Nordic Hydrology, 7, 1976, 81-94

The Use of Environmental Isotope Techniques together with Conventional Methods in Regional Groundwater Studies

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Regional hydrological investigations of the subsurface drainage in the neovolcanic area around lake Thorisvatn on the central Icelandic plateau have been carried out as well as geological exploration. Environmental isotopes, deuterium and tritium, proved decisive in finding the groundwater flow pattern and in separating the different groundwater systems and explaining local deviations as barriers and perched aquifers. The regional groundwater flow is only slightly dependent on the topography but highly on the geological conditions, as it virtually flows under mountain ranges as well as under the river Tungnaa.

Introduction

The present study started in 1969 and its aim was to investigate the hydrological conditions of the Thorisvatn area lying between the two rivers Tungnaa and Kaldakvisl (Fig. 1). Both of them are important for their hydro power potential as lake Thorisvatn will be the main reservoir for hydroelectric generation in the whole Thjorsa river basin. The groundwater drainage is an important contribution to the total discharge of the above river basins, and strikingly great fluctuations of the inflow into lake Thorisvatn had been observed. For optimal future utilization of the hydro power of these rivers and their reservoirs during winter a more thorough understanding of the hydrology of the area is important. When the study started the deuterium and tritium technique had been used successfully in geothermal research, thus it was natural to use this technique in the study of cold groundwater along with classical methods, and ultimately it proved to be the deciding factor in yielding positive results.

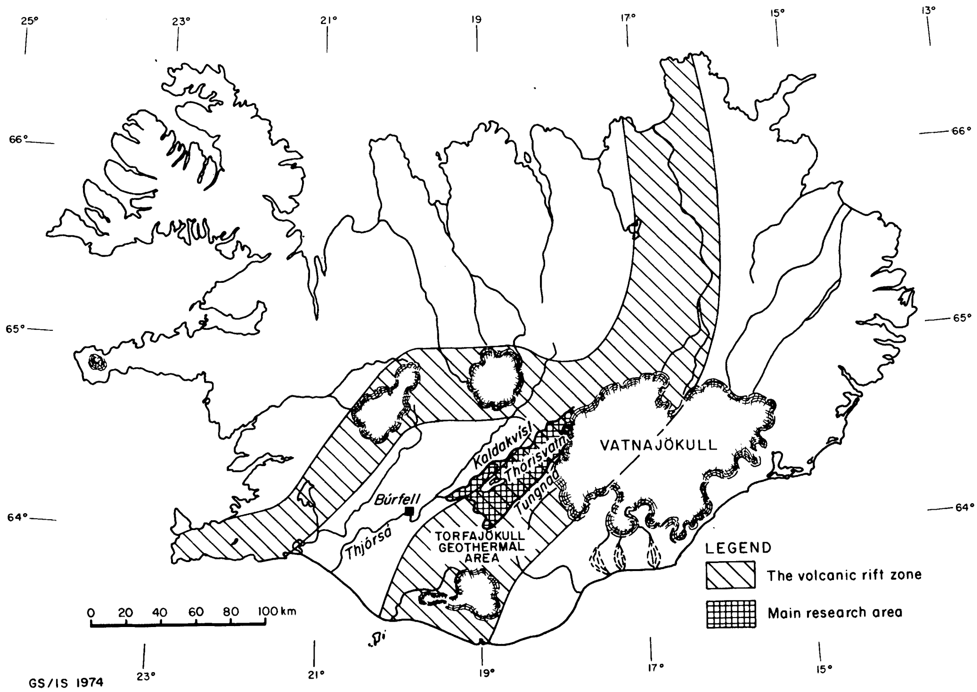

Fig. 1. Iceland. Location of the research area in relation to the neovolcanic rift zone.

An extensive study of the concentration of deuterium and tritium in natural water has been carried out for about ten years at the Science Institute of the University of Iceland. The concentration of these two isotopes in precipitation and in surface water as well as groundwater has been measured (Arnason et al. 1967, Theodorsson 1967). These measurements have mainly been used to study geothermal groundwater systems, but in the present study this technique was applied for the first time to study the hydrology of an extensive area.

The neovolcanic zones of Iceland are mainly drained by groundwater as the lava and pyroclastic rocks are very permeable. The precipitation percolates almost totally down to the groundwater table and flows subsurface until it appears again in marked spring zones where it forms »linda«-rivers (spring fed rivers) characterized by their stability (Rist 1956), or it discharges directly into the ocean. The lower boundary of these aquifers is not known. Deep drilling for geothermal water has shown them to extend as deep as 2 km below the surface (Björnsson et al. 1973) and it is highly probable that seismic layer 3, which Palmason (1971)suggests as a boundary between metamorphic facies, forms the lower boundary.

Deuterium Measurements

Measuring deuterium concentration in precipitation and local groundwater has made it possible to draw a map showing the distribution of deuterium in precipitation throughout the country. The highest deuterium content is found at the coast wherefrom it decreases gradually inland with a minimum in the mountainous central parts of the country because of an isotopic fractionation caused by evaporation and condensation processes, which are discussed in detail by Dansgård (1964) and Friedman et al. (1964).

Combined deuterium and oxygen-18 measurements carried out on hot and cold groundwater have shown that this water is of meteoric origin and has not changed its stable isotope composition during the underground passage (Bödvarsson 1962). The deuterium can, therefore, be used as a natural tracer to study hot and cold groundwater systems, the two natural energy sources available in Iceland. Furthermore, as groundwater and small rivers show very small fluctuations in deuterium concentration with time, a single sample taken from surface stream or groundwater and measured for its deuterium content is expected to represent a reliable mean value (Arnason et al. 1967).

Measurements of geothermal water emerging from hot springs and drill holes often show that the geothermal water has a deuterium concentration quite different from that of the local groundwater. This indicates that the recharge area of the geothermal waters lies far inland from the place where it emerges. In some cases the water emerging from geothermal areas on the lowland has flowed underground for a distance of 70 km. Only in a few cases do the hot water systems seem to be of a rather local origin.

More detailed deuterium measurements carried out on certain geothermal areas, together with tritium measurements and chemical analysis, have been found useful to distinguish between different water systems within the same area and trace their origin. For example, measurements carried out on the Reykjavik geothermal area in SW Iceland have shown that this area is fed by three separate hot water systems of different origin (Arnason and Tomasson 1970).

In some cases deuterium measurements on cold groundwater have been used to state whether the water is of a local or distant origin. Now, for the first time they are used, together with tritium measurements and hydrogeological studies, to evaluate in detail the cold groundwater systems in an extensive area.

The results are expressed as δ = pro mille deuterium enrichment (depletion negative) relative to SMOW (Standard Mean Ocean Water). All samples are prepared and analysed at least in duplicate. The standard deviation for a sample analysed in duplicate is 0.7 ‰.

Fig. 2 shows the distribution of deuterium in the southern part of central Iceland, including the research area. The isolines are obtained by using results of deuterium measurements of regular samples of precipitation, local groundwater samples, and

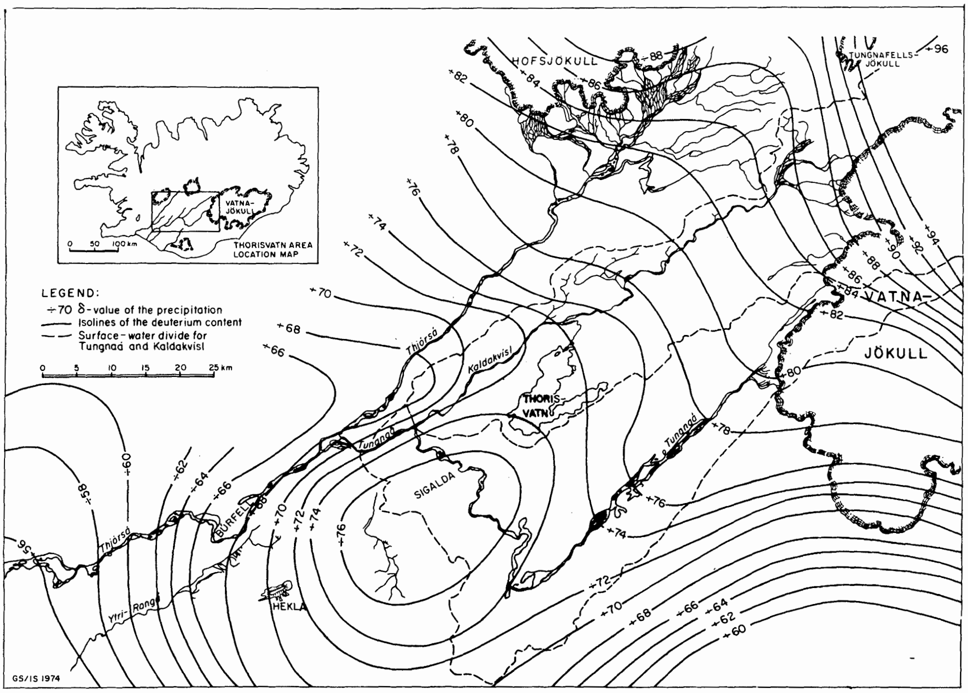

Fig. 2. Deuterium concentration of the local precipitation.

snow profiles taken from the uppermost winter layers on the glaciers (Arnason et al. 1967, Arnason 1969, 1970). The map shows how the deuterium content of the precipitation decreases gradually inland. The map also reflects the influence of the topography. The local minima found to the NE of the mountain Hekla is understandable when it is taken into consideration that the rain clouds have been depleted strongly in deuterium by travelling over high mountains such as the Myrdalsjökull and the Torfajökull area located to the south of the minima.

Tritium Measurements

Tritium is a radioactive isotope of hydrogen with a half life of 12.3 years. If it was not for constant renewal this isotope would not be found in nature. Tritium is constantly produced in the upper layers of the atmosphere by cosmic rays. Since 1952 large quantities of tritium have been injected into the atmosphere as a result of the frequent tests with thermonuclear devices.

The cosmic ray produced component of tritium in the precipitation has a constant mean value of about 20 T.U. (1 T.U. is equivalent to a T/H ratio of 10^{-18}). The

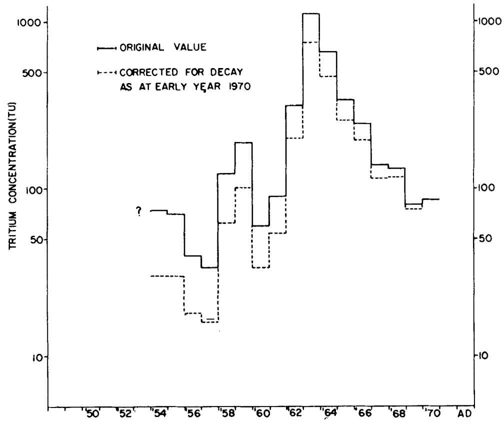

Fig. 3. The average yearly tritium content in the precipitation in Reykjavik. Solid line at time of fall, dotted line corrected for decay at time of measurements.

thermonuclear weapons component has, however, fluctuated very much. Each time a major test series with thermonuclear weapons has been made the tritium concentration in precipitation has risen sharply by 1-2 orders of magnitude. A substantial part of the tritium from each test is partially stored in the stratosphere, and it will leak for a period of years into the lower layers, primarily in the early summer.

The tritium in precipitation in Iceland reached its maximum in early sumer of 1963 when it rose to 4000 T.U. and the mean value for the whole year was 1100 T.U., 50 times the mean value of the cosmic produced component.

Fig. 3 shows the mean yearly values for tritium in precipitation in Reykjavik, Iceland. Measurements have shown that the geographical variations over the country in the tritium concentration in precipitation are small, so the mean values for Reykjavik can be used for the whole country as far as its use here concerns.

The changes in tritium concentration of springs are in most cases slow, so a single sample from a spring will represent the tritium concentration of the spring for a period of many months or often a longer period.

The large variation of the recharge of the groundwater will be reflected in the time variations of the tritium concentration of springs. The tritium in spring water can depend on the tritium concentration in precipitation in a complicated manner, as the spring can be composed of components of various age or come from a large, well mixed reservoir with some mean age.

Tritium measurements can, nevertheless, be very useful, because although they give no conclusive age of the groundwater, certain information about the mean age can often be given and such measurements can often show that two adjacent springs are fed by different groundwater systems. When the tritium concentration drops below about 100 T.U. this is a clear indication that the water is substantially of old origin, and when the tritium concentration drops below 50 T.U. the mean age of the water is of the order of decades. Lower tritium content than 20 T.U. in a sample from a mixed, unconfined groundwater reservoir shows that it must be several tens of thousands of Gl in size and that the average age of the water is more than 100 years.

The Research Area

Fig. 1 shows the location of the research area. It also illustrates the neovolcano-tectonic rift zones in Iceland and how the field of study is situated mostly within the eastern rift zone to the NE of the mountainous Torfajökull geothermal area. The research area covers the nearly 1500 km^2 space between the glacier fed rivers Tungnaa and Kaldakvisl, which issue from Vatnajökull about 40 km apart. They flow parallel towards SW for about 80 km until river Tungnaa bends nearly at right angles to the NW to join river Kaldakvisl about 20 km to the W from Lake Thorisvatn. The area between the rivers is a plateau, 35-50 km wide, rising gradually in height towards the NE from about 500 m to about 900 m above sea level. Some single mountains and NE-SW trending ridges of subglacial volcanic origin rise 200-300 m above the surrounding plateau whereof Snjoalda ridge, Gjafjöll, Blafjöll and the mountains around lake Thorisvatn are the most prominent. Only the lowest section of river Kaldakvisl flows in a rather mature valley, which cuts down to about 350 m a.s.l. at its confluence with river Tungnaa.

The greatest part of the research area is an unvegetated desert, as only its lowest part, named Thoristungur, at the valley floor along river Kaldakvisl, where there is a spring area, is covered with some vegetation. Lake Thorisvatn used to be the second largest lake in Iceland covering 70 km^2 at 571 m a.s.l., but in 1972 it was converted into a reservoir for hydro-plants by diverting river Kaldakvisl into it, raising its level for 5 m and changing its outlet via a channel to river Tungnaa at Sigalda.

Geology

As shown in Fig. 1 the research area is mostly located within the active volcanic rift zone with only the NW-most part of it extending beyond its limits. The main geological features are shown in Fig.4. One of the most distinctive features is a 8-10 km wide, very active volcano-tectonic graben zone, trending SW-NE. The zone is characterized by a great number of Holocene volcanic fissures and fresh faults. This marks the NW border of the eastern rift zone in S-Iceland (Fig.1), which is characterized by continuous formation of new crust by volcanic structures. The volcanic rift zone

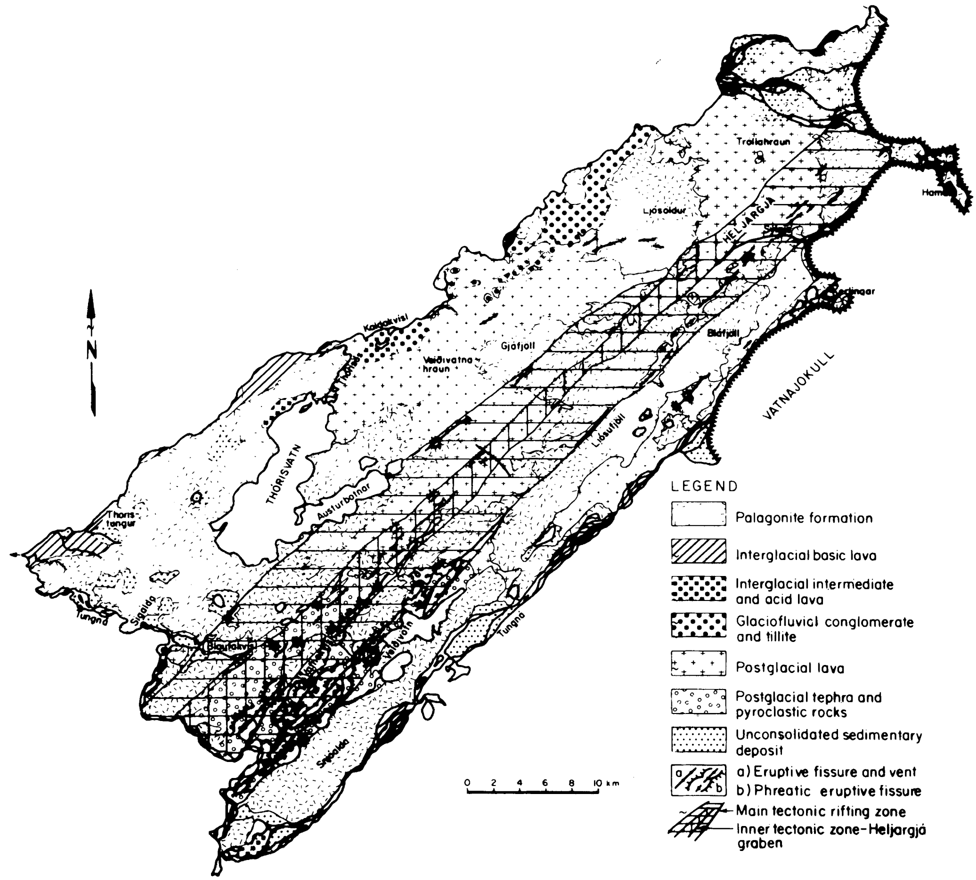

Fig. 4. Geological map of Thorisvatn area.

subsides subsequently forming tectonic zones with eruptive fissures along its borders. Seemingly the volcanic activity has moved from the central rift zone to its border at the end of last glaciation, at least in this area. In Fig.4 it is shown that the greatest part of the volcanic fissures are situated within the graben zone, only a few small ones are lying outside it. The greatest tectonic movements and also the greatest fissure eruptions have occurred in the 2-5 km wide Heljargja graben. Most volcanic fissures, faults, and grabens in the area follow the SW-NE trend of the rift zone. Still, exceptions are to be found. A few cross it at approximately right angels at the northern end of Blafjöll mountains and up to Ljosöldur mountains, where some small volcanic fissures extend west from the central zone.

Outside the graben zone the plateau is to a great extent covered with Holocene lava flows, e.g. Veidivatnahraun, that can be traced all the way to Thorisos. Although the greatest part of the lavas have flowed across Tungnaa, some can be traced all the way down to the ocean at the SW-coast (Kjartansson 1960).

Most of the lavas lie discordant on palagonite formations which were formed by volcanic eruptions during the Quaternary glaciations. Under the ice sheet the volcanic material piles up and forms ridges of pillow lava and cube-jointed basalt, sometimes capped by tuff layers, if the eruption has been powerful enough to break through the ice. All ridges and mountains rising above the lava fields are built up in that way except those in Veidivötn-Hraunvötn area, which are piled up of postglacial tephra by phreatic eruptions caused by water inflow from lakes or large groundwater reservoirs. The area along river Tungnaa consists mostly of palagonite ridges dating from the last glaciation. The lowest parts are covered by lava, except at both ends of Ljosufjöll mountains, where older palagonite formations outcrop. Yet these formations can hardly be older than from the beginning of the last or last but one glaciation.

The stratigraphy NW of the graben zone is more complex in structure and age, where not covered by postglacial lavas. The hills and mountains belong to the palagonite formation, mostly pillow lava, but in between som thick layers of conglomerate and tillite are to be found. At river Kaldakvisl there are a few patches covered by interglacial valley-filling lava flows. The highest mountains in this area are the palagonite ridges at the SE shore of lake Thorisvatn and in Gjafjöll mountains formed without doubt during the last glaciation. Other formations are older and erosional forms are therefore more prominent. They are all normally magnetized, but at the west bank of river Kaldakvisl we move into reverse magnetized strata, dating from the end of the Matuyama Epoch. All formations to the SE of Kaldakvisl thus date from the Brunhes Epoch, i.e. they are younger than 700 thousand years old.

Hydrology

Surface drainage is hardly to be found in the whole research area despite the fact that the precipitation ranges from 1200-3000 mm/year according to topographical setting. All the precipitation percolates down to the groundwater table, except during periods with frozen ground. Then some surface flow occurs on the NW side of the graben zone, except in the lava fields. In the lava fields and the graben zone and also in the area to the SE most part of the snow melt-water collects in depressions without any surface outlets and percolates gradually down to the groundwater. Therefore, it is safe to assume that the greatest part of the precipitation escapes to the groundwater, propbably >80%. The area is more or less covered by lakes during spells of thawing but most of them disappear during the summer. Permanent lakes are only to be found where the surface cuts groundwater table as at the lakes Veidivötn, Hraunvötn, and Thorisvatn. Fig.5 shows the location of the major spring areas

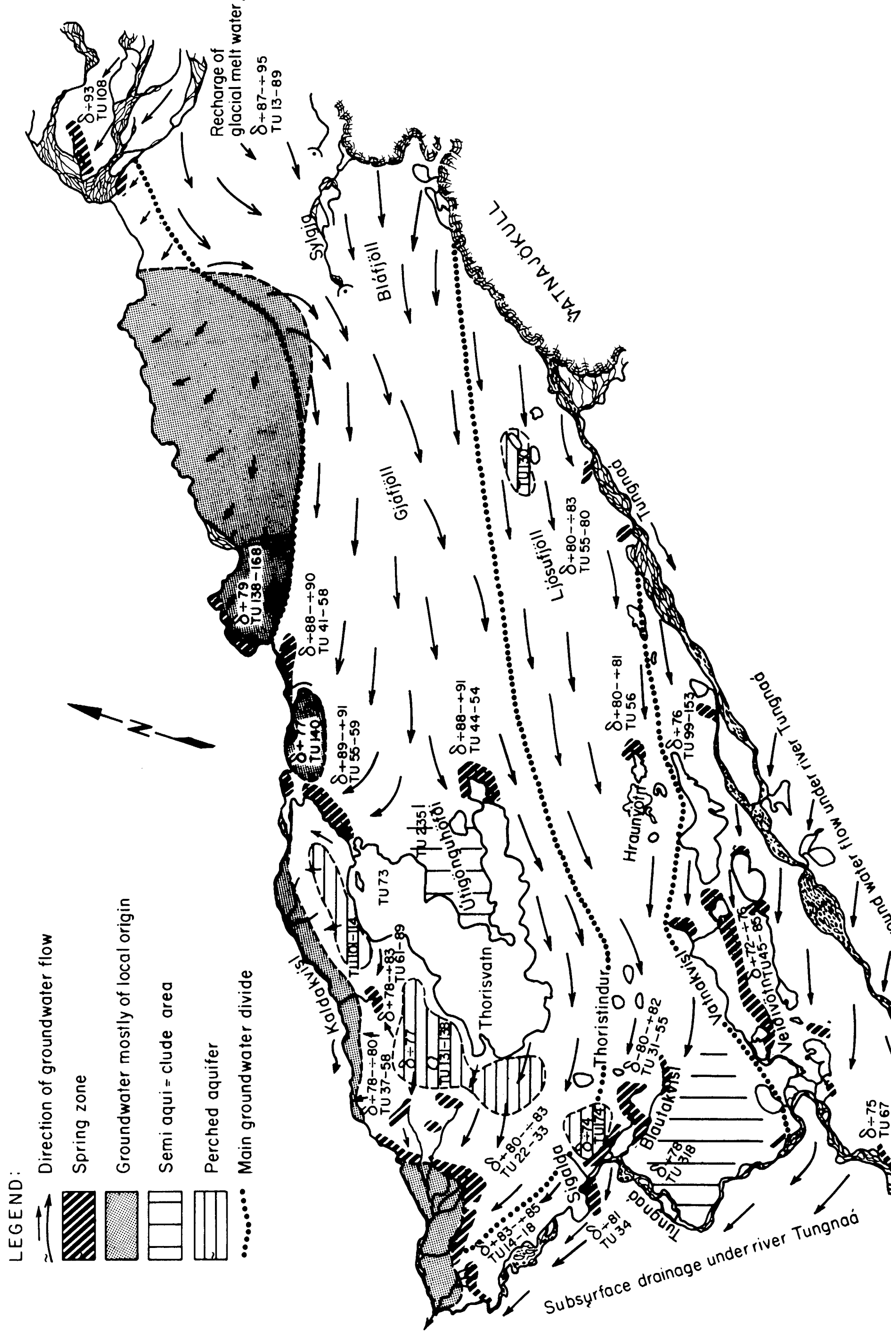

Fig. 5. Flow pattern of the groundwater systems in Thorisvatn area showing their range of deterium and tritium concentration.

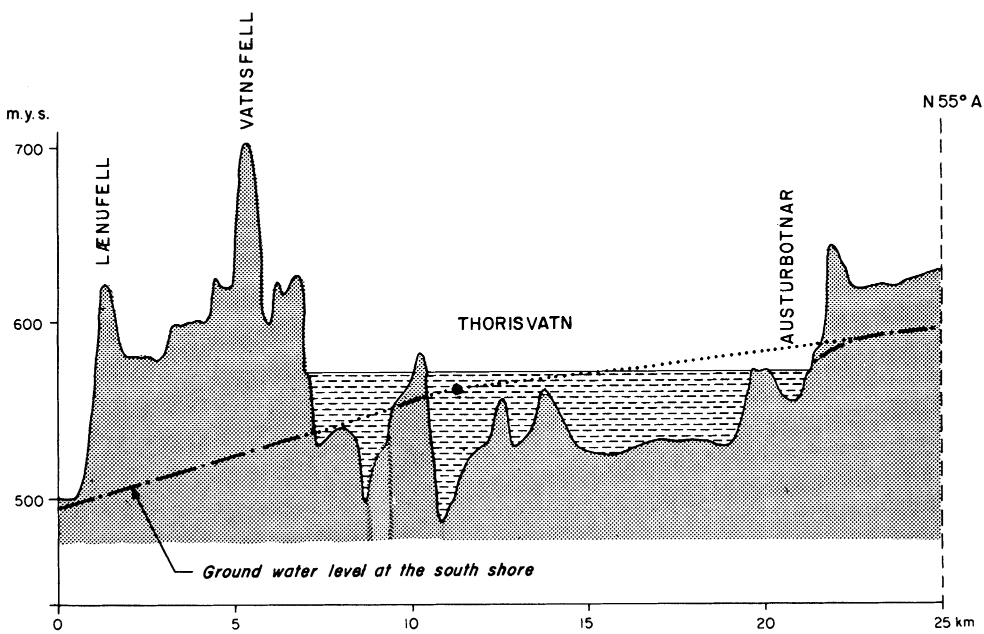

Fig. 6. Longitudinal section of Lake Thorisvatn showing the piezometric surface along its SE shore.

where the surface cuts the piezometric surface, partly alongside the deepest river channels, as in Thoristungur, at Sigalda, Blautakvisl and Thorisos, partly at the previously mentioned lakes. Fig.6 shows how the horizontal surface of lake Thorisvatn cuts the piezometric slope of the groundwater table measured in boreholes alongside its SE-coast. The NE end of the lake causes appr. 15 m drawdown while the lower end of the lake surface lies at about 40 m above the groundwater table. According to data acquired from boreholes the drawdown of spring zones affects the groundwater table only for a distance of a few hundred meters. In Thoristungur and at several other small areas upstream along river Kaldakvisl the groundwater table nearly coincides with the surface. The strata there seem to be less permeable than elsewhere. These formations are also the oldest ones in the research area.

During summer 1969 data for geohydrological mapping of the research area were collected. Springs were located and their elevation and temperature measured and water samples taken for measurement of their isotope content. The correlation between lake levels and the piezometric surface was also studied (Fig.6). A great number of boreholes have been drilled in the vicinity of lake Thorisvatn and thoughout the western part of the research area. The piezometric level is fairly well determined there. Based on this research a geohydrological map was drawn, showing the piezometric surface (Sigbjarnarson 1972). The groundwater contours are reliable in the western part of the area, but less accurate in the eastern part of it. No simultaneous discharge measurements exist on the total groundwater yield from the area, but it is estimated to be 50-60 m^3/s.

Discussion

The main results of the geohydrological investigations of the Thorisvatn area are shown in Fig.5. Together with geological reconnaissance of the research area the deuterium and tritium measurements are the base on which the interpretations rest. In some cases the isotopic composition of the groundwater gave a certain indication about the subsurface geological structures as groundwater barriers.

Temperature measurements of the springs used in combination with the other methods also proved valuable. The temperature range of different springs proved to be 1.8^0 - 5.6^0 C. The isotope content of the water samples from the warmest springs, which also are large ones, such as the southeastern branch of lake Thorisvatn and at Blautakvisl springs, indicated distant origin and that the water had been some decades on its way.

On the other hand low spring temperature usually indicates rather young water of local origin, often snow melt from the previous winter. These results show that the deep percolating groundwater is warmed by heatflow from the interior of the earth. They are also confined to the graben zone. If such groundwater flow percolates through less permeable bedrock or through surface lava resting on it, its temperature is somewhat lowered as shown by Thorisos and Thoristungur springs. It can be concluded that the difference in temperature of the springs is depending on the interplay between the surface temperature and the heat flow from the earth's interior.

At the Science Institute about 75 deuterium and 120 tritium measurements from groundwater samples from different spring horizons in the research area were analyzed. The results are shown in Fig.5, where the - δvalue given is the range of the deuterium content and T.U. value given is the range of the tritium content for all sampling stations within the same spring area. The results are usually in a very good agreement. The oldest groundwater according to the tritium content has in most cases originated at the greatest distance from the spring.

The measurements of the environmental isotopes support the assumption that the research area can be divided into three main streams, whereof the central one can furthermore be divided in two branches, on grounds of a groundwater divide observed in drill holes. In certain cases, especially to the NW of lake Thorisvatn, the tritium content of the water samples showed them to be young and the deuterium content manifested their local origin. By comparison with the piezometric surface and the isotope content of the regional groundwater flow it was clear that these springs were issued from perched aquifers sustained by tillite layers. The southernmost part of the area around Veidivötn lakes is fed by water of relatively high deuterium content, about δ - 75, which is approximately the same as the local precipitation, but its relatively low tritium content, mostly 45-60 T.U, shows that there must be either a large groundwater reservoir or an inflow of water with rather high deuterium concentration. The great disharge of Vatnakvisl, about 15 m^3/s, which drains the Veidivötn area, shows that there must be some additional inflow, even though the precipitation is here at its maximum within the research area. On the other hand water with such a high deuterium content is not found to the N or NE of Veidivötn. The only possible explanation is a groundwater inflow under river Tungnaa, and studies of its southern bank have also manifested that some of the streams there flowing to the NW, recharge before reaching the river.

There is no obvious geological evidence to explain why the groundwater system of the Veidivötn area is separated from the one lying on its north side. The water table of Hraunvötn is about 0.5 m lower than the northernmost part of Veidivötn. It indicates that the volocano-tectonic zone (Fig.5) diverts the main groundwater flow from the E and NE to the W where the water can escape through postglacial lava to Blautakvisl and furthermore through the lava under Tungna to Sigalda gorge where the deuterium content of the spring shows that the water originates from the north-eastern part of the research area. The total discharge of these springs exceeds 15 m^3/s, which causes drawdown of the groundwater in the main graben zone further to the E. Of course, there is some mixing between these two groundwater systems, but a weak groundwater divide keeps them separated. The divide can be variable depending on groundwater conditions at the time.

The groundwater system of the central area to the N of Veidivötn receives a large quantity of water with a deuterium concentration significantly lower than the local precipitation (Fig.2), ranging from δ - 80 to δ - 91. The southernmost branch of this groundwater system shows fairly constant value of deuterium concentration from Vatnajökull down to Thoristungur(δ - 80 to δ - 85), while the tritium concentration decreases gradually further downstream from about 80 T.U. down to 14 T.U. One could expect that the intermixing with the local precipitation would increase the deuterium concentration, but it does not. This can be explained by deep percolating inflow from the NE via the active volcano-tectonic zone, especially Heljargja graben. The great discharge from this area together with its low tritium concentration indicates a very large groundwater reservoir, at least several thousand Gl (1 Gl = 10^9l).

The northern branch of the central groundwater system drains mostly via Thorisvatn and Thorisos, about 12 m^3/s on the average, but a noteworthy part of it escapes further down to Thoristungur along the southern shore of lake Thorisvatn and possibly under the lake floor. Some leakage from Thorisvatn can also be assumed. The Thoristungur spring horizon discharges about 6-8 m^3/s. The isotope concentration of water samples shows their mixed origin. The southernmost springs show relatively low concentration both of tritiumand deuterium, but it increases towards the north. That shows an increasing influence of the local precipitation and the leakage from lake Thorisvatn on the regional groundwater flow, but still they are easily distinguished from the perched aquifers of local origin in that area by much lower isotope concentration. Fig.6 shows a sudden change in the slope of the piezometric surface at the southern shore of lake Thorisvatn. By comparing Fig.6 with Fig.4 it is obvious that this change in the slope occurs right at the margin of the main rift zone, depending on a great decrease in the permeability towards the NW.

The springs at Thorisvatn and Thorisos show the lowest concentration of deuterium to be found in the research area except at its NE corner, wherefrom it must be originated and from the NW part of Vatnajökull glacier. Some recharge of glacial meltwater is known where river Sylgja and some others flow onto recent lavas, where they disappear. Also some seepage to the groundwater must be expected at the glacier bottom. The isotope concentration of the glacial meltwater has a great range (Fig.5), and its influence on the composition of the groundwater is not known.

In two places, at Utigönguhöfdi and south of Blautakvisl, the water samples show unusually high concentration of tritium and also of deuterium in the latter case, but unfortunately no reliable deuterium measurement was obtained from the former one (Fig.5). There is no geological evidence found to separate those areas from their surroundings. The reason for those features must be groundwater barriers caused by Thorisvatn depression and former Sigalda lake in the latter case. Those barriers keep local groundwater bodies upstream behind them.

The third groundwater system is in the NW part of the area, along river Kaldakvisl. This system has a deuterium concentration δ - 77 to δ - 79, which shows local origin and tritium concentration 138-168 T.U., which indicates precipitation from the last couple of years. The bedrock in these areas is of low permeability, and it does not receive an inflow from the regional groundwater flow. The northern part of the lavas wherefrom Thorisos springs issue is probably underlain by a bedrock just allowing the groundwater to escape to the springs through the bottom layers of the lavas. By comparison of the geological structure (Fig.4) and the results obtained from the isotope measurements (Fig.5) and other hydrological studies there is an obvious correlation. It is clear that the main rift zone trends to guide the groundwater flow in its own direction. The continuation of the rift zone extends further to the SW outside the research area but the Torfajökull high temperature area (Fig.1) is nearly an aquiclude due to the geothermal alteration of the bedrock, which, together with large precipitation in the Veidivötn area, keeps the groundwater table high enough to force the inflow from the NE to escape through the lavas and less permeable bedrock towards the western part of the research area.

Our main conclusion is that it would have been very difficult, if not impossible, to solve the groundwater problems in the research area without combined methods as our results have shown. Especially, thorough geological knowledge in collaboration with the environmental isotope techniques proved to be of greatest value. Some computer models have already been based on the results gained (Eliasson 1971 and 1973), but some additional measurements are needed to fit them to nature itself.

References

Arnason, B., and Sigurgeirsson, Th. (1967) Hydrogen isotopes in hydrological studies in Iceland. *Isotopes in Hydrology.* Proceedings of IAEA symposium, pp. 35-47. Vienna.

Arnason, B., Theodorsson, P., Björnsson S., and Sæmundsson, K. (1969) Hengill, a high temperature area in Iceland. *Bull. Volcanol., 33,* pp. 245-259.

Arnason, B., and Tomasson, J. (1970) Deuterium and chloride in Geothermal studies in Iceland. *Geothermics*-Special Issue 2, pp. 1405-1415.

Arnason, B. (1970) Exchange of deuterium between ice and water in glaciological studies in Iceland. *Isotope Hydrology 1970.* Proceedings of IAEA symposium, pp. 59-71. Vienna.

Björnsson, S., Arnorsson,S., and Tomasson, J. (1972) Economic evaluation of Reykjanes thermal brine area, Iceland. *The American Association of Petroleum Geologist Bulletin,* 56, (12), pp. 2380-2391.

Bödvarsson, G. (1962) The use of isotopes of hydrogen and oxygen for hydrological purposes in Iceland. *Jökull,* II, pp. 49-54.

Dansgård, W. (1964) Stable isotopes in precipitation. *Tellus,* 16, pp. 436-468.

Eliasson, J. (1971) Mechanism of ground water reservoirs. *Nordic Hydrology, 2,* (4) pp. 266-277.

Eliasson, J., Arnalds, S. St.,Johannsson, S., and Kjaran, S.P. (1973) Reservoir mechanism in an aquifer of arbitrary boundary shape. *Nordic Hydrology 4,* (3), pp. 129-146.

Friedman, I., Redfield, A.C., Schoen, B., and Harris,J. (1964). The variation of deuterium content of Natural waters in hydrological cycle. *Reviews of Geophysics, 2* (1) pp. 177-224.

Kjartansson, G. (1960) The Thjorsa Lavas (Thjorsarhraun). *On the Geology and Geophysics of Iceland.* Int. Geol. Congr. XXI. Guide to excursion A2, pp. 38-41.

Palmason, G. (1971) Crystal Structure of Iceland from Explosion Seismology. *Soc. Sci. Isl. XL,* Reykjavik.

Rist, S. (1956) »Islenzk vötn« (Icelandic fresh waters). Reykjavik.

Sigbjarnarson, G. (1972). Hydrogeological map of Thorisvatn area. »Vatnafrædi Thorisvatnssvædis« (Hydrology of Thorisvatn area). Mimeographed report to NEA. Reykjavik.

Theodorsson, P. (1967) Natural Tritium in groundwater studies. *Isotopes in Hydrology.* Proceedings of IAEA symposium, pp. 371-379. Vienna.

Received: 6 February, 1975

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