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

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ABSTRACT

Regional groundwater investigations of the sub-surface drainage in the neovolcanic area around lake Thorisvatn on the central Icelandic plateau have been carried out as well as geological exploration. The measurements of the environmental isotopes, deuterium and tritium in the groundwater proved to be the most valuable test in finding the flow pattern and in separating the different groundwater systems. Local deviations, as barriers and perched aquifers, were easily found. The result shows that the regional groundwater flow there is only slightly dependent on the topography but highly on the geological conditions, and that it virtually flows under mountain ranges as well as under river Tungná.

INTRODUCTION

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 (Árnason et al. 1967, Theodorsson 1967). These measurements have mainly been used to study geothermal groundwater but with the present work this technique has been used 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 phyroclastic 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 "lindá"-rivers (spring fed rivers) that are characterized by their stability (Rist 1956), or it discharges directly into the ocean. The lower boundary of these aquifers are not known. Deep drilling for geothermal water has shown that they extend as deep as 2 km below the surface (Björnsson et al. 1973) and it is highly probable that seismic layer 3 (Pálmason 1971) forms the lower boundary.

The present study started in 1969 and its aim was to investigate the hydrological conditions of the Thórisvatn area lying between the two rivers Tungná and Kaldakvísl (Fig. 1). Both of them are important for their hydro power as well as the lake Thórisvatn damsite is the main reservoir for the hydroelectric generation in the whole Thjórsá river basin. The groundwater is an important contribution to the total drainage of these river basins, and there had been observed unusually great fluctuation of its inflow. In order to be able in the future to optimize the utilization of the water in these rivers and their reservoirs during winter times, it is important to gain a better understanding of the hydrology of the area. When the study started the deuterium and tritium technique had been used extensively in geothermal work and it was natural to use this technique also in the study of cold groundwater. The isotope technique was used together with classical methods and proved to be the deciding factor in yielding positive results.

DEUTERIUM MEASUREMENTS

Results obtained for the deuterium concentration of precipitation and local groundwater have made it possible to draw a map showing the distribution of deuterium in precipitation throughout the country. The highest deuterium content is found in precipitation at the coast from where it decreases gradually towards inland with a minimum in the mountaneous central parts of the country. This can be accounted for as a result 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. 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 fluctuation 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.

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 water lies far inland from the place where it emerges. Only in a few cases the hot water systems seem to be of a rather local origin. In some cases the water emerging from geothermal areas on the lowland has flowed underground for a distance of 70 km.

A 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 Reykjavík geothermal area in SW Iceland have shown that this area is fed by three separated hot water systems of different origin.

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 o/oo.

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 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 north-east 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 Mýrdalsjökull and the Torfajökull area located 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 weapons.

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 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 summer 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 Reykjavík, Iceland. Measurements have shown that the geographical variations over the country in the tritium concentration in precipitation are small, so the mean values for Reykjavík 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 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 for the groundwater, certain information about the mean age can often be given and it 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 ten thousand 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 represents also the neovolcano-tectonic rift zones in Iceland and how the field of studies 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, Tungná and Kaldakvísl, which issue from Vatnajökull about 40 km apart. They flow parallel towards the SW for about 80 km until river Tungná bends nearly at right angles to the NW to join river Kaldakvísl about 20 km to the W from Lake Thórisvatn. The area between the rivers is a plateau 35-50 km wide, gradually increasing 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 Snjóalda ridge, Gjáfjöll, Bláfjöll and the mountains around lake Thórisvatn, are the most prominent. Only the lowest part of river Kaldakvísl flows in rather mature valley which cuts down to about 350 m a.s.l. at its confluence with river Tungná. The greatest part of the research area is an unvegetated desert, only its lowest part named Thóristungur at the valley floor along river Kaldakvísl, where there is a spring area, is covered with some vegetation. Lake Thórisvatn was the second largest lake in Iceland covering 70 km^2 in the elevation 571 m a.s.l., but in 1972 it was converted into a reservoir for hydro-plants by diverting river Kaldakvísl into it, raising its level 5 m and its outlet changed via channel to river Tungná at Sigalda.

GEOLOGY

As shown on fig. 3 the research area is mostly located within the active volcanic rift zone, only the NW-most part of it lying outside. The main geological features are shown on 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 volcanoes, fresh faults and fissures. This marks the NW border of the eastern rift zone in S-Iceland which is characterized by continuous formation of a new crust by volcanic structures. The rift zone 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. On 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 Heljargjá 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 angles at the northern end of Bláfjöll mountains and up to Ljósöldur mountains, where some small volcanic fissures go 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 Thórisós. Although the greatest part of the lavas have flown across Tungná, some can be traced all the way down to the ocean at the SW-coast.

Most of the lavas lie discordant on palagonite formations which are formed by volcanic eruptions during the Quarternary glaciations. Under the ice sheet the volcanic material piles up and forms ridges of pillow lava and cube jointed basalt, sometimes topped by tuff layers, if the eruption has been powerful enough to get 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 have been piled up of postglacial tephra by phreatic eruptions caused by lakes or a great groundwater inflow to the vents. The area along river Tungná consists mostly of palagonite ridges dating from the last glaciation. The lowest parts are covered by lava, except at both ends of Ljósufjöll mountains, where older palagonite formations outcrop. Those formations can though hardly be older than from the beginning of the last glaciation or the last but one.

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 some thick layers of conglomerate and tillite are to be found. At river Kaldakvísl 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 Thórisvatn and in Gjáfjöll mountains, formed without doubt during the last glaciation. Other formations are older and erosion forms therefore more prominent. They are all normally magnetized, but at the west bank of river Kaldakvísl we move into reversely magnetized strata, dating from the end of the Matuyama Epoch. All formations to the SE from Kaldakvísl 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. The precipitation all percolates down to the groundwater table, except during thaw on frozen ground. Then some surface flow occurs on the NW side of the graben zone, except the lava fields. In the lava fields and the graben zone and also in the area to the SE the most part of the snowmelt 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, probably >80%. The whole area is covered by lakes during the thaw, but most of them disappear during the summer. Permanent lakes are only to be found where the surface cuts the groundwater table, as at the lakes Veidivötn, Hraunvötn and Thórisvatn. Fig. 5 shows where the main spring areas are situated, it is where the surface cuts the piezometric surface, partly alongside the deepest river channels, as in Thóris-tungur, at Sigalda, Blautakvísl and Thórisós, partly at prior mentioned lakes. Fig. 6 shows how the horizontal surface of lake Thórisvatn cuts into the piezometric slope of the groundwater table measured in boreholes alongside its SE-coast. The NE end of the lake causes approximately 15 m drawdown while the lower end of the lake surface lies up to 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 Thóristungur and several other small areas upstreams at river Kaldakvísl 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 the summer 1969 data was collected for geohydrological mapping of the research area. Springs were located and levelled, their temperature measured and water samples taken for measurements of their isotope content. The relation of lakes to the piezometric surface was investigated similar as shown on fig. 6. A great number of boreholes are located around lake Thórisvatn and in all the western part of the area where the piezometric level is fairly well determined. 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 can be estimated about 50-60 m^3/s.

DISCUSSION

The main results of the geohydrological investigacions of the Thórisvatn area are shown on Fig. 5. Together with geological reconnaissance of the research area the deuterium and tritium measurements are the base which the interpretations rest on. 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 tried also a helpful tool if they are used in combination with the other methods. The temperature range of different springs proved to be 1,8° - 5,6° C. The isotope content of the water samples from the warmest springs which also are large ones, showed that their origin was far away, and that the water had been some decades on its way, as at the southeastern branch of lake Thórisvatn and at Blautakvísl springs.

On the other hand a low temperature of a spring usually proved to indicate water of local origin and rather young, often a snow melt from the last 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 a groundwater flow penetrates through less permeable bedrock or through surface lava resting on it, its temperature is somewhat lowered as shown by Thórisós and Thóristungur springs. It can be concluded that the different temperature of the springs is depending on the interplay between the surface temperature and the heat flow from the earth's interior.

About 75 deuterium and 120 tritium measurements of groundwater samples from different spring horizonts in the research area were performed at the Science Institute. The results of which are shown on Fig. 5,where the $\div\delta$ value given is the range of the deuterium content and T.U. value given is the range of the tritium content for all sampling points within the same location. 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 streams, mostly based on 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 young and the deuterium content manifested their local origin. By comparison with the pezometric surface and the isotope content of the regional groundwater flow it was clear, that those springs issued from perched aquifers supported by tillite layers. The southernmost part of the area around Veidivötn lakes is fed by water of relatively high deuterium content about $\delta \div 75$, which is approximately the same as the local precipitation, but its relatively low tritium content, mostly 45-60 TU, shows that there must be either a large groundwater reservoir or an inflow of water with rather high deuterium concentration. The great discharge of Vatnakvísl, about 15 m^3/s., which drains Veidivötn area, shows that there must be some inflow somewhere from, even though the precipitation there is at its maximum in the research area. On the other hand water with such a high deuterium content is not found to the N or NE from Veidivötn. The only possible explanation is a groundwater inflow under river Tungná, and studies of its southern bank have also manifested that some of the streams there flowing to the NW, recharge before reaching the river..

No geological evidence seems to explain why the groundwater system of Veidivötn area is separated from that one lying on its north side, but the water table of Hraunvötn is about 0.5 m lower than the northernmost part of Veidivötn. It indicates that the most volcano-tectonic zone (Fig. 5) turns the main groundwater flow from the E and NE to the W where the water can escape through postglacial lava to Blautakvísl and furthermore through the lava under Tungná 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 those 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 changeable depending on groundwater conditions at each 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 Thóristungur (δ÷80 - 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. It can be explained by deep percolating inflow from the NE via the active volcano-tectonic zone, especially Heljargjá graben. The great discharge from this area together with its low tritium concentration indicates a very large groundwater reservoir, at least several thousand Gl.

The northern branch of the central groundwater system drains mostly via Thórisvatn and Thórisós about 12 m^3/s on the average, but a noteworthy part of it escapes further down to Thóristungur along the southern shore of lake Thórisvatn and maybe under the lake floor. Some leakage from Thórisvatn can also be assumed. The Thóristungur spring horizont 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 tritium and 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 Thórisvatn. By comparing Fig. 6 with Fig. 4 it is obvious that this change in the slope is just at the margin of the main rift zone, which depends on great decrease in the permeability towards the NW.

The springs at Thórisvatn and Thórisós show the lowest concentration of deuterium to be found in the research area except at its NE corner, wherefrom it must be originating and from the northernmost 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's 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 Útigönguhöfdi and south of Blautakvísl, the water samples show unusually high concentration of tritium and also of deuterium in the latter case, but alas no reliable deuterium measurement was obtained from the former one (Fig. 5). There is no geological evidence found to separate those areas from their surrounding. The reason for those features must be groundwater barriers caused by Thórisvatn 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 Kaldakvísl. This system has a deuterium concentration $\delta \div 77$ to $\delta \div 79$ which shows a local origin and tritium concentration 138-168 T.U. which indicates the last couple of years precipitation. 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 where from Thórisós 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 goes 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 there 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, a good geological knowledge in collaboration with the environmental isotope techniques proved to be of great value. The present authors are, of course, aware that the gained results are only preliminary and much more detailed investigations are needed to complete the picture. Some computer models have already been based on the results (Elíasson 1973), but much more investigations are needed to fit them to the nature itself.

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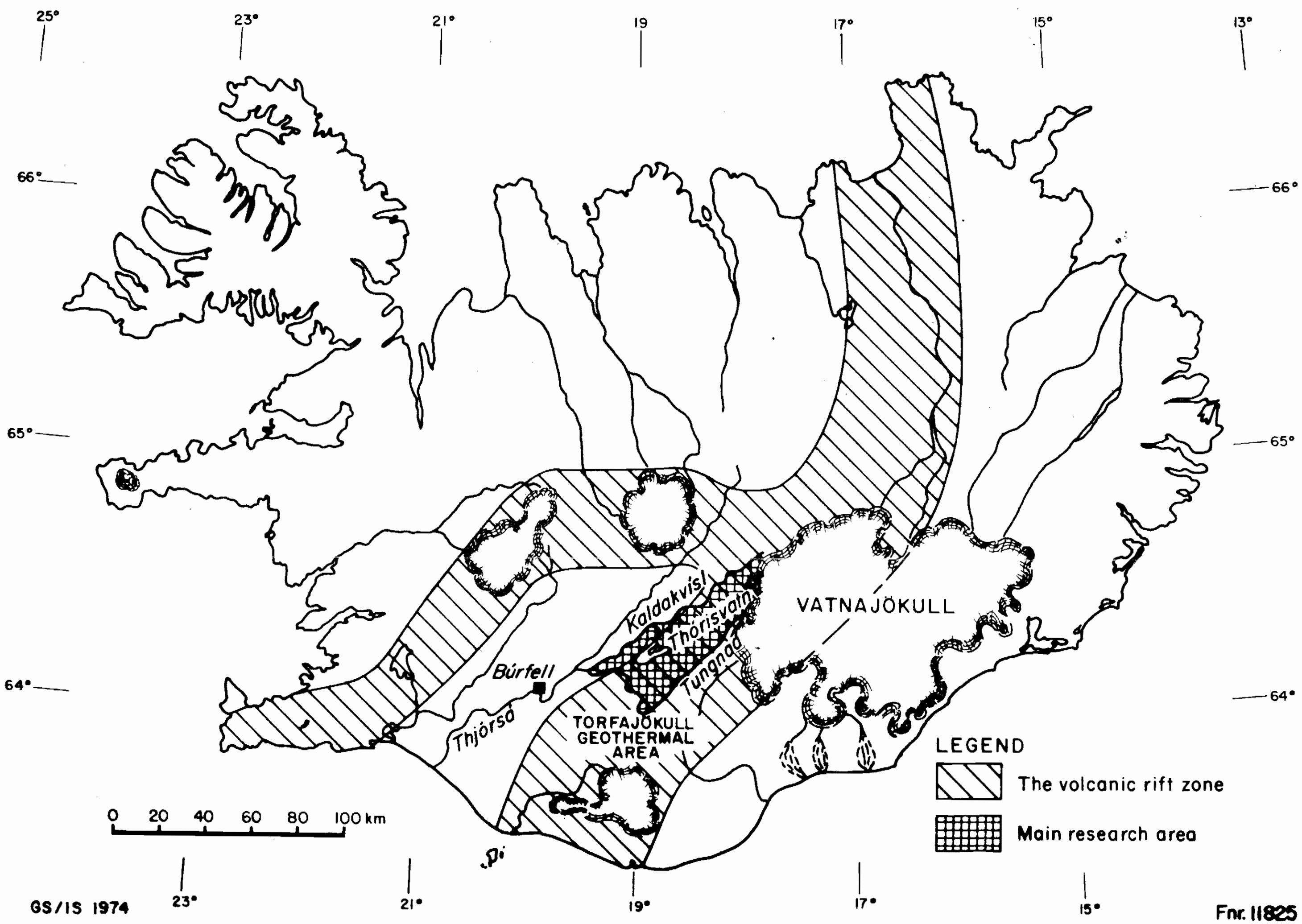

Fig. 1. Iceland. Location of the research area in relation to the neovolcanic rift zone.

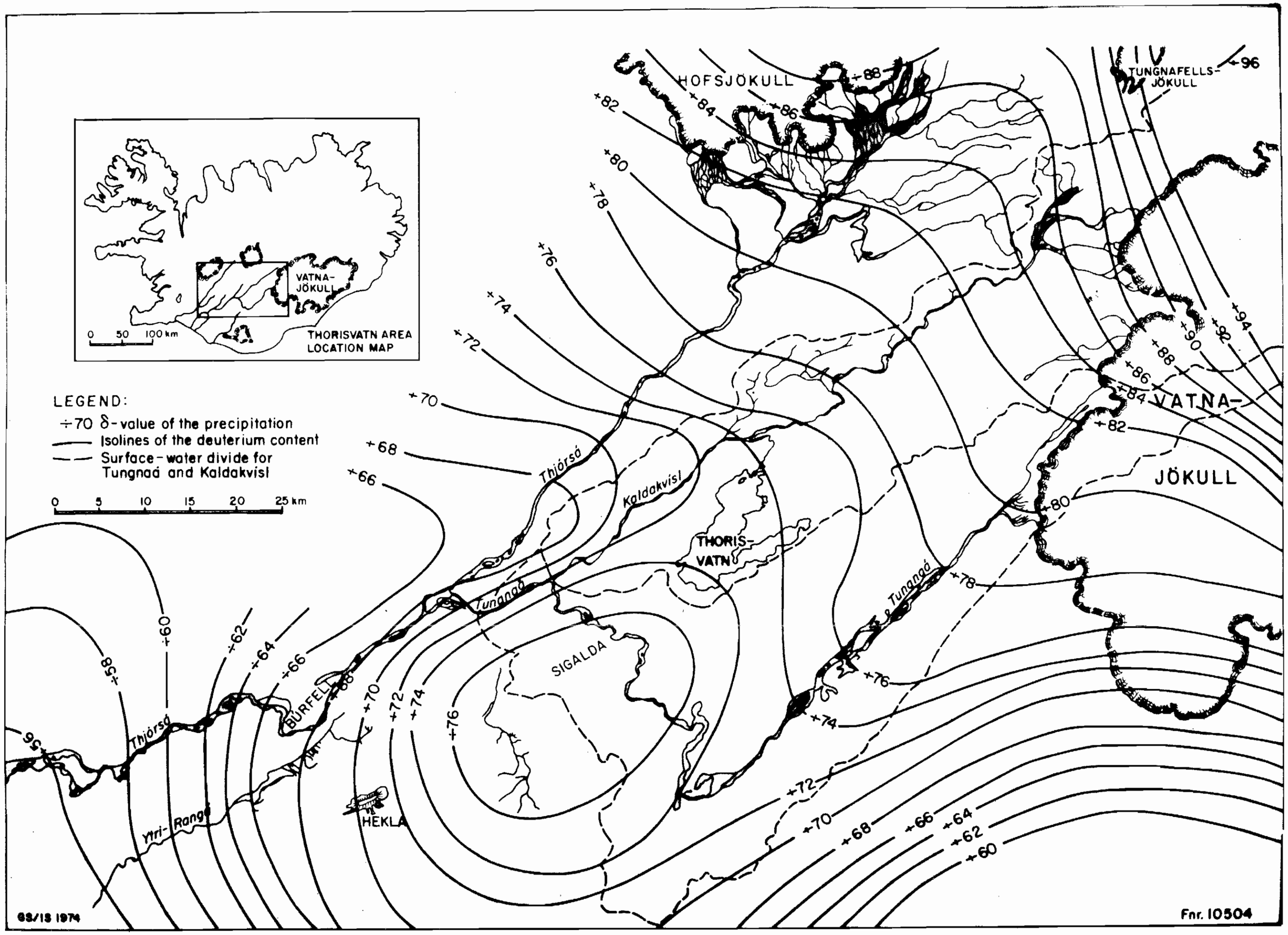

Fig. 2. Deuterium concentration of the local precipitation.

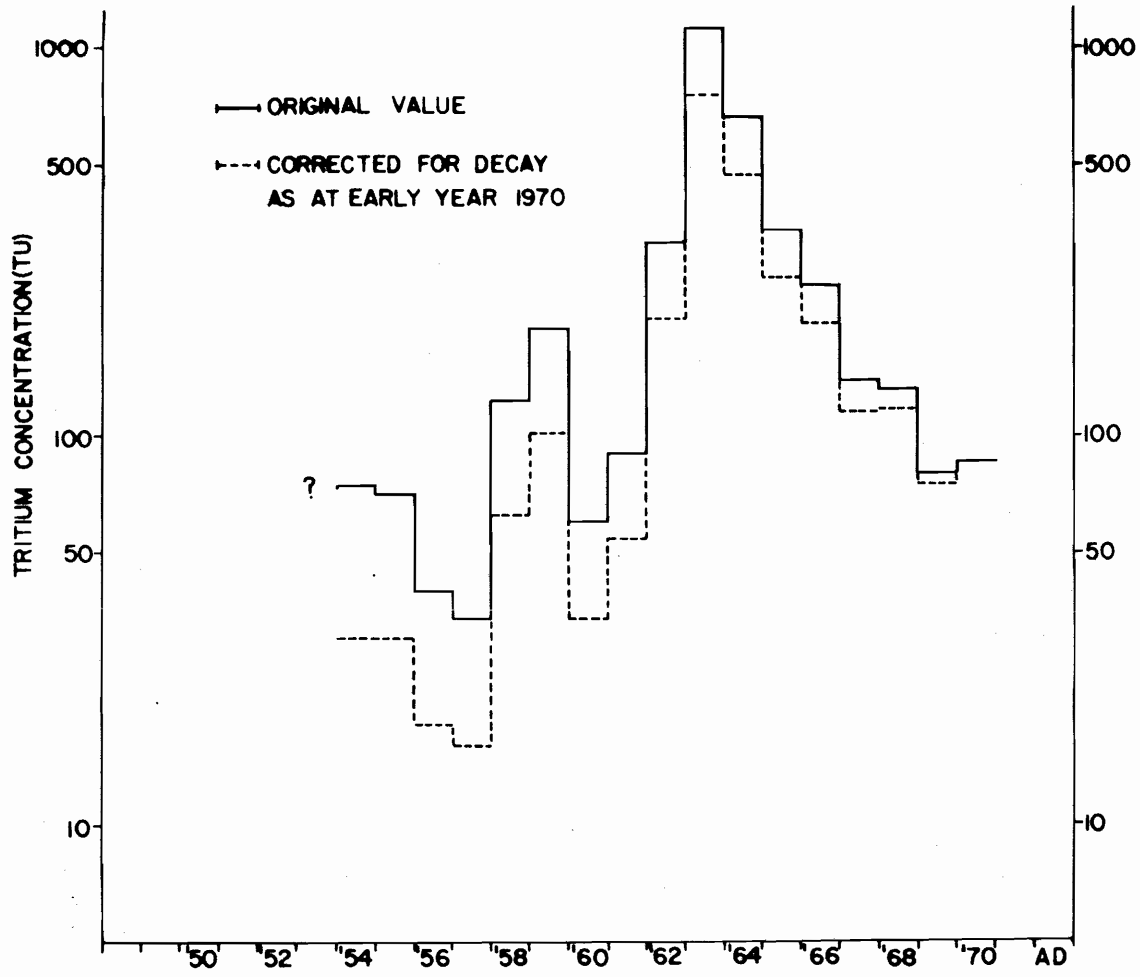

Fig. 3. The average yearly tritium content in the precipitation in Reykjavik.

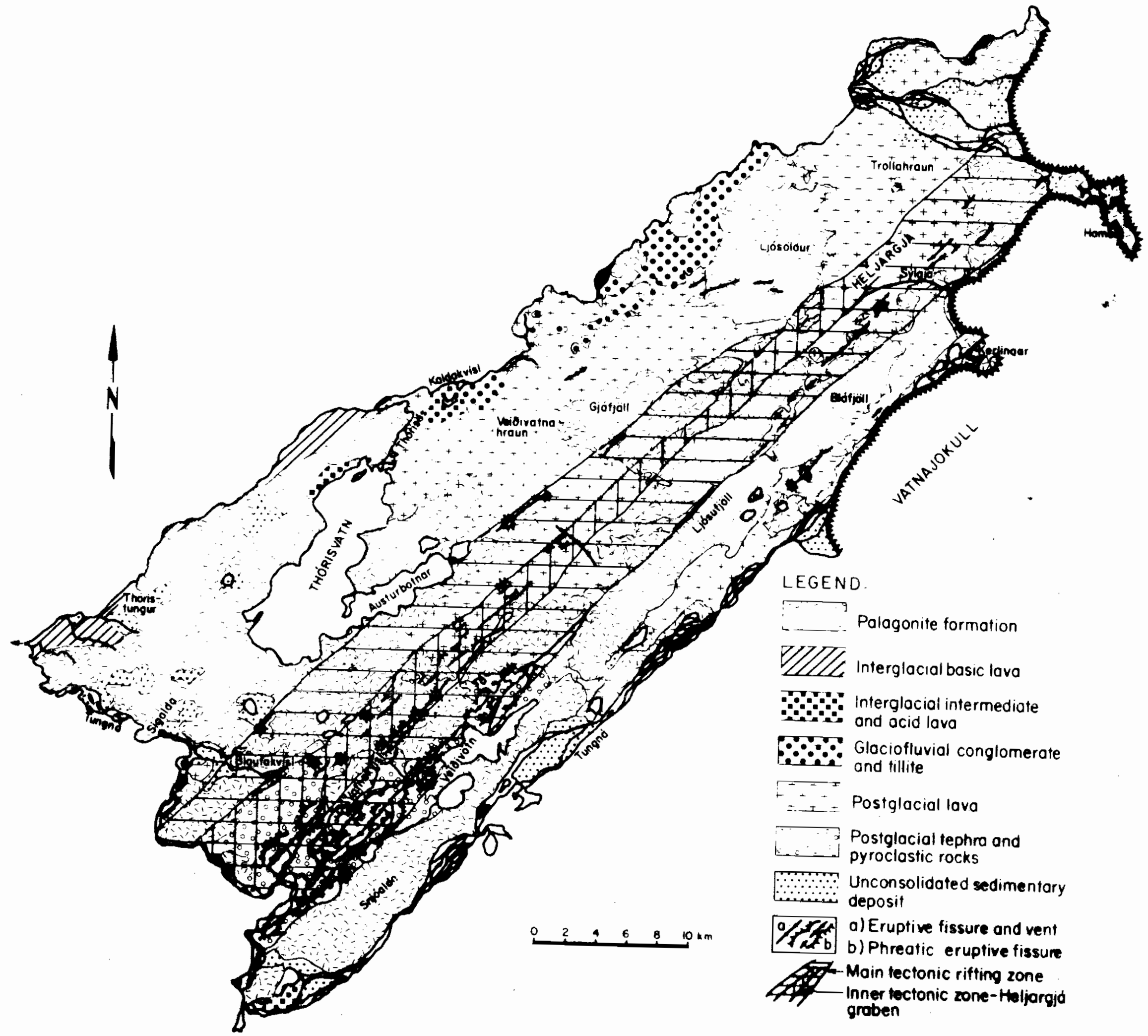

Fig. 4. Geological map of Thórisvatn area.

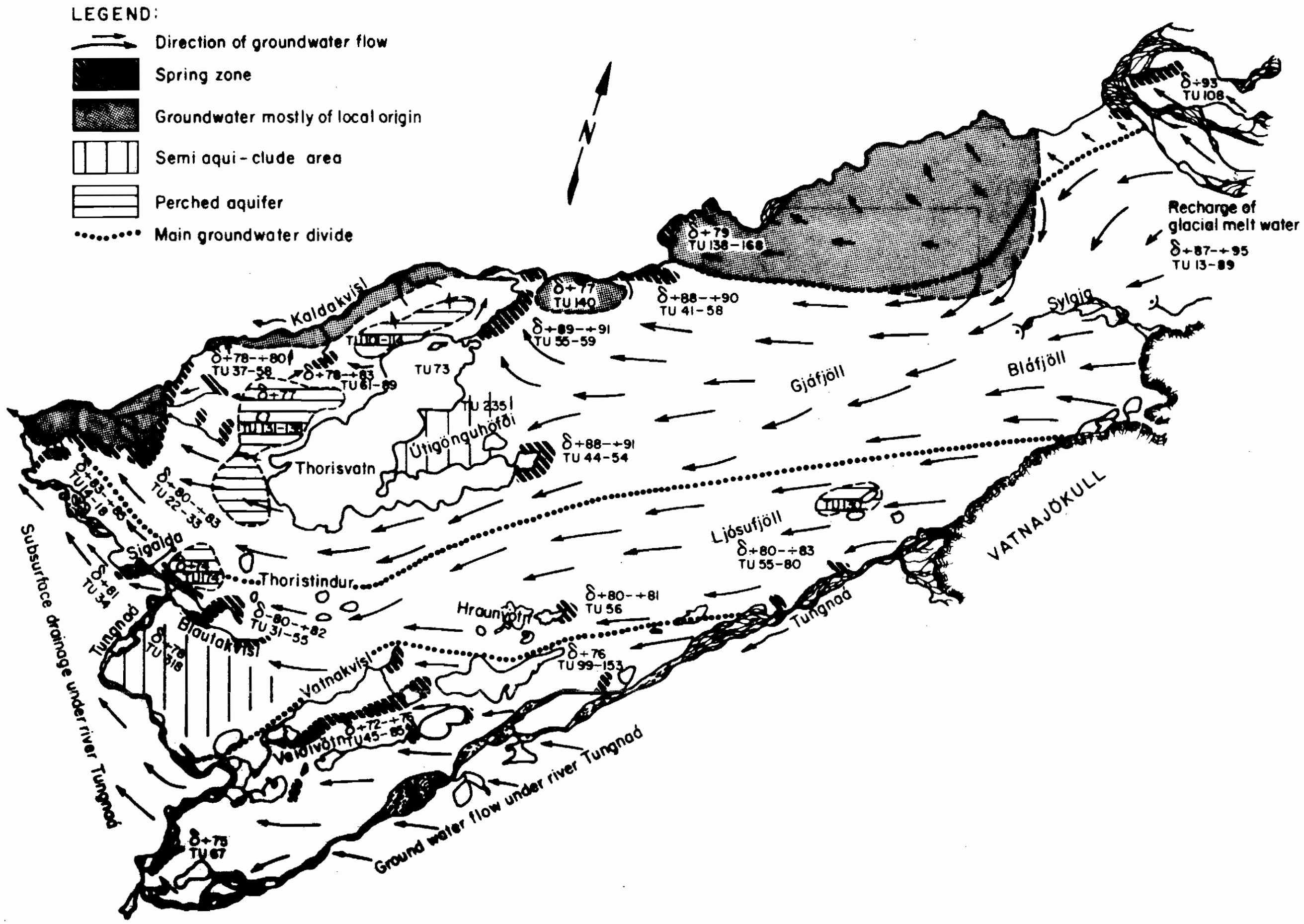

Fig. 5. Flow pattern of the groundwater systems in Thórisvatn area showing their range of deuterium and tritium concentration

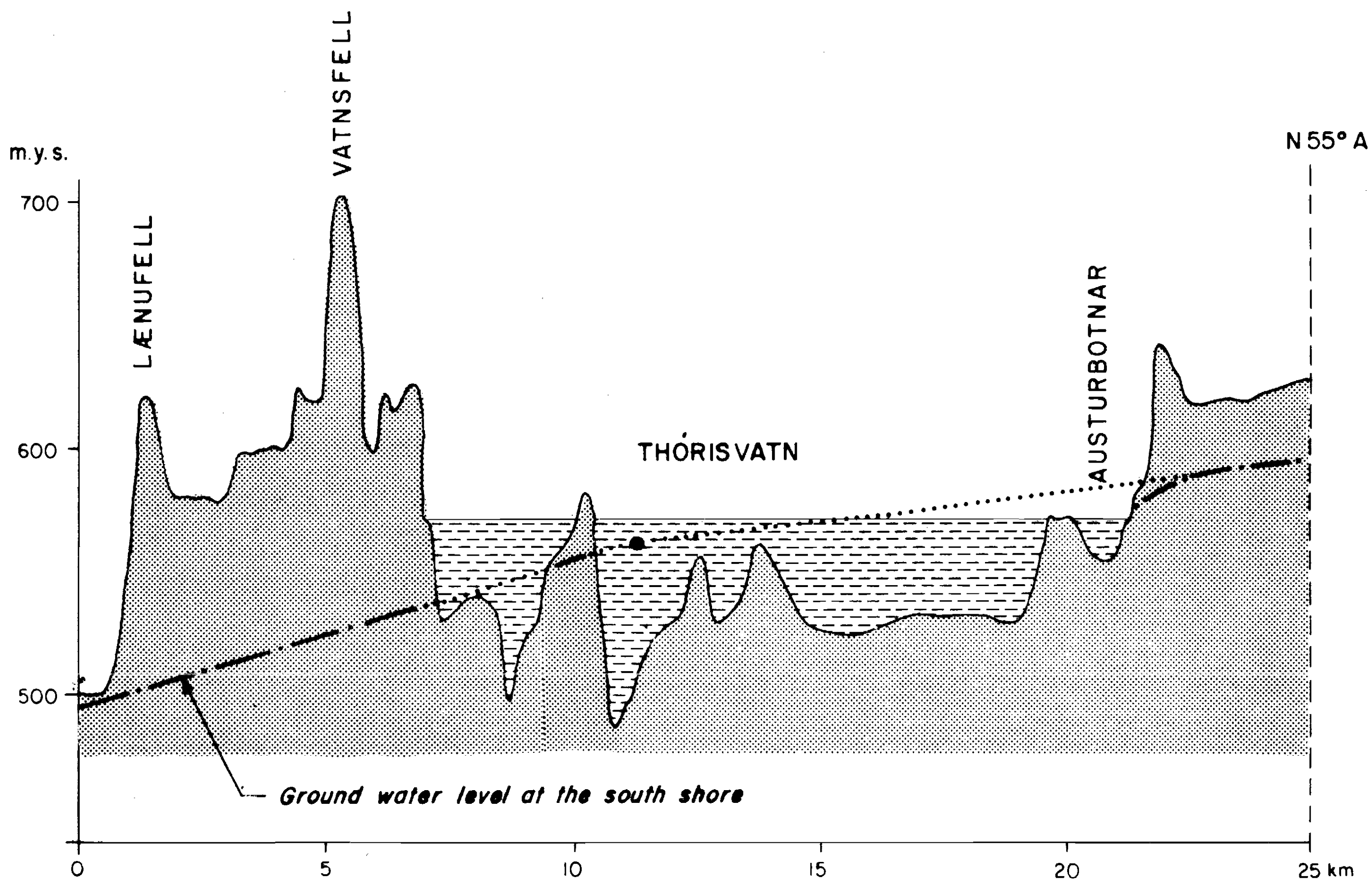

Fig. 6. Longitudinal section of Lake Thórisvatn showing the piezometric surface along its SE shore.