-1344'	5.00	12.5	4.42	2.56	5.8	2.3
L3-562'	4.30	10.9	4.19	2.27	4.0	2.5
L3-599'	5.25	13.4	4.08	2.66	1.7	2.6
L3-704'	5.33	14.4	4.11	2.75	1.9	2.7

Average = 2.46
SD = 0.259

** assuming a density of 2.65g/cc (quartz monzonites of this area)

Analysis prepared by Dr. T.J. Lewis, Pacific Geoscience Centre.