Heat flow in the Nipigon arm of the Keweenawan rift, northwestern Ontario, Canada

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[1] In the Archean Superior Province, the Nipigon Embayment, in the area of Lake Nipigon north of Lake Superior, is covered by MidProterozoic sediments intruded by Keweenawan diabase sills. It has been interpreted as a failed arm of the ca. 1100 Ma Keweenawan rift. Six new heat flow values in this area show that the region of low heat flow associated with the Keweenawan rift in Lake Superior extends northwards along the western margin of the Nipigon Embayment. The average heat flow in the Nipigon area (39 ± 5 mWm^{-2}) is only slightly lower than that of the adjacent western Superior Province (42 ± 8 mWm^{-2}), indicating that the volume of Keweenawan mafic intrusives in the Nipigon crust is small. *INDEX TERMS:* 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8130 Tectonophysics: Heat generation and transport; 8125 Tectonophysics: Evolution of the Earth; 8094 Structural Geology: Instruments and techniques. **Citation:** Perry, H. K. C., C. Jaupart, J.-C. Mareschal, F. Rolandone, and G. Bienfait (2004), Heat flow in the Nipigon arm of the Keweenawan rift, northwestern Ontario, Canada, *Geophys. Res. Lett.*, *31*, L15607, doi:10.1029/2004GL020159.

1. Introduction

[2] The Superior Province of the Canadian Shield is the world's largest Archean craton. It is made up of east-west trending belts which fall into four types: volcano-plutonic (granite-greenstone), metasedimentary, plutonic, and high-grade gneiss [*Card and Ciesielski*, 1986]. The mixture of continental and volcanic terrain fragments in the province suggests that the Superior Province was accreted by a sequence of subduction-driven processes [*Langford and Morin*, 1976; *Card*, 1990] that lasted until 2.7 Ga. [*Henry et al.*, 1998; *Tomlinson et al.*, 2002].

[3] The Keweenawan igneous event at ca. 1100 Ma [*Van Schmus et al.*, 1982] was the last major event in the crustal evolution of the Lake Superior region. The main episode of volcanism occurred between 1109 Ma [*Davis and Sutcliffe*, 1985] and 1086 Ma [*Palmer and Davis*, 1987]. The Keweenawan rift can be traced by its gravity anomaly pattern from Kansas to Lake Superior where it turns and continues under the Michigan Basin (Figure 1). The shape of the rift is believed to be largely controlled by pre-existing structures [*Klasner et al.*, 1982]. The GLIMPCE seismic experiment has shown a 35 km thick pile of sediments and volcanics in the center of the rift beneath Lake Superior [*Cannon et al.*, 1989]. The Keweenawan rift apparently branched out northward of Lake Superior toward Lake Nipigon, through what is now called the "Nipigon Embayment" [*Sutcliffe*, 1991]. *Franklin et al.* [1980] proposed that the Nipigon Embayment acted as a failed arm during the Keweenawan event.

[4] The "Nipigon Embayment", formerly known as the "Nipigon plate" [*Stockwell et al.*, 1972], is a broad basinal structure extending 160 km north from Lake Superior through the Quetico and Wabigoon subprovinces (Figure 2). Surface rocks consist primarily of a sequence of Late Proterozoic pre-Keweenawan sedimentary rocks of the Sibley Group intruded by Keweenawan Logan diabase sills ca. 1109 Ma [*Davis and Sutcliffe*, 1985; *Sutcliffe*, 1991]. Prior to the Keweenawan event, the Archean basement of this region experienced two thermal perturbations. Anorogenic felsic magmatism occurred at ca. 1700-1600 Ma in Lake Nipigon and northern Lake Superior, leaving the Osler Volcanic Group [*Davis and Sutcliffe*, 1985]. This was followed by subsidence and deposition of the Sibley Group sediments at 1339 ± 33 Ma [*Franklin et al.*, 1980]. Thermal perturbations related to these events have decayed away.

[5] In stable continents, crustal heat generation contributes the largest component of the surface heat flow, implying that heat flow variations reflect changes in bulk crustal composition. In this paper, we report six heat flow measurements in deep boreholes in the Nipigon Embayment region which can be used to estimate the amount of Keweenawan mafic intrusives in the Nipigon crust.

2. New Heat Flow and Heat Production Data

2.1. Measurement Methods

[6] Heat flow Q is determined from measurements of the borehole temperature gradient and the conductivity of rock samples:

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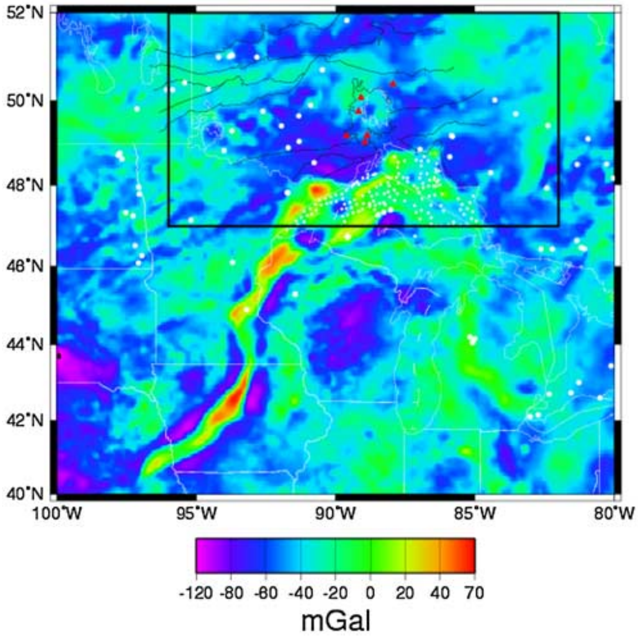

Figure 1. Map of Bouguer gravity anomaly of the Keweenawan rift system. The black box marks the limits of the heat flow study area. The thin black lines show subprovince boundaries and the Nipigon Embayment. The red triangles mark the locations of new heat flow measurements and white circles show locations of previous heat flow sites.

$$Q = k\frac{\partial T}{\partial z} \qquad (1)$$

where k is the thermal conductivity, T is the temperature and z is depth from the surface. Conductivity measurements were made with the divided bar method on core samples at an interval of ≈80 m throughout the depth of the borehole where possible. For each sample, measurements were made on five cylinders of varying thickness in order to detect small-scale compositional heterogeneity non-representative of the overall rock composition.

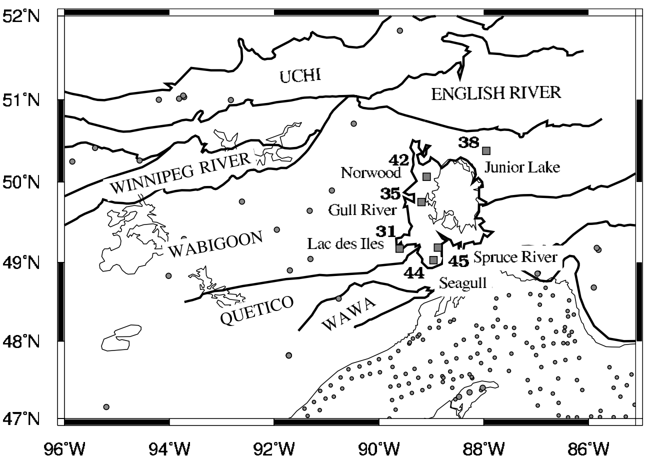

Figure 2. Locations of heat flow sites in the Superior Province. The new sites (grey squares) are identified. Previous land and Lake Superior values are shown as grey circles. The Nipigon Embayment is the region outlined in black encompassing Lake Nipigon lying between the Quetico and Wabigoon subprovinces as defined by *Davis and Sutcliffe* [1985]. The numbers represent the heat flow values for each site.

[7] Reliable continental heat flow measurements require deep boreholes because recent climate changes and surface perturbations can affect temperature to 200–300 m depth. The quality of each heat flow value was rated following *Pinet et al.* [1991]. Sites rated A consist of either several boreholes deeper than 300 m giving consistent heat flow values or a single borehole deeper than 700 m where heat flow is stable over more than 300 m. Sites where the heat flow is less consistent between neighboring boreholes or where the heat flow is obtained from a single borehole shallower than 600 m are rated B. Sites consisting of shallower boreholes or sites where differences between adjacent boreholes are larger than two standard deviations are rated C. All heat flow values were corrected for temperature variations following the retreat of the Laurentide ice sheet at 10 ka.

2.2. New Site Descriptions

[8] We present new heat flow data from six sites in and around the Nipigon Embayment. The locations are shown in Figure 2. The temperature-depth profiles are shown in Figure 3. Table 1 presents all of the relevant information.

2.2.1. Seagull 01–12, 01–13, 02–06

[9] Three very deep boreholes (01–12: 785 m, 01–13: 885 m, 02–06: 807 m) traverse thick peridotite sequences and small amounts of biotite pyroxenite. The lowermost section of these holes is dominated by Quetico sediment sequences. The temperature profiles exhibit marked changes in the geothermal gradient with depth. In order to verify that these changes are not related to large perturbations to the hydrological system due to drilling, the measurement at borehole 01–13 carried out in 2001 was repeated one year later in 2002. Within experimental error, the measurements are identical confirming that the temperature field is in steady state. The changes in

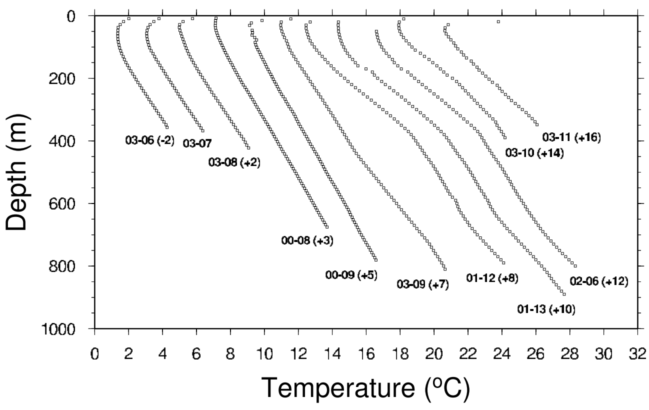

Figure 3. Temperature-depth profiles for borehole data in and around the Nipigon Embayment region. The profiles are shifted horizontally as indicated to avoid superposition.

Table 1. New Heat Flow Measurements Near the Nipigon Embayment Region, Superior Province[a]

Site Hole #	Lat North	Long West	Dip deg	Δh m	N_k	⟨k⟩ W m^{-1} K^{-1}	Γ mK m^{-1}	Q	σ_Q	ΔQ	Q_c
								m Wm^{-2}			
Seagull											**44** (A)
01–12	49 01 39	88 57 27	90	200–780	7	2.53	15.9	40.4	6.0	3.7	44.0
01–13	49 01 39	88 57 30	90	200–790	8	2.54	16.1	41.0	4.9	3.6	44.5
02–06	49 01 35	88 57 23	90	200–790	9	2.53	15.8	39.9	3.6	3.7	43.7
Lac des Iles											**31** (A)
00–08	49 10 17	89 36 18	52	268–666	11	2.54	10.8	27.4	0.9	3.1	30.6
00–09	49 10 19	89 36 19	51	345–770	13	2.63	10.5	27.6	1.8	3.1	30.7
Spruce River											**45** (C)
03–11	49 11 07	88 52 23	75	145–329	4	2.15	19.7	42.3	4.8	2.8	45.1
Gull River											**35** (A)
03–09	49 45 07	89 11 16	90	130–720	8	2.43	13.3	32.3	1.2	2.6	35.0
Norwood											**42** (C)
03–10	50 03 47	89 05 22	90	220–330	6	2.21	17.8	39.2	1.0	3.0	42.3
Junior Lake											**38** (A)
03–06	50 22 55	87 56 58	70	195–339	5	2.88	12.1	34.9	1.1	2.6	37.4
03–07	50 22 51	87 56 59	70	195–359	5	2.88	12.2	35.1	1.6	2.5	37.6
03–08	50 22 57	87 57 09	70	197–395	5	2.88	12.2	35.2	1.1	2.5	37.7

[a]Δh is the depth interval over which heat flow is estimated, k is thermal conductivity, N_k is the number of conductivity samples, Γ is the temperature gradient, Q is heat flow, σ_Q is the standard deviation on the heat flow, ΔQ is the climatic correction for heat flow, and Q_c is the corrected heat flow.

geothermal gradient are compensated by changes in thermal conductivity and there is no significant variation of heat flow with depth in the three wells. The value of 44 mWm^{-2} is rated A.

2.2.2. Lac des Iles 00–08, 00–09

[10] Two very deep boreholes (00–08: 675 m, 00–09: 780 m) traverse alternating sections of gabbro-melanogabbro-norite with relatively thick layers of magnetite bearing gabbro between 400–600 m. The two holes give very consistent values and the mean value of 31 mWm^{-2} is rated A.

2.2.3. Spruce River 03–11

[11] This deep borehole (340 m) traverses relatively uniform layers of olivine, Sibley Sediment, and pegmatoidal and melano gabbro. This borehole typifies the geology of the Nipigon Embayment with mafic diabase sills intruding the older Sibley sediment. The value of 45 mWm^{-2} based on a single hole is rated C.

2.2.4. Gull River 03–09

[12] This very deep borehole (820 m) traverses a thick layer of granitic gneiss followed by olivine rich gabbro. The gradient is slightly lower in the top half of the borehole than below 440 m. This change in gradient is compensated by a change in thermal conductivity and the heat flow is constant. The value of 35 mWm^{-2} is rated A.

2.2.5. Norwood 03–10

[13] This deep borehole (390 m) traverses ≈150 m of high-conductivity pyroxenite at the surface and ≈50 m of pyroxenite near 290 m. This locally increases the heat flow. A region of gabbro and diabase between 220 and 330 m provides a relatively constant temperature gradient. Below the gabbro and diabase layer, the temperature gradient increases in a thin sandstone unit. The heat flow value of 42 mWm^{-2}, estimated over less than 300 m, is rated C.

2.2.6. Junior Lake 03–06, 03–07, 03–08

[14] These three deep boreholes (03–06: 347 m, 03–07: 367 m, 03–08: 422 m) traverse relatively homogeneous gabbro-melanogabbro sequences with intrusive mafic dykes and volcanics encountered in 03–06 and 03–07. The heat flow is consistent between these holes and the mean value of 38 mWm^{-2} is rated A.

2.3. Heat Production

[15] Table 2 presents the summary of heat production determinations on samples from the drill holes. Measurements method are described by *Mareschal et al.* [1989]. The analytical errors are small and the main source of error comes from sampling. The results illustrate that the intrusions have much lower heat production than the Archean basement. The targets of all the measured drill holes were mafic and ultramafic intrusives in the Nipigon Embayment. As expected, heat production is extremely low on all the samples from these intrusions, ≈0.15 μW m^{-3}. At Seagull, the drill holes intersect the Quetico metasedimentary Archean basement which has a heat production of 1.13 μW m^{-3}, close to the average value for upper crust of the Superior Province [*Pinet et al.*, 1991]. Surface heat flow could thus be reduced by ≈1 mWm^{-2} per km of mafic intrusives in the crustal column.

3. Heat Flow in the Nipigon Embayment Region

[16] The heat flow values range between 31 and 45 mWm^{-2}, with a mean and standard deviation of 39.2 ±

Table 2. Heat Production at the Heat Flow Sites in the Nipigon Embayment[a]

Site	U	Th	K	A	σ_A	N_A
				μW m^{-3}		
Seagull intrusives	0.12	0.31	0.40	0.09	0.03	19
Seagull metasediments	1.9	6.89	1.93	1.13	0.21	5
Lac des Iles	<0.17	0.20	0.18	0.08	0.04	24
Spruce River	0.21	0.91	0.25	0.14	0.05	3
Gull River intrusives	0.2	0.72	0.21	0.12	0.02	3
Gull River gneiss	0.35	2.34	0.5	0.3	0.2	5
Norwood intrusives	0.33	1.22	0.35	0.20	0.04	5
Norwood gneiss	0.44	2.05	1.19	0.36	-	1
Junior Lake	<0.21	<0.69	0.28	0.12	0.19	7

[a]U and Th are Uranium and Thorium concentrations in ppm, K is Potassium concentration in per cent, A is heat production, σ_A is standard deviation and N_A is the number of samples.

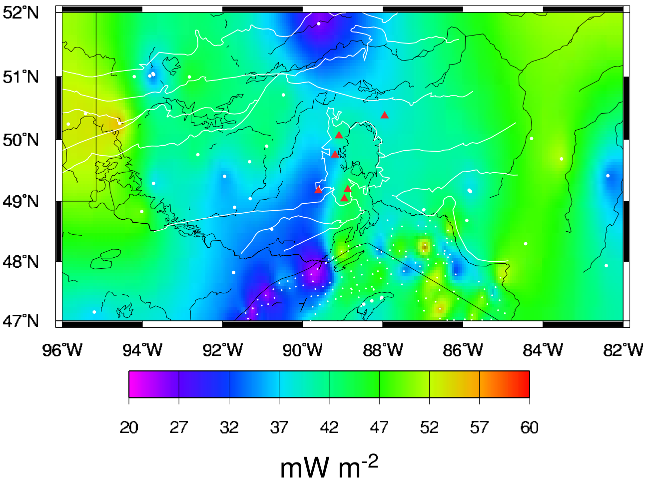

Figure 4. Heat flow map of the Western Superior Province. The six new heat flow measurements around the Nipigon Embayment are shown with red triangles. Previous land data are shown as large white circles. Data from Lake Superior are shown as small white circles. White lines mark the subprovince boundaries.

5.5 mWm^{-2}. The range of heat flow values (31–45 mWm^{-2}) is the same as that of other regions in the Superior Province of the Canadian Shield. The mean heat flow 39.2 ± 2.2 mWm^{-2} (standard error) is slightly lower than that of the adjacent western Superior Province 42 ± 1.9 mWm^{-2} [*Rolandone et al.*, 2003].

[17] The last major thermal perturbation in this region was the intrusion of Logan diabase sills which occurred at ca. 1100 Ma. Therefore, any thermal transient has now vanished and the crust has returned to thermal steady state. This implies that the surface heat flow is the sum of the crustal heat production and the heat supply at the base of the crust (referred to as the mantle heat flow). The mantle heat flow for the eastern Superior region and in the Trans-Hudson Orogen, which bound the study area to the east and west respectively, has been estimated to be small and in the range of 11–15 mWm^{-2}, consistent with estimates throughout the Canadian Shield [*Jaupart and Mareschal*, 1999]. Recent seismic tomographic studies show a 200 km wide negative P-wave velocity anomaly in the mantle beneath the Nipigon Embayment region descending to depths of ≈300 km [*Sol et al.*, 2002, Figure 7]. We interpret this anomaly as a relict of the ancient upwelling which fed the Nipigon magmas. The negative velocity anomaly of about 1% corresponds to the contrast between Archean and Proterozoic continental root material [*Griffin et al.*, 1998]. Heat production in the lithospheric mantle is poorly known [*Russell et al.*, 2001; *Rudnick et al.*, 1998] but is small, and usually assumed to contribute less than the uncertainty (±2 mWm^{-2}) to the estimated mantle heat flow [*Mareschal and Jaupart*, 2004]. Variations in heat production in the lithospheric mantle are therefore undetectable in the surface heat flow. The variations of heat flow occur over a small length-scale: heat flow varies from 31 mWm^{-2} at Lac des Iles to 44 mWm^{-2} at Seagull over a distance less than 50 km (Figures 2, 4). For such a short distance, differences in surface heat flow cannot be of deep origin and can only be due to local changes in crustal heat production.

[18] The range of heat flow values in the Midcontinent Rift System (MRS) near the northwestern shore of adjacent Lake Superior is low, between 20–31 mWm^{-2} [*Hart et al.*, 1994], indicating that crustal heat production is low as expected for a mafic crustal composition. The region of low heat flow in Lake Superior coincides with a band of very high Bouguer gravity anomalies (Figures 1, 4). A low heat flow lobe extends north of Lake Superior along the western margin of the Nipigon Embayment. Within the Nipigon Embayment, the heat flow values are within the range of the western Superior Province suggesting that the fraction of mafic rocks in the crust is less than in the MRS. Recent interpretation of a seismic refraction line just north of the Nipigon Embayment confirms that the volume of Keweenawan mafic intrusives is small (<3 km) [*Musacchio et al.*, 2004]. The marked Bouguer gravity high over the MRS does not extend to the Nipigon Embayment, also suggesting that the volume of Keweenawan intrusives in the region is small.

[19] In summary, in the Nipigon Embayment, the heat flow distribution suggests that the crust is more mafic along the western margin than in the central part. The low heat flow area likely results from the intrusive events which occurred during the tectonic propagation of a failed arm of the Keweenawan rift system.

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