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Evidence for thermal mining in low temperature geothermal areas in Iceland

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Abstract

This study deals with thermal mining in several geothermal systems in Iceland. A number of 2500- to 3000-m deep drillholes have been drilled into low temperature geothermal areas in the country. The conductive gradient outside active geothermal areas has also been mapped, and shows a systematic variation from lower than 50°C/km in the outer parts of the Tertiary basalts to over 100°C/km on the borders of the volcanic zones (rift zones). The difference between formation temperatures inside geothermal systems and the surrounding conductive gradient can be computed as a function of depth. This difference is termed ΔT in this paper. The ΔT-curves show that the upper parts of the geothermal systems are heated and the lower parts are cooled compared to the undisturbed conductive gradient. In many cases the cooling of the lower part is greater than the heating in the upper part, so that a net thermal mining has occurred. This thermal mining is calculated for several geothermal systems, and the systems are compared. The net thermal mining in the top 3000 m appears to be much greater in formations of Pleistocene and Pliocene age. It gradually decreases to zero for formations older than 6 million years. However, the net thermal mining is critically dependent on the maximum depth of water convection in these systems, which is unknown. © 2000 CNR. Published by Elsevier Science Ltd. All rights reserved.

Keywords: Thermal mining; Convection; Conductive thermal gradient; Low temperature geothermal systems; Iceland

1. Introduction

In the middle of the 19th century it was recognized that geothermal water is of meteoric origin (Bunsen, 1847). Einarsson (1942, 1966) postulated that the low

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temperature geothermal water is part of the general groundwater flow from highlands to the lowlands, and that the water is heated when flowing through hot rocks at depth in the crust. Einarsson's model assumes a steady-state between the crustal heat flow and the heating of the water. On the other hand, Bödvarsson (1982, 1983a,b) suggested that geothermal water is heated by the rock in the geothermal system itself, through convection in vertical fractures, and that geothermal systems are transient in nature. He proposed a process of convective downward migration. This process assumes that the convective fluid motion in open vertical fracture spaces is associated with withdrawal of heat from the formation at the lower boundary. Such cooling results in thermoelastic contraction of the adjacent rock, which increases the local aperture of the fractures causing further cracking of the rock and opening of additional fracture spaces at the bottom. Björnsson et al. (1990) and Tómasson (1988, 1993) based their discussions on this process and call it thermal mining. Tómasson (1993) suggested that thermal mining could also reach outside geothermal systems.

The purpose of this paper is to compare formation temperatures as estimated from individual drillholes inside geothermal systems to normal conductive thermal gradients of surrounding areas and calculate the ΔT-curves and the degree of thermal mining inside the geothermal systems as described by Tómasson (1988).

2. Methodology and the thermal mining calculations

Fig. 1 shows a contour map of the conductive geothermal gradient in Iceland. The location of the geothermal systems and individual drillholes, where the formation temperatures have been estimated in this study, are shown in Figs. 1 and 2. Reykjavík and vicinity in particular include several geothermal systems studied here. The Reykjavík area includes about 100 drillholes ranging from 800 to 3000 m in depth. This area is the largest market for geothermal water for house heating in Iceland, containing about 70% of the population of the country.

In Table 1 we list the geothermal systems of this study as well as one cold locality (Kaldársel drillhole). The table also shows the distance of the systems from the rift axis and the formation age, as well as the natural discharge and water temperature prior to exploitation of the fields.

In this study we define ΔT as the difference between the estimated formation temperature and the expected temperature, based on a linear conductive thermal gradient under normal conditions outside the geothermal area. This difference is:

$$\Delta T(z) = T_{\mathrm{f}}(z) - (T_0 + az) \tag{1}$$

where z is depth, T_{f} is the formation temperature at a given depth, a is the expected conductive gradient, and T_0 is the surface temperature. T_0 was chosen as 5°C for this study, which is close to the annual mean surface temperature in Iceland.

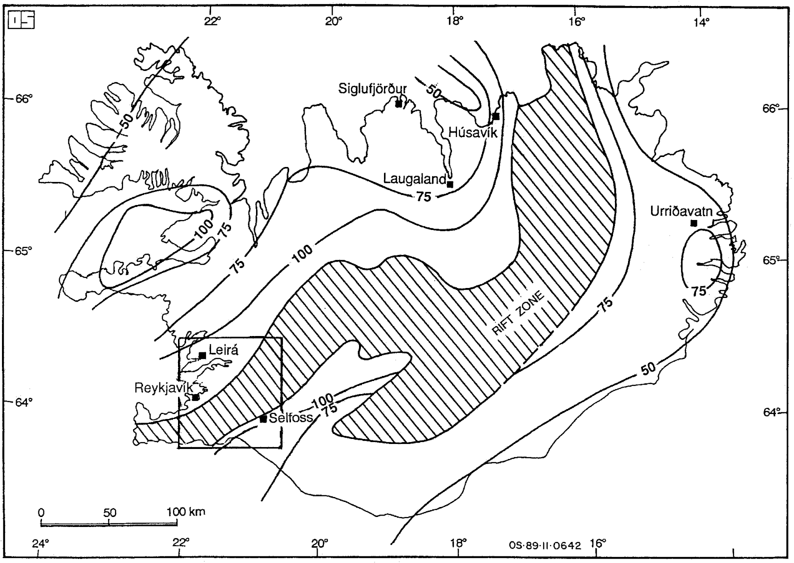

Fig. 1. Map of conductive thermal gradient in Iceland (°C/km) and location of the geothermal fields of this study (modified from Björnsson et al., 1990).

The expected conductive gradient for each geothermal field was chosen from Fig. 1, where the contour curves show conductive gradients varying from less than 50°C/km in the outer part of the Tertiary basalts to over 100°C/km on the border of the volcanic zones. Iceland is often divided into three geological zones: the volcanic zone, or rift zone, which passes through Iceland from southwest to northeast; to each side of the volcanic zone we have Quaternary rocks, and further out Tertiary basalts (Sæmundsson, 1979).

The highest temperature gradient drillholes are all in southwest Iceland (see Fig. 2). A 1400-m deep drillhole in Akranes is close to these areas, and has a constant temperature gradient to the bottom (Tómasson, 1993). The thermal gradient in this drillhole is 125°C/km, which puts significant constraints on the normal temperature gradient of the area.

A single temperature logging was used in two cases as our formation temperature estimate, i.e. for drillhole RV-36 at the Ellidaár geothermal area and LA-06 in Laugaland area. In both cases the temperature in the drillholes had not changed for many months. The formation temperature curves for the drillholes in the Reykir area were estimated by Björnsson and Steingrímsson (1995). Most of the formation temperature profiles were estimated from more than one drillhole in a field. Usually drillholes of different depth lie close to one another in the middle of the geothermal area where horizontal temperature differences are small.

For this study we have also estimated the thermal mining from the geothermal systems. The thermal mining from the surface to a specified depth, z, was calculated by

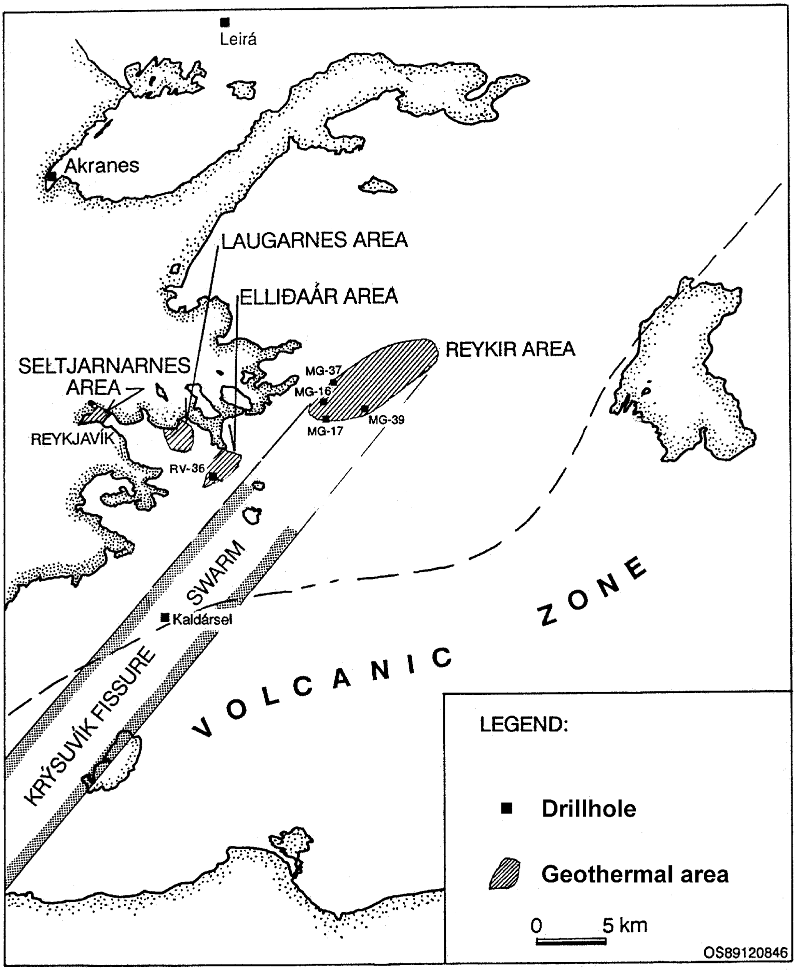

Fig. 2. Expanded map of Reykjavík and surrounding areas showing some of the geothermal fields and drillholes of this study (modified from Tómasson, 1993).

$$E(z) = \int_0^z \rho c \Delta T(\zeta) \mathrm{d}\zeta \tag{2}$$

where E is the thermal mining (J/m^2), ρ is the density of the wet formation (kg/m^3) and c is the heat capacity of the wet formation (J/kg°C). For our calculations we have used $\rho = 2700$ kg/m^3, and $c = 1000$ J/kg°C.

Fig. 3 and Table 2 show an example of our calculations for well RV-36 in the Ellidaár geothermal area. For this field we have an estimate of the formation temperature down to 2200 m. For comparisons between sites we extrapolated the formation temperature to 3000 m. The conductive gradient is not well constrained,

Table 1
The geothermal systems of this study

Geothermal area	Distance to ridge axis (km)	Formation age (Ma)	Natural discharge (l/s)	Water temperature (°C)
Kaldársel	5	0–1	0	–
Ellidaár	15	1.5–2	?	40
Reykir	20	1.5–2	117	83
Laugarnes	20	2–2.5	11	88
Selfoss	25	1.5–3	?	48
Seltjarnarnes	25	2.5–3	0	–
Húsavík	30	3–5	3.5	34–63
Leirá	30	5–6	0.3	55
Laugaland	75	7–9	2	54
Urridavatn	90	10–12	?	60
Siglufjördur	110	10–12	1.7	46

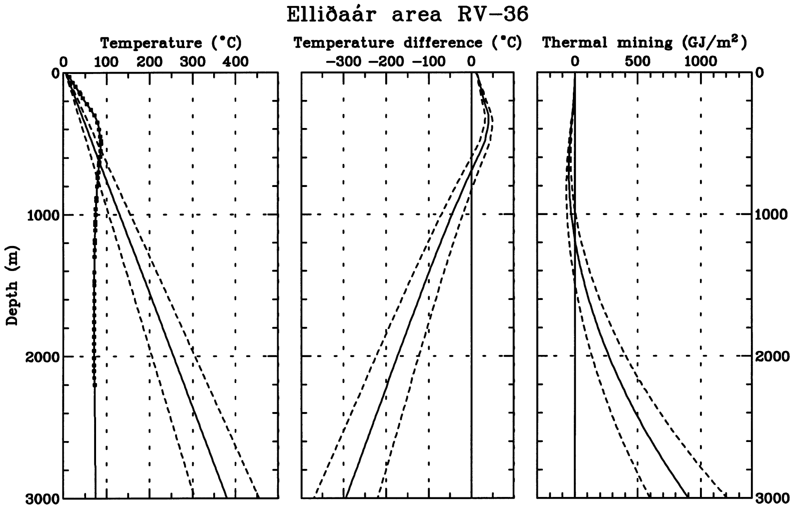

Fig. 3. Example of thermal mining calculations for the Ellidaár geothermal area (RV-36), showing three different estimates of conductive thermal gradients: best guess (solid), and low and high estimates (dashed).

especially near the volcanic zone, so that we show three curves in Fig. 3. For the formation temperature curve, ΔT-curves were calculated for three different estimates of conductive thermal gradients; a low estimate, our best guess, and a high estimate. The high and low estimates are shown as dashed curves in Fig. 3.

For the three various gradients and two depths, we calculated the thermal mining from surface down to the specified depth. We also show the average cooling of the system as compared to the gradient model. Finally, we present the average hot water

Table 2
Example of thermal mining calculations for the Ellidaár area (well RV-36)

Thermal gradient (°C/km)	Depth (m)	Thermal mining (GJ/m^2)	Average cooling (°C)	Equivalent average flow (kg/s)/(km^3 10 ky)
100	2200	207	35	1.1
125	2200	370	62	2.0
150	2200	533	90	2.8
100	3000	598	74	2.3
125	3000	902	111	3.5
150	3000	1205	149	4.7

flow rate, equivalent to the calculated thermal mining, assuming it has taken place during a period of 10 thousand years. It should be kept in mind, however, that a natural flow rate would diminish in 10 thousand years, so that the observed natural flow at the end of the period would be lower than the average flow rate.

The ΔT-curves were calculated for the depth range of the drillholes, and the formation temperatures were also extrapolated down to 3000 m in all cases. The results of these calculations are shown in Tables 3 and 4. The temperature curves from these drillholes show that the gradient in formation temperatures is similar below 2000 m depth to the gradient above, indicating that the circulation of water in these geothermal systems generally reaches a depth of at least 3000 m. For reasons of comparison, we, therefore, decided to extrapolate the formation temperatures from the last several hundred meters above the bottom of the deepest drillholes down to

Table 3
Thermal mining calculations of this study down to specified depth

Geothermal area	Thermal gradient (°C/km)	Depth (m)	Thermal mining (GJ/m^2)	Average cooling (°C)	Equivalent average flow (kg/s)/(km^3 10 ky)
Urridavatn UV-06	65	1580	−93	−22	−0.7
Laugaland LA-08	65	2820	−30	−4	−0.1
Leirá LG-04	125	1994	-41	−8	−0.2
Ellidaár RV-36	125	2200	370	62	2.0
Laugarnes	125	2680	255	35	1.1
Laugarnes- 5 km[a]	125	5000	2174	161	5.0
Siglufjördur SK-04	60	1320	−134	−38	−1.2
Kaldársel K-1	125	990	144	54	1.7
Seltjarnarnes SN-06	125	2600	379	54	1.7
Reykir MG-17	125	1766	152	32	1.0
Reykir MG-16	125	2033	178	32	1.0
Reykir MG-37	125	2000	195	36	1.1
Reykir MG-39	125	2025	236	43	1.4
Selfoss PK-10	120	1821	−46	−9	−0.3
Húsavík HU-01	90	1345	−142	−39	−1.2

[a] Extrapolation of the convective geothermal system down to 5 km.

Table 4
Thermal mining calculations for the top 3000 m

Geothermal area	Thermal gradient (°C/km)	Thermal mining (GJ/m^2)	Average cooling (°C)	Equivalent average flow (kg/s)/(km^3 10 ky)
Urridavatn UV-06	65	154	19	0.6
Laugaland LA-08	65	8	1	0.0
Leirá LG-04	125	264	33	1.0
Ellidaár RV-36	125	902	111	3.5
Laugarnes	125	411	51	1.6
Siglufjördur SK-04	60	−3	0	0.0
Kaldársel K-1	125	1125	139	4.4
Seltjarnarnes SN-06	125	594	73	2.3
Reykir MG-17	125	894	110	3.5
Reykir MG-16	125	763	94	3.0
Reykir MG-37	125	764	94	3.0
Reykir MG-39	125	828	102	3.2
Selfoss PK-10	120	399	49	1.5
Húsavík HU-01	90	219	27	0.8

3000 m. One exception to this method is that of the Kaldársel drillhole (K-1), which we will discuss later.

Fig. 4 shows the thermal mining to a specified depth for the geothermal fields in Table 3. From this graph it is evident that the maximum depth of circulation for the fields, which is unknown, is critical in determining the total thermal mining of the fields.

In Table 4 we have calculated the average flow of hot water for 10 thousand years from 1 km^3 of rock, which is equivalent to the thermal mining in the top 3000 m. In these calculations we assume that the water is heated from 5 to 70°C. We chose 10 thousand years because this date marks the end of the last glaciation, which probably had a great influence on water circulation. The changes in the ice cap load over Iceland are presumed to have opened many fractures and increased the water circulation. Bödvarsson (1982) estimated the age of most of the low temperature systems to be about 10 thousand years on the basis of this argument.

3. Thermal mining in individual geothermal systems

One of the highest thermal mining estimates, according to the calculations of this study, is for RV-36 in the Ellidaár area (Fig. 2). The thermal mining down to 3000 m in RV-36 indicates that the cooling of 1 km^3 would provide enough energy to sustain for ten thousand years an average flow to the surface of 3.5 l/s of 70°C hot water. The surface activity was widespread before drilling. In the middle of the area there were many hot ponds with temperatures up to 40°C, but with hardly any outflow. These springs disappeared when production began. In the north- and northeast part of the area there are 7–16°C springs with a total outflow of 30–40 l/s. These springs

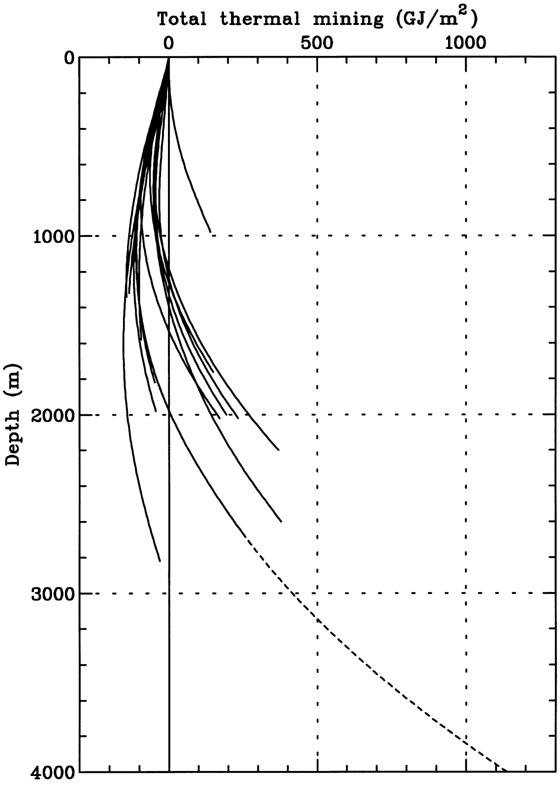

Fig. 4. Estimated thermal mining for the various geothermal fields of this study.

have probably little connection to the production field. The cooling of 1 km^3 would thus be enough to explain the thermal activity in this area. The size of the production field is greater than 3 km^2, so the calculated thermal mining is at least an order of magnitude higher than indicated by surface manifestations. The total thermal mining for the Ellidaár area is probably little below the calculations based on RV-36, because there is a temperature increase from RV-36 to the northwest toward the Laugarnes area (Tómasson, 1993).

The thermal mining in the Laugarnes area would provide enough energy to sustain an average flow of 1.6 l/s for ten thousand years per km^3 of the system. Before drilling, the flow from the springs was 11 l/s of 88°C hot water. To obtain this amount of water, cooling of 9 km^3 would be required for 10 thousand years. The area of the geothermal reservoir is on the order of 10–20 km^2, so there is no need for any other explanation than the thermal mining inside the geothermal reservoir to explain the surface thermal activity of this geothermal area.

The thermal mining in the Seltjarnarnes area of 1 km^3 would provide enough energy to produce 2.3 l/s for ten thousand years. Before drilling no surface activity was known in the area, so we cannot compare the surface flow and the thermal mining in the area. The discharge from this system may have been directly into the ocean.

For the Reykir area we have calculated thermal mining on the basis of four drillholes (Tables 3 and 4). The greatest thermal mining is calculated on the basis of MG-17. The variation of thermal mining for the drillholes in the Reykir area is, however, small. It would provide enough energy to produce, on average, 3–3.5 l/s for each 1 km^3 of 70°C hot water for 10 thousand years. The hot springs in the Reykir area yielded 117 l/s of 83°C hot water before production began. To heat this amount of water the thermal mining requires a cooling of 40–50 km^3 of rock. The area of the geothermal reservoir is in the order of 150–300 km^2, which is more than enough to explain the natural flow.

In the southeastern part of the Krýsuvík fissure swarm (the shaded area of Fig. 2) cold water is found down to 700–1000 m depth. The thickness of the cold water lens decreases to the northwest and it seems to disappear 2–10 km from the Reykir area. This is indicated by logging in drillholes and resistivity measurements (Tómasson, 1993; Björnsson and Steingrímsson, 1995). The deepest drillhole in the swarm is the Kaldársel drillhole K-1, 986 m deep (Fig. 2). This drillhole is cold down to 750 m, but below that depth the temperature gradient is about 70°C/km. Using the same method as for the other drillholes, we would extrapolate this gradient down to 3000 m. This is, however, unlikely, as the fissure swarm is highly permeable as a result of numerous open faults and fissures. This applies in particular to the vertical permeability of the swarm. The hydrological model proposed by Tómasson (1993) involves a downflow of cold water that washes all the heat out of the rock in the upper part of the Krýsuvík fissure swarm. Well RV-36 (see Fig. 2) has a constant temperature of 72°C from 1200 m depth to the bottom of the drillhole (2200 m). It is proposed that this water originates as a deep circulating water from the Krýsuvík fissure swarm. Well MG-17 at Reykir (see Fig. 2) has water of similar temperature as in RV-36, 75°C at 1200 m, but which decreases to 71°C at the bottom (1766 m) (Björnsson and Steingrímsson, 1995). This could indicate the presence of a large convection cell in the Krýsuvík fissure swarm where the outer part of the convection cell has a temperature of about 70°C. In our calculations in Table 4 of thermal mining around K-1 we extrapolated the 70°C/km to 75°C and consequently assumed a constant temperature down to 3000 m depth. This results in a slightly higher (20%) thermal mining estimate than if we had chosen to extrapolate 70°C/km all the way to 3000 m.

In the Leirá geothermal system (LG-04), the cooling of 1 km^3 of rock provides enough energy to produce 1 l/s for 10 thousand years according to our calculations. The flow from the surface springs was only 0.3 l/s of 55°C hot water, so cooling of less than 1 km^3 would be enough to explain the natural flow. The area of the geothermal reservoir is 10–20 km^2, quite sufficient to explain the observed outflow from the area.

The Selfoss geothermal area is located close to the 100°C/km contour line in Fig. 1. We chose a thermal gradient of 120°C/km. This conductive gradient (Table 3) shows no thermal mining at the depth range of the drillholes, but down to 3000 m the thermal mining of 1 km^3 is enough to provide energy to produce 1.5 l/s of 70°C hot water for 10 thousand years. The only surface activity before drilling was a 48°C hot spring with no outflow. One km^3 is, therefore, more than enough to explain the surface activity and the area of the geothermal reservoir is at least several km^2.

There is a 1506-m deep drillhole in Húsavík (H-2) between the 110 and 75°C conductive gradient lines in N-Iceland (Fig. 1), but the temperature measurements reach 1345 m depth only. In the depth range of the measurements there is no thermal mining, but for rock temperature extrapolated to 3000 m there is thermal mining for all three conductive gradients, albeit rather small. For the middle conductive gradient (90°C/km), thermal mining of 1 km^3 would provide enough energy to produce an average of 0.9 l/s at 70°C for 10 thousand years. There were two springs before drilling, one with a flow-rate of 0.5 l/s at 63°C and the other with 3 l/s at 34°C. This is equivalent to 2 l/s of 70°C hot water, which would require about 2 km^3 of rock for thermal mining. The area of the geothermal reservoir is poorly known but is at least 1–2 km^2, so there is no need for other explanations than thermal mining.

The 2820-m drillhole LA-08 at Laugaland in Eyjafjördur in N-Iceland was used as the most reliable formation temperature for thermal mining calculations in the low conductive gradient zone of the Tertiary basalts in northern Iceland. There is little or no thermal mining, neither in the depth range of the drillhole nor as regards the extrapolated rock temperature down to 3000 m (see Table 4). The total flow of springs in the geothermal area was 2 l/s of 54°C hot water, prior to production from the field. The energy of the natural flow must come from water outside the area or through deeper circulation.

Siglufjördur is located in the northern part of Iceland (see Fig. 1), where the conductive gradient is likely to be lower than at Laugaland; our guess is 60°C/km. We have reliable formation temperatures to 1320 m depth. There is no net thermal mining above 3000 m depth, which means that thermal mining in the lower part of the system is all used for heating in the upper part. The flow from the thermal spring before drilling was 1.7 l/s of 46°C hot water. The energy to maintain the springs for ten thousand years must come from deeper circulation.

Urridavatn is located in eastern Iceland in Tertiary basalts. The middle conductive gradient was chosen, 65°C/km, and there are reliable formation temperatures down to 1580 m. There is little or no thermal mining above 3000 m for the middle conductive gradient. The thermal mining down to 3000 m would provide enough energy to produce 0.6 l/s of 70°C hot water for ten thousand years. The geothermal area is situated at the bottom of a lake with unknown flow rate, but temperatures up to 60°C existed.

4. Discussions

Thermal mining appears to take place in the lower part of all geothermal systems of this study and, if we assume that circulation extends to at least 3000 m, this thermal mining is usually greater than the heating in the upper part of the system. The geothermal systems are, in general, hotter in the upper part of the system than in the surrounding formations, and colder in the lower part than in the surrounding formations. This behaviour of geothermal systems fits well with the theory of

Bödvarsson (1982) who proposed that thermal mining was taking place in the deeper parts of geothermal systems and that geothermal systems deepened with time. Most of the water flowing into the geothermal systems must enter at shallow depths and is colder than the temperature at the bottom of the systems.

To facilitate comparison between the geothermal systems of this study we extrapolated the formation temperatures down to 3000 m depth, and calculated the net thermal mining in the top 3000 m. The results of this comparison are shown in Table 4. In Fig. 5 we compare these results with the formation age, from Table 1, noting that the thermal mining decreases with distance from the ridge axis and increasing formation age.

Tables 2 and 3 show that thermal mining is greatest in the Krýsuvík fissure swarm, which is inside the rift zone, and decreases away from the zone. In the Tertiary basalts in northern and eastern Iceland the thermal mining in the lower part is about the same as the heating in the upper part, i.e. the heat mined in the lower part of the system is preserved in the upper part. However, the net thermal mining depends critically on the depth of these geothermal systems.

Near the edge of the fracture zone in the Reykir and Ellidaár areas, the thermal mining is estimated to have produced 3.0–3.5 l/s of 70°C water on average for 10 thousand years, for each cubic kilometer of the system. In all these cases the depth of the geothermal system is assumed to be 3000 m. However, there are no indications that the bottom of geothermal systems in Iceland is reached at 3000 m depth.

The alteration temperature is based on the formation temperature of certain minerals in the range 20–300°C. In K-1, the Kaldársel drillhole, the first alteration minerals appear at 412 m depth, indicating alteration temperatures of 30–50°C, and the alteration temperature is 70–80°C at 870 m depth (Tómasson and Franzson, 1992).

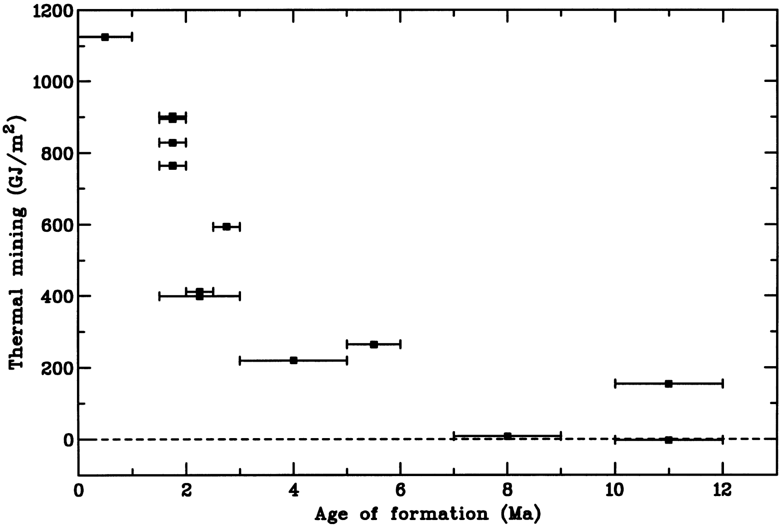

Fig. 5. Total thermal mining in the top 3000 m as a function of formation age for the geothermal fields of this study.

There are a few drillholes with depths in the range 250–400 m in the Krýsuvík fissure swarm north of Kaldársel. All these drillholes are cold to the bottom, but alteration mineralogy shows a clear increase of the alteration temperature to the northwest. The drillholes nearest to the Ellidaár area show that alteration temperatures at 190 m depth are on the order of 30–50°C (Tómasson and Franzson, 1992). The alteration temperature in the Krýsuvík fissure swarm shows a higher value than the present temperature, and the cooling from the highest temperature could be 60–70°C. However, the alteration temperature is lower than the temperature expected from a normal gradient. It therefore appears that there has always been a cold water layer of variable thickness in the upper part of the swarm, which suggests that part of the thermal mining is of similar age as the rocks, dating back a few hundred thousand years. The present rock temperatures are still lower than the alteration temperatures, indicating that the rate of thermal mining varied from one time to another.

The cooling could have happened after the last glaciation. However, it is just as likely that during every glaciation period the system is heated up because of the almost total termination of water recharge, due to the permafrost of the ice cap. The alteration thus reflects the highest temperature that the rock reached during some glaciation periods, but not necessarily during the last one. This cycle of heating and cooling of the rock has probably happened during every glacial/interglacial period.

The geothermal areas at Reykir, Laugarnes and Ellidaár are all fossil high temperature areas, as indicated by alteration mineralogy. The depths to these high temperature indications are variable: nearly at the surface at Reykir, at 600 m depth in Laugarnes, and at 1000 m depth in the Ellidaár area. According to the alteration mineralogy, the temperature in these high temperature areas has reached 300°C (Tómasson et al., 1977; Fridleifsson et al., 1985; Smárason et al., 1989; Tómasson, 1995). It is likely that these high temperature geothermal areas were located inside the volcanic zone at 1–2 Ma and later drifted out of the active volcanic zone and cooled down. These thermal areas are therefore 1–2 million years old, and the thermal mining from high temperature to low temperature areas has taken a long time (million years). It is also probable that most of the geothermal systems are older than 10 thousand years, although the geothermal activity may have stopped or slowed down considerably during glacial periods. During deglaciations, it is likely that the locations of old geothermal systems would be the most favorable spots to recreate a geothermal system, so we could expect the heat mining during the last 10 thousand years to be somewhat less than the calculations based on the conductive gradient.

5. Conclusions

Thermal mining takes place in geothermal systems in Iceland, and appears to be greatest near the volcanic zone (rift zone), and to decrease towards the older Tertiary basalts. In the older formations there is almost no net thermal mining in the top 3000 m. The total thermal mining is, however, strongly influenced (parabolic increase) by the thickness of the convective cells in the geothermal systems. Were the thermal mining in the Laugarnes area to be extrapolated to 5000 m, then thermal mining would increase nearly nine-fold.

Glaciations probably have a strong influence on water circulation and recharge of geothermal systems. Groundwater flow would be almost nil during glacial periods. During deglaciations, large-scale tectonic movements resulting from the release of overburden weight are likely to lead to the opening of old cracks and reinitiation of water convection in old geothermal systems, where considerable thermal energy had accumulated during the preceding glacial period.

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