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Hot Groundwater Systems in Iceland Traced by Deuterium

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Bragi Arnason
University of Iceland, Science Institute
Reykjavik, Iceland

This paper summarizes the result obtained for hydrothermal systems in Iceland, by using deuterium and oxygen-18 as natural tracers.

The deuterium content of a single sample of a local cold spring or river, except those rivers fed by considerable amount of glacier melt water, can be used to estimate the mean deuterium concentration of precipitation in the corresponding locality. Furthermore the deuterium content of the last winter layer, collected on Icelandic glaciers in spring before the melting season, is practically identical to the mean value of the corresponding annual precipitation. These facts have been used to draw a detailed map showing the amount of deuterium in precipitation over the whole country. Deep ice core studies show that the deuterium content of precipitation in each place has remained more or less unchanged during the last 8000 years.

Measurements of both deuterium and oxygen-18 in the groundwater have confirmed that all groundwater in Iceland is originally meteoric and that the deuterium content of the thermal water does not change on its way through the bed-rock.

The deuterium content of water discharging from hot springs or drill holes is often very different from the deuterium content of local precipitation. On the other hand, by comparing results obtained with the deuterium map, it is often possible to find where this water has fallen as rain and to trace its underground flow path. Deuterium measurements have been made on water from nearly all geothermal areas in the country. The results are drawn up together in one picture, which shows the origin and flow paths of most of the hot groundwater systems in Iceland.

Finally it has been possible to give som idea of the age of the thermal groundwater, i.e. the time past since precipitation. The thermal water is obviously of varying ages. The »youngest« water seems only to be a few decades old, whereas the »oldest« appears to be from the last glaciations.

Introduction

When the deuterium and oxygen-18 measurements became sufficiently accurate and simple to be used on a large scale, numerous people began to apply this technique to the study of stable isotope variations in the hydrologic cycle (Mc Kinney et al. 1950, Epstein et al. 1953, Friedman 1953 and Dansgaard 1961). A large number of deuterium and oxygen-18 analysis were carried out on water samples all over the world by various researchers (Craig et al. 1956, Craig 1961 and 1963, Friedman et al. 1964 and Dansgaard 1964).

The first deuterium measurements on water from Iceland were made in 1948 following a suggestion of H. Urey. These measurements were then followed by measurements of both deuterium and oxygen-18 content of some hot and cold springs and rivers (Bödvarsson 1962) and by deuterium measurements of 160 samples of hot and cold springs, surface waters and monthly precipitation from one meteorological station (Friedman et al. 1963). These studies supported the theory that the thermal water in Iceland was of meteoric origin. These measurements also suggested that more detailed stable isotope studies on Icelandic waters might be very useful in tracing the recharge areas and the general flow pattern of ground water systems in Iceland.

Since 1963 extensive deuterium measurements have been carried out on natural waters in Iceland. In addition numerous samples have also been measured for their oxygen-18 content. A part of the results obtained from these studies has already been published in several papers (Arnason et al. 1967, 1969 and 1970).

This paper summarizes the results obtained for the thermal systems and thus gives an idea of the application of stable isotope studies in solving thermal ground water problems in Iceland. Those, who are interested in more detailed results, are referred to the more extensive work »Ground water systems in Iceland traced by deuterium« (Arnason 1976).

The deuterium measurements have all been carried out with a mass spectrometer. The results are expressed as δ = per mille deuterium enrichment relative to SMOW (Standard Mean Ocean water). The standard deviation for a sample analysed in duplicate is 0.7 $^0/_{00}$.

The Deuterium Map and Its Validity for Groundwater Studies

Although there are quite considerable variations in the deuterium content of precipitation in Iceland (the root mean square deviation for monthly samples is approximately 13 $^0/_{00}$), such variations in spring and river waters other than glacial rivers are very small (the root mean square deviation between 1 $^0/_{00}$ and 3 $^0/_{00}$) (Arnason 1976). Therefore a single sample taken from cold springs or surface streams, except glacial rivers, may be used to obtain information about the mean deuterium content of the respective water source.

Furthermore it has been found that the deuterium content of local cold springs and streams is practically the same as the mean deuterium content of the precipitation in the recharge area of the corresponding source. Consequently a single sample from a local spring or a surface stream of known origin can be used to give the mean deuterium content of precipitation in the respective area. This is the simplest method to obtain information about the mean deuterium content of precipitation in those areas in Iceland not covered by glaciers.

Approximately 10 % of Iceland is covered by glaciers. In order to draw a map showing the distribution of deuterium in the precipitation throughout the country it is therefore important to know the annual mean deuterium content of the precipitation on the glaciers.

Icelandic glaciers can be classified as soaked zones (Benson 1962), where only a part of the annual precipitation is accumulated, a part of it escapes as runoff during the following summer. When the runoff percolates through the winter layer it causes an extensive isotopic exchange between water and solid ice, leaving the remaining firn appreciably enriched in deuterium (Arnason 1969). Therefore a profile taken through a glacier's accumulation usually gives no reliable information about the deuterium content of earlier precipitation. It has, however, been found, that the period October-April is the part of the year when the precipitation on Icelandic glaciers usually falls as snow, no melting occurs, and conditions are similar to those on the polar glaciers. Therefore samples of the winter layer may be taken as representative for the precipitation in this period. It has also been found, that in spite of some annual periodicity in the deuterium concentration of the precipitation, with low concentration in winter and high in summer, the mean annual deuterium concentration is only slightly higher than the mean concentration for the period October - April.

Consenquently composite samples collected from the winter layers of the glaciers in Iceland, before the beginning of the melting season, may give reasonably accurate values for the deuterium concentration of the mean annual precipitation in the corresponding locality.

Deuterium measurements carried out on samples from 657 sampling points for local groundwater and surface streams, from 24 points where winter precipitation has been collected on glaciers, and from 3 meteorological stations, have been used to construct a map showing the present-day distribution of deuterium in precipitation throughout the country. All these points are shown in Fig. 1. In cases where only a point is shown on the map, the water is believed to originate as precipitation in the area around the sampling point. In other cases a line has been drawn from the sampling point into the middle of the expected recharge area. Figure 1 consequently gives a good idea of the number and distribution of the data used in constructing the deuterium map.

The deuterium map is shown in Fig. 2. The inaccuracy in location of the isolines is believed not to exceed ± 2‰. Consequently isolines with 4‰ difference in the δ-

Fig. 1. Distribution of sampling points of precipitation, local groundwater and streams, and winter precipitation on glaciers in Iceland. The winter precipitation is collected before the beginning of the melting season. When only a black point is given the water is believed to originate as precipitation around the sampling point. In other cases a line has been drawn from the sampling point into the middle of the proposed recharge area.

values can be considered reliable.

The map shows well how the δ - values generally decrease from the coastal areas inland. The decrease in δ inland can be accounted for by the combined altitude inland effect. The experimentally obtained values for the altitude and inland effects are: $K_H = 1.87 \pm 0.07‰$ pr. 100 m and $K_L = 0.128 \pm 0.010‰$ pr. km respectively.

The difference between the δ - values on the north and south coasts ($\Delta\delta = 14\,^0/_{00}$) can be accounted for as a result of a latitude effect. The latitude effect appears to be approximately 7.5 $^0/_{00}$ pr. degree of latitude, which is similar to the value, 8 $^0/_{00}$ pr. degree of latitude, found along the coast of Greenland (Dansgaard et al. 1973).

The deuterium map offers the possibility of using deuterium as a natural tracer to locate the recharge areas of groundwater systems and to study their flow patterns. When a sample of groundwater, discharging from a cold or hot spring, has a δ - value similar to the mean δ - value of the precipitation in the respective district this suggests a local origin of the groundwater. Different δ - values of the precipitation and spring water on the other hand indicate a distant origin of the spring water. In that case

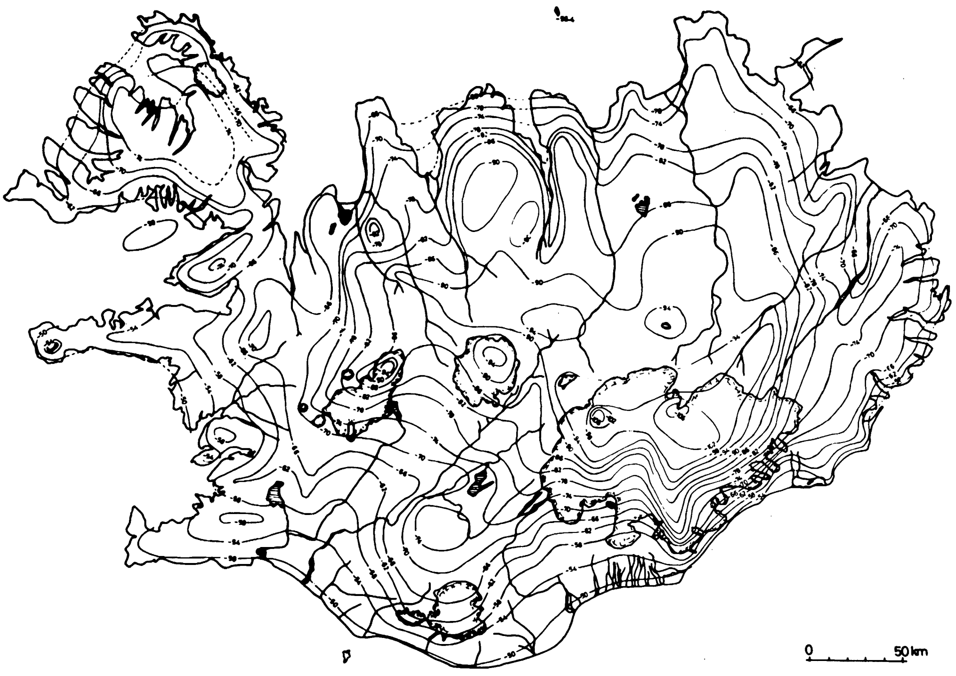

Fig. 2. Map showing the distribution of deuterium in precipitation in Iceland.

comparison of the δ- value of the spring water with the deuterium map may be used to locate the recharge area of the groundwater feeding the spring.

The use of deuterium as a natural tracer in groundwater studies is based on the assumptions that the groundwater is derived from precipitation and that the deuterium content of the water does not change in the ground by exchange with rockmaterial. Extensive studies where both deuterium and oxygen-18 have been measured have shown that even thermal waters from high temperature areas (underground temperature higher than 250°C) have not undergone any changes in its deuterium concentration, although the oxygen-18 concentration may have changed in the ground (Craig et al. 1956 and 1963, Banwell 1963, Arnason 1976).

The method furthermore assumes that the deuterium concentration of the precipitation has not changed significantly during the time the water has remained underground. Studies of the deuterium content of a 415 m long ice core from the Vatnajökull ice cap, when compared with oxygen-18 measurements of the 1390 m long ice core from Camp Century Greenland (Dansgaard et al. 1969), show that the deuterium content of the precipitation in any particular area in Iceland has not changed greatly during the past 8000 years. Before that time dating back 60.000 years from the time of last glaciation the deuterium content of the precipitation was much lower, probably 50‰- 100‰ lower, than today. Therefore if the thermal water has remained underground less than 8000 years its δ - value is directly comparable to the δ - values of the deuterium map and the deuterium content of the groundwater can be used to locate the approximate recharge area of the respective groundwater system. On the other hand, if the groundwater is derived from precipitation deposited in the period 10.000 to 60.000 years ago, this should be reflected in an unusually low δ - value of the water.

Within the spatial limits of this paper it is not possible to discuss in detail the information which have been obtained about the age of the thermal waters in Iceland, i.e. the retention time underground. For more detailed informations the reader is referred to Arnason (1976). It will only be mentioned here, that various studies suggest the water in the thermal systems, in all cases except one, to be between 50 and 4000 years old. In only one case, the Husavik hydrothermal system (see system No. 46 in Fig. 3), the water is obviously derived from precipitation deposited more than 10.000 years ago.

The Origin and Flow Pattern of Thermal Groundwater Systems in Iceland

Deuterium measurements have been made on water from almost all the geothermal areas of the country. In areas where only a few measurements have been made, a rough, but still significant picture of the origin and flow pattern of the thermal water has been made. In areas where more intensive measurements have been made, it has been possible to draw the picture in greater detail. In some cases, more than one hot water system has been found within the same geothermal area. For detailed results obtained for each individual thermal area in Iceland the reader is referred to Arnason (1976). In this paper only a general picture of the origin and nature of the hydrothermal systems in Iceland will be presented.

Since the δ - values obtained for the thermal water, together with the deuterium map, obviously can be used to locate the recharge area of the corresponding groundwater system and to trace its general flow pattern underground, the deuterium measurements offer an excellent opportunity to study the importance of the tectonics and of the hydrostatic pressure in affecting the direction of the groundwater flow.

When cold groundwater flows in the uppermost part of the ground where fissures and cracks observed at the surface are still well open, the groundwater flow is likely to be directed along these fissures. It is thus generally accepted that the cold ground water in Iceland mainly flows along the tectonic lines rather than across them. The main tectonic lines lie SW - NE in the southern part of the country but N - S in the northern part.

At a depth of 1 - 3 km, which is believed to be the depth of the rock formations through which the thermal water flows, the fissures occurring in the uppermost formations may possibly have shrunk to such an extent, that the horizontal permeability of certain layers will be dominating rather than that of vertical fissures. It is therefore questionable whether the thermal groundwater flow is directed mainly by the tectonic lines or whether it rather flows through permeable horizontal layers in the ground with its flow mainly directed by the hydrostatic pressure.

If the deep thermal water is directed mainly by hydrostatic pressure in the ground it should in principle be possible to construct the flow pattern for thermal water, when the hydrostatic pressure is known. As far as the author knows, however, no information is available from which a picture of the hydrostatic pressure of the deep groundwater can be obtained.

The following may be considered as an attempt to obtain qualitative information about how the hydrostatic pressure of the deep thermal water changes, in general, within the country. The average heights of rectangular areas, approximately 520 km^2, are used to construct an average topographic map of Iceland. The data for the average height of each rectangle have been made available through the courtesy of Mr. Gunnar Thorbergsson, the head of the Survey Department of the National Energy Authority. The contours of this average topographic map are shown in Fig. 3.

Now assume that the hydrostatic pressure of the deep thermal water roughly follows the average heights. The general flow pattern of the water should then always be perpendicular to the altitude contours.

The deuterium map, the average topographic map and the δ-values obtained for the thermal water samples measured are now used to draw the main underground flow pattern for most of the thermal water systems in Iceland. The results obtained are shown in Fig. 3. In Fig. 3 the thermal area and the respective recharge area are joined by arrows, such that the arrow always points to the thermal area. The recharge area is located from the deuterium measurements. Thermal systems of almost local origin are shown as shaded areas.

In Fig. 3 all hydrothermal systems have been assigned numbers from 1 - 47. The relation between these numbers and the names of the areas are as follows:

1. Torfajökull
2. Seljavellir
3. Vestmannaeyjar
4. Hveravellir
5. Nauthagi
6. Raudukambar
7. Geysir
8. Hreppar and Skeid
9. Biskupstungur
10. Bödmodstadir
11. Laugarvatn
12. Selfoss
13. Hengill
14. Reykjanes
15. Ellidaar
16. Laugarnes
17. Seltjarnarnes
18. England
19. Brautartunga - Leira - Akranes
20. Reykholtsdalur
21. Husafell

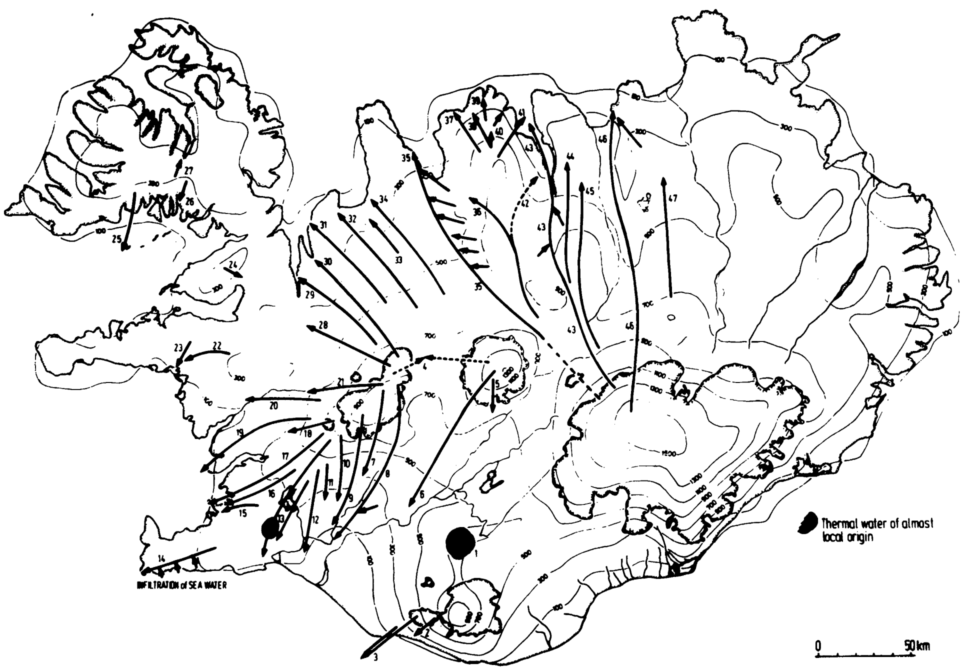

Fig. 3. The recharge areas and the general pattern of flow of thermal groundwater systems in Iceland. The general pattern of flow is shown by arrows joining the thermal area and the respective recharge area as proposed from deuterium measurements. In cases where there are two possible recharge areas, both possibilities are shown by broken arrows. The isolines shown are average topographic heights in meters, based on rectangular areas 520 km^2. The arrows of the flow pattern are finally modified such that they are almost perpendicular to the isolines.

22. Landbrot
23. Kolvidarnes
24. Sælingsdalur
25. Breidafjördur
26. Muli
27. Isafjördur
28. Sléttafell
29. Reykjaskoli
30. Reykir Midfjördur
31. Skard
32. Sigridarstadir
33. Reykjabraut
34. Saudanes
35. Skagafjördur
36. Reykir Hjaltadal
37. Reykjaholl
38. Fljot
39. Siglufjördur
40. Olafsfjördur
41. Svarfadardalur
42. Laugaland
43. Eyjafjördur
44. Fnjoskadalur
45. Storu - Tjarnir
46. Laugar - Reykjadal - Husavik
47. Namafjall - Krafla

Finally the arrows in Fig. 3 are modified such that they are almost perpendicular to the altitude contours on the average topographic map. In no case, however, would the picture change significantly, if only the deuterium results were used to construct the general flow pattern of the thermal systems.

There seems no logical reason to assume other recharge areas for the thermal systems than those given in Fig. 3. Only in few cases is it not possible to choose between either of two possible recharge areas. This is for instance the case for system No. 4, where it cannot be stated whether the water originates in the Hofsjökull or the Langjökull glacier. The deuterium content of the thermal water is the same as found in both of these glaciers. According to the average topographic map, the water could flow from both these glaciers. For this water we have therefore chosen to show both possibilities by broken arrows.

The general conclusions which can be drawn about the origin and general flow pattern of thermal water systems in Iceland are summarized in Fig. 3.

The thermal water is of meteoric origin. It is derived from precipitation deposited on the mountainous interior of the country. It descends to a great depth, whereby becoming heated as a result of the geothermal gradient. From there it flows towards the lower parts of the country, forced by hydrostatic pressure, until it finally escapes through fissures and faults in the rocks of the lowland or at the bottom of the ocean.

This model was initially suggested by Einarsson (1942) and it may now be considered as proved by the deuterium work.

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Address:
Science Institute,
University of Iceland,
Dunhaga 3,
Reykjavik,
Iceland.