RAFORKUMÁLASTJÓRI

# ON THERMAL ACTIVITY IN ICELAND

by

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December 1948


BREIÐIFJORD
HÚNAFLÓI
Hrútafjörd
Eyjafjord
Akureyri
Tertiary Basalt
Main Zone of Post-Glacial and Quaternary Volcanism Basic tuffs
Tertiary Basalt
Hofsjökull
Langjökull
BORGARFJORD
VATNAJÖKULL.
Geysir
Reykjavik
Hengill
Krýsuvik
Hekla
Torfajökull
Mýrdalsjök.
+ minor alkaline springs
medium -"- -"-
large -"- -"-
acid spring
ÍCELAND
0 10 20 30 40 50 60 70 80 90 100 km.

# CHAPTER I

## REVIEW OF THERMAL ACTIVITIES IN ICELAND.

Iceland is almost entirely built up by volcanism. The chief formation of the country is a basalt plateau which appears to be not less than 3000 meters in thickness. This plateau, which consists of a great number of individual layers of lava, is a remnant of the great North Atlantic basalt plateau which was built up in Tertiary time. Remnants of this plateau are also found in Scotland, Northern Ireland, Greenland and the Faroe Islands. While volcanism is extinct in the latter countries it has prevailed in Iceland right upto this time. During the latter part of the Tertiary period and, in particular, during the Quaternary period, this plateau has been subject to extensive tectonic movement and glacial erosion. The plateau of Iceland is, therefore, cut by numerous valleys, faults and dikes, the latter being formed of basaltic material similar to the rocks of the plateau. The height of the plateau in the East, North and West parts of the country is 800 - 1200 metres above sea-level, but in the center and South-West, the plateau is sunk, particularly in the South-West where it is sunk below sea-level. The volcanism during the Quaternary period has mainly occurred in the latter-mentioned regions. This volcanism has added on top of the plateau, yet almost only in the center and the South-West, a layer mainly consisting of basic tuffs of a thickness of many hundred meters.

Although the main picture of Icelandic geology be simple, the local geology of the areas where Quaternary volcanism has occurred is, in detail, most complicated.

The writer does not intend to give a detailed account of Icelandic geology, but the aforesaid is only to present elementary information. Reference is, on the other hand, made to the well-known texts on Icelandic geology by Thoroddsen, Pjeturs, Einarsson and others. (1, 2, 3).

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It appears to be logical to classify the thermal activities in Iceland in two groups. This was commenced by Thoroddsen and subsequently continued by other investigators.

First comes the group comprising thermal springs which, in most cases, have a temperature below 100 degrees Centigrade and alkaline water. The greatest number of the alkaline springs is found in the Tertiary basalt area in the Northern and Western parts of Iceland, but some are found in the South-Western part of the Quaternary tuff area. The springs in the tuff area have a considerably higher mean flow than those in the basalt area. Alkaline springs are found in 291 places. The second group, called the acid springs, comprises springs issuing acid water, which in most cases, is boiling and accomanied by steam. These springs are found outside the Tertiary basalt area. This group will be dealt with later in this chapter.

According to the investigations of Sigurdsson the integrate flow of all alkaline springs is about 1.500 litres per sec ond, and their total heat flow measured from zero degree C is $400 \times 10^6$ kilogram calories per hour. Hence the mean temperature of the alkaline springs is 75°C. Their total number is about 600, but this figure is rather uncertain as in many cases springs which are very close together may be regarded as one spring.

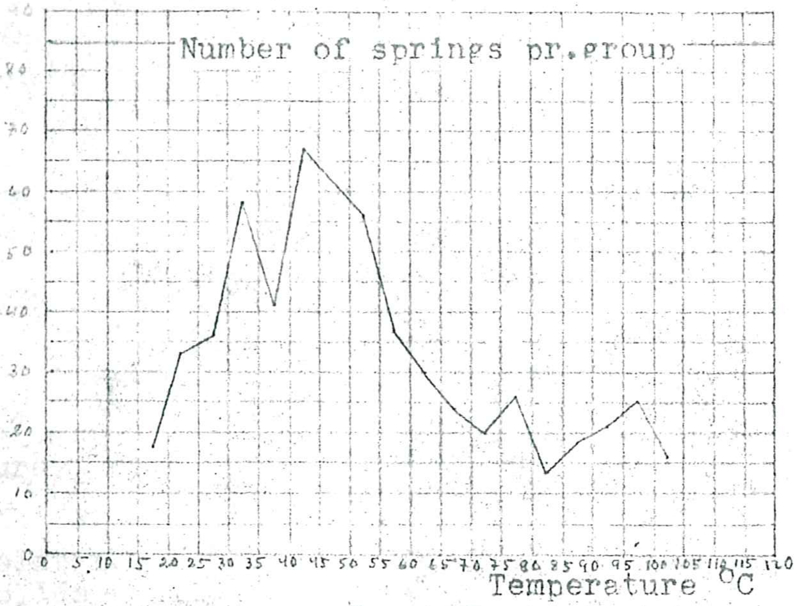
In Northern Iceland from Hrútafjörður to Eyjafjörður there are about 150 springs issuing 150 liters per second of water, having a mean temperature of 61°C. Their total heat flow is about 33 x $10^6$ calories kilogram/per hour. In Western Iceland from Breiðafjörður to Húnaflói there are also about 200 springs, but here the total flow is 300 litres per second of water having a mean temperature of 51°C. The total heat flow is 55 x $10^6$ kcal per hour.

In the Western and South-Western parts from Breiðafjörður to Thjórsá there are about 250 springs issuing 1050 litres of water having a mean temperature of 82°C.

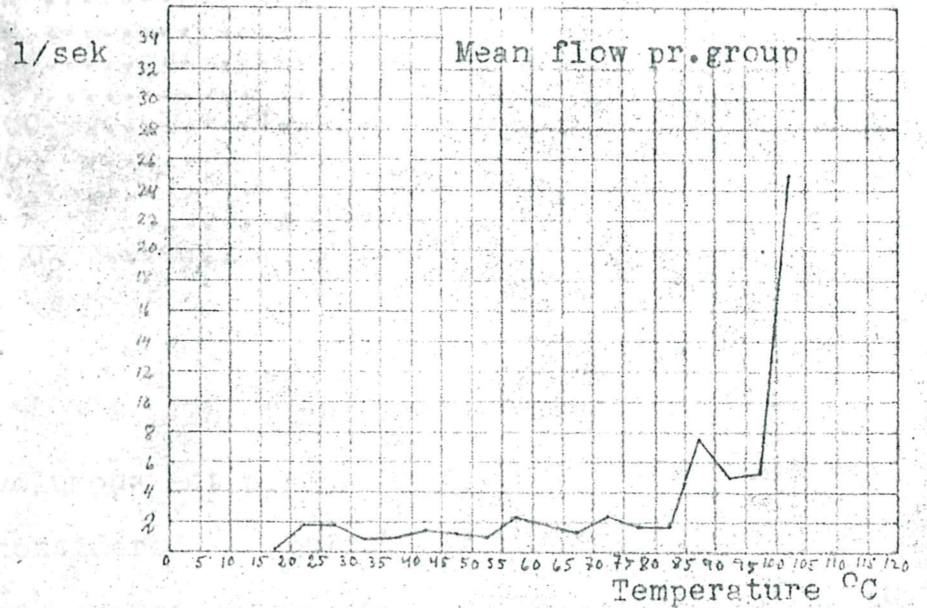
In order to present a better picture of the relation of flow and temperature of the individual springs, the writer has formed the springs into temperture groups, each group covering the interval of 5 degrees C. The distribution of the number of springs, the mean flow and the total flow for each group are shown in the graphs 1,2 and 3.

The graphs show out the interesting phenomenon that the mean flow is an approximate linear function of the temperature upto 80 degrees C. Above this temperature it increases abruptly. One will furthermore note that the number of springs is greatest in the lower temperature region.

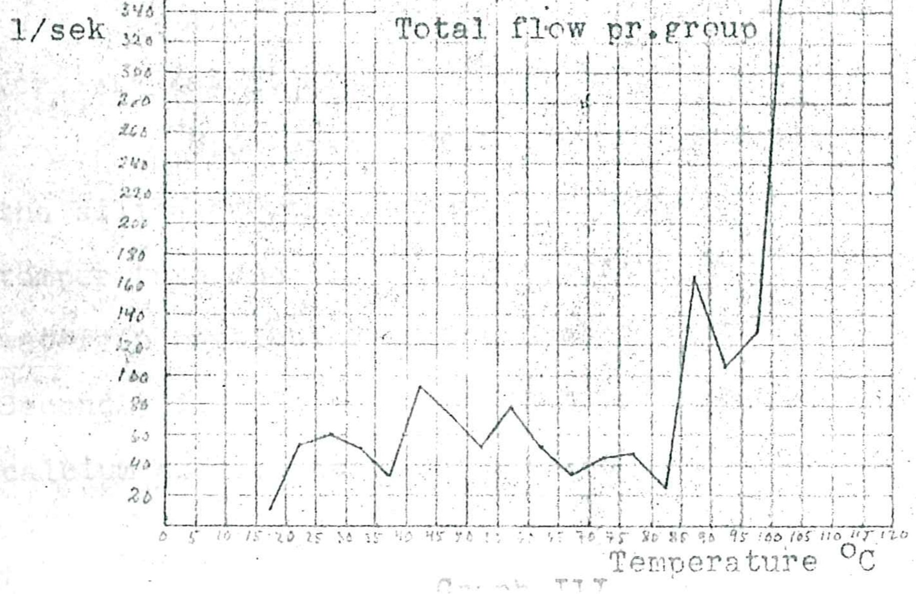
The chemical character of the alkaline water is fairly uniform although the water of the hotter springs usually has the highest contents of solids. In order to grant a better idea of this, three analyses will be given:-



Graph I



Graph II



Graph III

Table I

1) Deildartunguhver in Borgarfjörður
2) Kristnes in Eyjafjörður
3) Tjarnargarðshorn inEyjafjörður
4) Surface water from Eyjafjörður (cold spring)

| | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Temerature | °C | 100 | 75 | 30 | 5 |
| Flow | l/sec | 250 | 1,5 | 0,5 | - |
| Ph-value | | 9,0 | 9,3 | 9,3 | 7,5 |
| Spec.Resistance (25°C | Ohmcm | 2600 | 3760 | 6650 | 6940 |
| Total solids (105°C) | p.p.m. | 361 | 275 | 140 | 105 |
| Na | " | 79 | 55 | 30 | 14 |
| K | " | 4 | 0 | 0 | 0 |
| Ca | " | 5 | 6 | 3 | 14 |
| Mg | " | 1 | 2 | 1 | 5 |
| Fe | " | 0,25 | 1,2 | 0,2 | 0,2 |
| Cl | " | 48 | 13 | 8 | 15 |
| $HCO_3$ | " | 0 | 0 | 0 | 68 |
| $CO_3$ | " | 42 | 45 | 36 | 0 |
| $SO_4$ | " | 60 | 49 | 12 | 10 |
| F | " | 1,3 | 0,7 | 0,3 | 0,2 |
| $SiO_2$ | " | 128 | 110 | 45 | 27 |

The first spring listed, Deildartunguhver, is the most volumous hot spring in Iceland and its chemical character may be considered as typical for the hotter springs. The second spring enumerated can be regarded as an average for the entire alkaline group while the third one, represents the colder springs.

A typical analysis of surface water (number 4) from the Tertiary basalt area is given for the purpose of comparision.

Upon reviewing these analyses one particularly notes that the silica and the sulphate contents of the water increase with the temperature and that the hot spring water differs from the surface water in particular in the higher contents of these elements. Secondly it will be noted that hot spring water contains less calcium and no bicarbonate which constitutes one of the main components of the surface water. The chloride contents of the hot spring water is in most cases not definitely higher than in the surface water. This is, however, somewhat irregular as few hot springs located near the sea show a very high chloride contents.

The water of numerous hot springs often contains some amount of free gases. These have been analysed particularly by Thorkelsson (7) and his conclusions show that these gases in the alkaline group consist of 98 - 99 per cent of nitrogen. Mr. Thorkelsson's analysis of gases from Deildartunguhver is given for further explanation, but here he has found:-

c
1) Nitrogen plus/arbon 99 volume per cent.

2) Carbon dioxide 0.7 per cent.

3) Oxigen in one analysis 0.2 per cent, but a year later nil.

4) Methane 0.1 per cent.

Although Thorkelsson has analysed the gases from many alkaline hot springs he has not investigated the total gas contents of the water. Einarsson (4) has, on the other hand, investigated the total contents of gases in a number of hot springs and concluded that the volume of gas in the water be generally not higher than the gas contents of surface water.

The geological distribution of the alkaline hot springs shows some interesting features. These springs are generally found below 100 meters over sea level. According to the investigations of Thoroddsen and Thorkelsson, alkaline springs seem to be connected with faults and the latter has pointed out that many hot springs could be situated on the crossing of tectonic lines. Einarsson (5) has continued these investigations and carried them further and the result of his research is that the springs are in many localities in closer connection with basalt dikes and he produces a number of examples of this. He also points out that a great number of the dikes are magnetic (6).

Extensive drilling for hot water has been performed by Sudur Reykir in Mosfellssveit, a distance of 15 kilometers from Reykjavík. Prior to drilling being commenced in this place, there were 100 litres per second of alkaline water with a mean temperature of 85 degrees C. As this group of springs was situated so near Reykjavík, it was decided to commence drilling there in order to increase the flow and utilize the water for a central heating plant for the city of Reykjavík. The drilling was commenced in 1932 and has been continued to date. Some 50 wells have been drilled there, 400 - 600 metres deep. The diameter of the wells is 4" - 8". The water flow has been increased by this drilling upto nearly 400 litres per second, but the temperature of the water has not changed and this is, in most cases, about 85 - 87 degrees C. Temperature measurements in the wells have not indicated a higher temperature in this place. Most of this water in now being used for the central heating plant in Reykjavík where 35.000 people live in houses heated by this means. Drilling for hot water has been performed in several other places in Iceland where there are alkalin springs and success has ensued in increasing the flow. The total flow of boreholes in Iceland is now approximatly 500 litres per second.

The second group of hot springs is found outside the Tertiary basalt area. These springs are generally called acid hot springs although some of them have alkaline water. These springs are found in the Quaternary parts of the country mainly in central and South-West Iceland. As previously mentioned, the chief surface rock in these regions are the basic tuffs which are of volcanic origin. These springs differ from the alkaline springs inasmuch as their water is generally boiling and accompanied by considerable amounts of steam. These springs are not as uniformly scattered, but are found in large groups. The entire area of each group is characterized through a high temperature gradient in the surface. There are ten such groups of acid springs in Iceland. Whilst it is generally considered that the hot spring group in the Torfajoekull area and the group in the Hengill produce the largest volume of steam, the steam flow has not been measured accurately. According to estimates, however, it appears to be fairly certain that the group in the Hengill produces 50 - 75 metric tons of steam per hour, but the springs in the Torfajoekull have apparently a somewhat higher flow. It has been estimated that the integrate steam flow of the hot springs of the entire acid group be 300 - 500 metric tons per hour. The water flow of the springs is, in most cases, small. The group in the Hengill is, however, somewhat particular as it produce approx. 50 litres of boiling water per second. The steam flow of the individual springs is low and is only in very few cases in excess of 5 tons per hour.

As the group in the Hengill appears to have industrial possibilities, this will be further enlarged upon. This area is about 40 kilometres East of Reykjavík, the capital of Iceland. The Hengill is a mountaineous terrain rising to a maximum height of 600 metres and cut by mumerous valleys. These mountains are remnants of the plateau built up of basic tuffs with thin layers of basalt lava. The entire area is cut by numerous basalt dikes. Volcanism appears to have been considerable in this area during the Pleisto-cene period, and in post-glacial time, there have been a few eruptions. The hot spring group in the Hengill covers an area of about 70 square kilometers. These springs are found mainly in a line running in a North to South direction for 12 kilometres. At the Southern end of this line where the terrain is a mere 30 metres above sea-leval most of the water flow occurs while the more Northerly springs have a very small water flow. Most of the water in the Southern end is alkaline and resembles the water from the previously mentioned alkaline group.

The water from the springs with the lesser flow is, on the other hand, seldom alkaline and contains some free sulphuric acid which makes it acid. Hence the name of the acid springs. A typical example is the following analysis taken from a solphatara in the Krísuvík area:-

| | | |
|---|---|---|
| Ph value | 2.5 | |
| Total solids | 825 | p.p.m. |
| Ca | 32 | |
| Mg | 27 | |
| $Fe_2 O_3$ | 72 | |
| $SO_4$ | 409 | |
| $SO_2$ | 103 | |
| Cl | 23 | |

Of recent years drilling has been performed in the Southern part of the Hengill area both with diamond drills, percussion drills and the calyx type of drills. About 25 wells have been drilled all less than 100 metres deep and the integrate steam flow of the wells is about 30 metric tons per hour. Most of the wells are only of a diameter of 3", but there are six wells of 6" - 8" dia. A considerable quantity of water accompanies the steam from each well

The deepest well drilled in this area extends to a depth of 205 metres and here the temperature proved 215 degrees C., but this well does not produce steam or water. The temperature distribution indicates that higher temperature will be encountered by deeper drilling.

As a result of the investigations in the Hengill area, it appears that the total heat flow from this area is about 150 million kilogram calories per hour as nearly half of the heat is carried away by the steam and the water from the springs, but the remainder is carried away by heatconduction to the surface and surface water. If these estimates are made for the entire country, the total heat flow from all hot spring areas in Iceland appears to be 1 to 1.5 billion kilogram calories per hour, but this is about 10 to 15 per cent of the heat conducted through the whole surface of Iceland by the normal temperature gradient.

Several wells have also been drilled in another area 30 kilometers South of Reykjavík, at Krisuvík. This area is smaller than the one in the Hengill and the springs practically exclusively produce steam. The springs are typical sulphataras. A 10" well was drilled down to 140 metres and this produced about 15 metric tons per hour of almost dry steam. Another well of 3" diameter was drilled to 125 metres and this produced 7 tons of steam per hour. In this area considerable calcium carbonate scale has formed in the wells. This phenomenon appears to present some difficulties for the utilization of the wells as it would, in a proportionately brief space of time, decrease their steam production. This formation of scale is due to the fact that a small amount of hard water accompanies the steam and the calcium carbonate precipitates from the water when the pressure drops.

The gas which accompanies the steam in the acid springs has been analysed by Thorkelsson (7) and others. This gas is entirely different from that of the alkaline group springs as it consists of 80 - 90 volume per cent of carbon dioxide and, in most cases, contains less than 10 volume per cent of nitrogen. Besides carbon dioxide the gas contains a few per cent of free hydrogen and hydrogen sulphate. Methane is also present in a quantity of about 1 volume per cent. The total gas contents of the springs is 2 to 5 per cent by weight of the steam. The hydrogen sulphate is partly or wholly oxydized when it comes into contact with the air and in this way the characteristic sulphur deposits around the acid springs are formed.

## CHAPTER II.

Bunsen (8) Thoroddsen, (9) Thorkelsson, (7) Barth (10), and Sonder (11), all of whom have studied the thermal activity in Iceland, are of the opinion that the hot springs are of volcanic origin. All of them consider acid springs to have direct connection with sub-surface magma and that a considerable amount of the water and steam be juvenile. The main support for this conclusion is that the gases of the acid springs are typically volcanic and furthermore that the acid springs are mainly in locations where Pleistocene and recent volcanism has been considerable. Their opinions, on the other hand, differ on whether alkaline springs have direct connection with sub-surface magma. Thorkelsson, who has done the greatest amount of analyses of gases in Iceland, considers the water in the alkaline springs to be surface water which is heated by cônduction from a sub-surface heat source, the absence of volcanic gases in the springs being his main supporting rule. Barth and Sonder are, on the other hand, of the opinion that the water in the alkaline springs be surface water heated by mixture with juvenile water and that the volcanic gases have not reached the surface.

Einarsson (4) opines that the geothermal problems cannot be solved without taking the heat-balance of the hot springs into account. He points out that the alkaline springs are scattered in those places where no postglacial volcanism has occurred and that the hot springs in these parts of the country show no connection with the few known Pleistocene volcanic centers. He has undertaken calculations in connection with the heat-balance of the alkaline springs and comes to the conclusion that the only possible heat source be the normal heat current through the surface. He also indicates that the connection between the acid springs and post-glacial volcanism be not as close as has been maintained and he is highly doubtful as to whether these springs be connected with sub-surface magma. He points out that the acid springs seem to be in much closer contact with tectonic lines than volcanic centers. Einarsson considers it possible to explain the chemistry of the springs without reckoning with juvenile gas.

It is known to be generally accepted that radio activity as a local heat source and heat formed by mechanical stresses cannot be of importance for thermal activity in general. In the judgement of the writer this need not be further enlarged upon, but reference is made to well-known texts on thermal activity. (see Einarsson 4). The radio activity of rocks in Iceland has recently been measured and these measurements do not show any abnormalty. The well-known measurements of radon contents of the hot spring gas in Iceland by Thorkelsson do not either indicate any abnormalty for as Einarsson mentions the radon contents in Iceland is not higher than that of many cold springs in Scandinavia.

Having regard to the various facts concerned, it will not be possible to explain the thermal activity in Iceland except in three ways:-

a) The heat is carried to the circulating surface water by juvenile steam and gas and in this case some part of the thermal water would be juvenile.

b) The heat is conducted from a local heat source to circulating surface water.

c) The only heat source is the normal heat current through the surface and the thermal water has been heated through deep circulation.

These three ways will now be discussed in connection with thermal activity in Iceland.

## The Alkaline springs.

The alkaline springs will first receive attention. As will be seen from the above Einarsson maintains that these hot springs obtain their heat from the normal current through the surface. As previously stated he has pointed out that the distribution of the alkaline springs shows no connection with recent or Pleistocene volcanism, but that the springs are in close connection with basalt dikes which are of Tertiary age. His calculation of the size of the magma reservoir which would be necessary to maintain these springs even only through post-glacial time, show that the possibility for the existence of such a reservoir are remote when one considers that the springs be maintained by juvenile steam and gases from such reservoir. He has estimated the temperature drop of the springs when flowing from their source to the surface and finds this is in most cases small so that the temperature of the larger springs at the surface is only slightly lower than at the origin. When one considers that the alkaline springs do in large areas have about an even temperature, he opines that one may conclude that the temperature at the origin be very similar. It appears to him that the variation in temperature in general be connected with the height of the plateau in such a manner that the springs situated in the deepest sunk plateau have the highest temperature. The possibilities of the cooling down of the springs by mixture with surface water, he feels, may be eliminated by the fact that the largest springs are, as a rule, the hottest ones.

His conclusion is that on account of topographic unequalities, and a consequent difference of the ground water level a general deep circulation from the highlands towards the lowlands might go on. But for some reason a considerable part of this circulation reaches great depths probably to the basement of the basalt plateau and he is therefore inclined to think that especially porous layers may favour the deep circulation.

Chemical analyses (see Table I) of the hot spring water which have been made since Einarsson's work was published show that alkaline water is no more different from the normal surface water in the basalt areas than that it be possible to explain the higher contents of solids in the hot spring water by the mere fact that it has travelled a longer distance, is hotter and that it has, therefore, been able better to dissolve the rock. Besides sodium chlorid sodium and calcium bicarbonate constitute the main ingredients of the surface water. It is a known phenomenon that carbonate and bicarbonate have dissolving influence on the silica in the rocks and that this action increases with the temperature. As the surface water, which is cold and has travelled a short distance only, has absorbed even over 20 milligrammes per litre of silica, there seem to be no difficulties in explaining the comparatively high silica contents of the hot spring water. It was previously stated that the gas in the alkaline springs consisted mostly of nitrogen and has none of the so-named magmatic components. It is the author's opinion that the aforementioned evidence be sufficiently strong to make it impossible to contradict Einarsson's theory successfully by any theory which maintains the magmatic origin of the alkaline springs. But even though this is so, the possibility remains that the heat of the springs be derived from deep-seated magmatic intrusions which are cooling. The absence of volcanism in Northern and Western Iceland where the springs are uniformly scattered, appears to contradict this in particular when one considers the distribution of the springs. It must, on the other hand, be said that Einarsson does not further enter the field of the thermal mechanism which is essential to maintain the alkaline thermal activity and the author, therefore, considers it necessary to look further into this point prior to excluding the latter possibility. We must, therefore, ask whether it be possible to maintain the alkaline activity without reckoning with an abnormal temperature gradient due to deep seated intrusions. In order to reply to this question various calculations connected with heat conduction in rocks will now be gone into. Although these calculations are not involved from a mathematical point of view, it would be right not to confuse the main matter with the calculations which will, thereagain, be shown in the appendix and the conclusions only will be referred to herein.

The calculations in part of 1 of the appendix show that the heat transmission co-efficient for the heat transfer between rock and water flowing through a long, narrow horizontal pipe is:-

$$k = \frac{2\ c}{\ln \frac{4h}{d}} \quad \text{kcal/m, } ^{o}\text{C, h.}$$

In this formula, h is the depth of the pipe in meters c, the co-efficient of heat conduction for the rock and d the diameter of the pipe in meters. It is being assumed that c be about 1,5 kcal/m $^{o}$C h for basaltic rock and if we take the depth of the pipe as 1.500 meters and a diameter of 10 meters, k will be approx. 1,5 kcal/m, °C h. As the water travels through basaltic rock it must be assumed that it flows through long and narrow fissures and one must, therefore select the diameter of the pipe of a size similar to the length of the opening of the fissure. Hence d is selected as 10 meters. Although this figure be rather uncertain, this influences the heat transfer co-efficient k only slightly as d is in the form of logarithm in the formula.

The co-efficient k can now be used to calculate the distance x in meters, a certain amount of water, q litres per hour, must travel in order to be heated from zero upto the temperature t. It is assumed that the water travels through a horizontal pipe at a depth of h meters and that the normal temperature in this place be $T_0$ , in accordance with formula 2 in the appendix:-

$$T = T_0 \left( 1 - e^{-\frac{k.\,x}{S.\,q}} \right)$$

In graph 2 on page 3 A one finds that the mean flow of the alkaline springs is for temperatures less than 80 degrees C., 2 litres per second or less. It must, however, be borne in mind that this figure is uncertain as springs close to each other in many cases belong to the same subsurface channel and although this has been taken into consideration in the counting of the springs, this figure may be somewhat higher. There is also a possibility that a part of the hot water does not reach the surface so there is good reason to use a higher figure than 2 litres per second.

It is, on the other hand, possible that some of the hot water be mixed with cold water, but this would make the apparent mean flow higher than it really is.

On taking this into consideration, it does not seem unlikely that a figure of 5 litres per second be a rather high value for the mean flow of springs having a surface temperature below 80 degrees C.

The above formula shows that this quantity with the initial temperature zero must flow a distance of 17 kilometers/at a depth where the normal temperature is 133 °C.) in order to be heated from zero and upto 100 degrees C., but in order to reach 67 degrees C., the water must travel about half this distance. A smaller quantity of water must flow a proportionately shorter distance.

One must, therefore, ask whether this be possible within the basalt plateau. This plateau which is built up of a great number of layers cut by numerous dikes and faults must have highly particular hydrological qualities. The basalt itself is very dense and is certainly nearly impermeable. But along the side-walls of the dikes are possibilities for channels passing through the whole formation and, as Einarsson has shown, the hot water in many cases issues from these channels. There are also possibilities for horizontal channels on the contacts of the invidual layers although there is, as a rule, a thin layer of very dense sediments in between.

In the few cases where horizontal and vertical channels communicate, there is a possibility for surface water to reach a certain depth, flow through a horizontal channel, be heated up and to reach the surface again through another vertical channel. Because of the impermeability of the basalt and the few channels, it must be assumed that the water can undertake this circulation without being mixed with any counting quantity of cold water. The greatest possibilities for mixing are right at the surface. By assuming the existance of long channels. within the plateau the above figures show that it should be possible to explain the average alkaline spring through a local circulation of surface water.

But an answer must be found to the question of how deep the water must flow. This depth will be determined by the temperature field and the cooling of the water on its way to the surface, but the latter phenomenon is again dependent upon the temperature gradient.

It is unfortunately most difficult to form an idea of the average temperature gradient in Iceland, although a number of boreholes have been made, as the vast majority of these are drilled where the surface temperature is abnormal, owing to the presence of hot springs. These holes are, therefore not suitable to find the average temperature gradient.

The temperature gradient found on the European Continent in most cases varies from 1 degree per 30 meters to 1 degree per 40 meters. For the United States of America one obtains approximately the same figures, but in that country, where so many oil wells have been drilled, one gets a good idea of the temperature gradient in various places. Ostrand has presented a survey on temperature gradient in oil wells in the U.S.A. (12 ). According to this survey, variations occur owing to various geological and hydrological conditions, but it should be noted that temperature gradients even higher than 1 degree per 20 meters have been recorded.

It appears fully logical that the average gradient in Iceland be higher than that of areas where no volcanism has existed during many periods in the earth's history. The great number of dikes which are well scattered over the Tertiary basalt areas in Iceland seem to indicate that the stable part of the earth's crust be relatively thin in Iceland. In the same manner the immense volume of basic lava which has issued indicates a great weakness in the earth's crust. A further fact is that basic rocks have a lower heat conductivity than acid rocks, but acid rocks found the basement in most parts of the world.

A consequence of this is that the temperature gradient in basic rocks is higher than that in acid rocks for the same heat flow. It is also known that a great number of intrusives are found in Iceland and heat from these will, over a certain period, influence the temperature field. (see page )

It is, of course, a most difficult matter to form a quantitative idea of the influence of the above factors, but the author does not hesitate to consider the gradient not below 1 degree per 20 meters and is inclined to belive that the average gradient in Iceland will be found between 1 degree per 10 meters and 1 degree per 20 meters. In this report 1 degree per 15 meters will be reckoned with.

The temperature gradient in the surface varies in different localities besides the obvious variations caused/by thermal activity. These variations are first and foremost caused by topographic effects and there remain possibilities for the rapid erosions which have occurred in glacial times in Iceland to have had some influence on the temperature distribution in the surface. In order to explain this further a small example will be given, but detailed calculations of this will be found in appendix. V.

When one thinks of a circular valley in the basalt plateau, the temperature gradient near the surface in the bottom of the valley must be twice as high as elsewhere in the plateau independent of the diameter of the valley. Taking a circular valley with a depth of 1 kilometer and assuming that the gradient be 1 degree C., per 15 meters, one finds the temperature at a depth of 1 kilometer from the bottom to be 100 degrees C., and at a depth of 2 kilometers 178 degrees C. If this valley has been formed through a very rapid erosion, e.g., in 250.000 years, the temperature at 1 kilometer from the bottom should be approx. 107 degrees C., and at a depth of 2 kilometers approx. 188 degrees C.

It is extremely difficult to make use of such theoretical calculations under actual topographic conditions and neither will it be attempted to attain any quantitative result, but the calculations will only be used to point out that these matters do not have any negligible influence on the temperature field. This is particularly mentioned here because the great number of alkaline springs in Northern Iceland are in places where one will have to assume a locally higher gradient owing to topographic conditions. This fact further supports the idea of the high gradient which has been formed particularly in places where there is thermal activity.

It is interesting to note that the only hole drilled in Iceland and which could grant an idea of the temperature gradient (although it is drilled near a small hot spring) is in the Northern part of the country. This well was drilled at Kristnes in Eyjafjord near to the bottom of a deep valley. In this well which is 400 meters deep a temperature of 54 degrees C., was encountered in the bottom and this shows a gradient about twice as high as has been assumed inthis report, but the presence of the hot spring prevents one's asserting this gradient for estimating the gradient of the area. The author is inclined to consider the influence of the hot spring as small.

This brings one to estimating the cooling down of the water on its way to the surface. As previously stated, most of the hot springs in Northern Iceland are found at the outcrops of basalt dikes.-

As most of these dikes have a very slight slope, one may assume a nearly vertical channel for the water. Earlier in this report the heat transfer co-efficient for a horizontal pipe has been calculated. From a mathematical point of view it entails considerable difficulties to calculate the heat transfer co-efficient to the vertical pipe,but calculations which will not be gone into at this stage indicate that the co-efficient for the vertical pipe will differ only slightly from that of the horizontal pipe. This is due to the fact that the greatest resistance to the heat conduction is in the immediate vicinity of the pipe so that the position of the pipe in the rock has less influence.

In assuming a co-efficient k, kcal/m, $^{o}C$, h,q the flow of the spring in litres per hour, s the specific heat of the water, kcal/$^{o}C$, kg., and $T_o$ the initial temperature of the water which is commencing at a depth of h meters, one obtains a result as shown in the calculations in appendix, IV. the temperature of the water at the surface:-

$$T = g \cdot \frac{S\,q}{k}\left(1 - e^{-\frac{k\,h}{s\,q}}\right) + \left(T_o - gh\right) e^{-\frac{k\,h}{S\,q}}$$

Here it is being assumed that the hot water does not mix with colder water on the way to the surface.

This formula shows out the interesting fact that the surface temperature of springs which have a very small flow is approx. $g.\frac{S.q}{k}$ as the factor $C - \frac{k.h}{S.q}$ is negligible in this case. This brings out two important facts as far as small springs are concerned, first that it will be impossible to estimate the initial temperature of these springs from the surface temperature and secondly that the relationship between the flow and the surface temperature of such springs will be linear.

Taking a look at the graph (2) this is found to be the very case in nature. If one takes the slope of the graph for the coldest springs where the graph is approximately a straight line, this will be just $g.\frac{q.5}{k}$ and it is, therefore, possible to calculate the numerical amount of k and one finds, with a gradient of 1 degree C., per 15 meters that k is 6 kcal/m, $^{o}$C,h.

This figure, which then appears to be actual heat transfer co-efficient for the vertical channel in nature, is 4 times as large as the calculated co-efficient for the horizontal channel.

Upon reviewing the many uncertain assumptions, the author does not find a great difference between the theoretical value and that calculated from the graph. The temperature gradient and the coefficient of heat conduction are not accurately known. Even a slight mixture of cold water affects the coefficient taken from the graph. The size of the channel is also uncertain. It must, on the other hand, be borne in mind, as previously stated, that there are reasons for using a higher value than that taken from the graph for the mean flow, but this will increase the difference between both the values. It is, however, impossible to get a quantitative idea of the influence of these factors and the author, therefore, assumes that values of k for the vertical channels of the various springs lie between 2 kcal/m, °C,h and 6 kcal/m, °C,h.

By using these values it is possible to calculate according to the formula the cooling of the springs. In order to grant a better idea of this two examples will be given. In the first example it is supposed that the spring commences at a depth of 1.000 meters where the normal rock temperature is assumed to be 67° C, and that the temperature of the water at that depth is 50° C. The surface temperature of the water for various values of k and the various discharges are /shown in the following table:

| q | k | 2 | 4 | 6 kcal/m, °C, |
|---|---|---|---|---|
| 1 | 1/sec. | 42 | 35 | 29 |
| 2 | " | 46 | 42 | 38 |
| 5 | " | 48 | 47 | 45 |
| 10 | " | 49 | 48 | 48 |
| 25 | " | 50 | 49 | 49 |

If the spring commences with a temperature of 100°C at a depth of 2.000 meters, where the normal rock temperature is supposed to be 133°C the following surface temperatures will be obtained:

| q | k | 2 | 4 | 6 kcal/m, °C,h. |
|---|---|---|---|---|
| 1 | 1/sec. | 69 | 49 | 36 |
| 2 | " | 84 | 69 | 59 |
| 5 | " | 93 | 87 | 81 |

| | | | | |
|---|---|---|---|---|
| 10 | l/sec. | 96 | 93 | 89 |
| 25 | " | 98 | 97 | 96 |

These tables show that the cooling of the springs having a discharge latger than 5 litres per second is not excessive and that it is negligible for springs larger than 25 litres per second. The most important consequence of this is that it will be possible to explain the alkaline springs, with a few exceptions, as being fed by a local circulation of surface water not going deeper than about 2.000 meters. This circulation is therefore wholly withing the plateau, but this is essential.

The length of the horizontal channel for the average spring is not in excess of 15 - 20 kilometers. Larger springs than 5 litres per second may be fed by more than one channel. If the heat transmission coefficient for the actual channel is larger than 1.5 kcal/m, °C,h. and if the water is able to reach a greater depth than 2.000 meters, e.g., 2.500 meters, this distance will be somewhat reduced. This circulation can be maintained by both hydrostatic head and the difference in specific weight between the hot and the cold water. A general deep circulation of the ground water as Einarsson assumes should, therefore, be unnecessary for the explanation of the average alkaline spring. This is of some importance as e.g., the rather great discharges of the springs on the peninsula between Breidafjord and Hunafloi (the West Firths) could hardly be explained by the general circulation.

Whilst the mean flow of the springs in Northern Iceland and on the West Firths is not in excess of 5 litres per second, there are four groups of alkaline springs having a much larger discharge.

This applies, first and foremost to the spring group in Borgarfjord including the Deildartunguhver referred to at the outset. The discharge of this spring is 250 litres per second and another spring in this group has a discharge of 100 litres per second. The total flow of the springs in this group is about 400 litres per second, and the temperature is generally 100 degrees C. This group is situated in the Tertiary basalt area.

The three other groups are situated outside the Tertiary basalt area. These are the group in the Reykjahverfi in North-Eastern Iceland with a total discharge near to 80 litres per second and a temperature 100 degrees C., the group in Mosfellssveit near Reykjavik having a total discharge of 400 litres per second and a temperature of 86 degrees C., but hereof 300 litres issue from bore-holes, and the group near to the Great Geysir in South-Western Iceland and this has a total discharge of 120 litres per second, but here the temperature of the water flowing to the place is somewhat in excess of 100 degrees C.

It is, however, doubtful whether the last-mentiones group can be classified with the alkaline springs.

The chemical character of the water from these springs does not in principle differ from that of the average alkaline spring, the only visible difference being the high temperature and the high discharge. Looking at the figures given above for the average alkaline springs, it appears at first to be impossible to explain the existence of these springs by a local circulation of ground water within the plateau basalt, the great discharge presenting the obstackle. But here there seem to be two ways of explaining the phenomenon. The first consists of the great discharge being merely a temporary phenomenon created by some very recent tectonic movements and the second of a general deep circulation of ground water as Einarsson has assumed.

If the first possibility is looked into in connection with springs in Borgarfjord, it will be possible to obtain the following picture. It is not improbable that one may reckon with a somewhat higher temperature gradient in Borgarfjord than that assumed to be the average gradient in Iceland, so that e.g., the rock temperature in this place be 200 degrees C., at a depth of a mere 2.000 meters If recent tectonic movements have opened a great number of horizontal and vertical channels within the rock one must assume that a volumous circulation of surface water will commence owing to the difference in specific weight of the hot and the cold water or even through some hydrostatic head. A simple calculation will show that the heat contents of 40 cubic kilometers of basalt having a temperature of 200 degrees C., will suffice for the maintenance of the springs in Borgarfjord during a period of a thousand years if it is taken into account that the rock is only cooled down to 150 degrees C.

As the heat flow to the subsurface channels in this case is unsteady, one may reckon with a heat transmission coefficient many times larger than that which is used in the above calculations for the average alkaline spring. This is of great importance as the length of the channels is determined by this coefficient. Taking this into account it should even be possible to explain these large springs through a local circulation of surface water, but it must be borne in mind that the phenomenon can last only for a fairly short time, e.g., 2.000 years or thereabouts. It is unfortunate that measurements of the discharge of the springs from previous times do not exist so it is not possible to decide whether any alteration has occurred in this respect.

On looking into the latter possibility a different picture is obtained. It is being provided that the springs be fed by a deep circulation of ground water covering a great area and that the heat flow to the ground water be steady. It is, in this case, possible to calculate the size of the area which this circulation must cover in order to grant a sufficient contact for the heat conduction. Here-in-after this calculation will be performed for the spring group in Borgarfjord.

The temperature distribution for water flowing through a deepseated porous layer is shown in appendix III and one finds that if $T_o$, being the normal temperature at a depth of h meters of the layer, b the width of the layer, C the heat conductivity of the rock in kcal/m, $^oC$, s the specific heat of the water, the temperature T at the distance x from the origin of the flow is:-

$$T = T_o \ (1 - e^{-\frac{C.b}{h.q.s} \cdot x})$$

It cannot be escaped that this layer be at a depth of about 2.000 to 2.500 meters, but the normal temperature at that depth should be about 150 degrees C. Providing for this and taking the layer as 20 kilometers wide, one finds that the water must have travelled at least 100 kilometers in order to attain a temperature of 100 degrees C.

The author would hesitate to provide for the possibility of such a system of circulation. Firstly, it is most doubtful whether, at such a depth, it be possible to find a layer with the requisite porosity and permeability essential for this circulation. Secondly, these calculations provide that the water in its 100 kilometers travel does not mix with surface water entering elsewhere, but this is also very hypothetical for if this layer existed one would provide for water entering it in many places.

The author therefore finds less difficulty in connection with the first explanation.

One might, at this stage, enquire whether there could not be a possibility of the springs in the Borgarfjord being maintained by jurenile steam from a local magma intrusive, but taking into account the chemical character of the water and the facts mentioned in the following article on the acid springs, this seems to be very unlikely. Neither are there any signs of an intrusive in Borgarfjord.

It is worth while now to look into a further point. The temperature variations for the surface water during the year are certainly not less than 10 degrees C., and one can, therefore, enquire whether this variation should not show out in the springs in some measure. It is possible, by means of reckoning with a simple harmonic variation in the surface temperature during the year, to calculate the effect of this on the temperature of the springs. Such a calculation is done in appendix VI and it shows that for hot springs in general the temperature variation in the surface water reaches but a small depth. This is due to the fact that the heat capacity of the rocks through which the water is flowing has a very great damping effect on the temperature variations. All further explanations will be found in the appendix. This is also the case in nature for no annual variations have been measured in the springs.

If we summarize the points on the alkaline springs discussed above, we find the following facts:-

The analysis given in the beginning of this report shows that the alkaline water is similar to the normal surface water and that the difference found will be easily explained through the fact that the hot spring water has a greater dissolving effect on the rock due to its higher temperature and the longer travel. The gas analyses by Thorkelsson and the gas contents measurements by Einarsson show that the alkaline springs do not contain other gases than those contained in surface water and that the quantity of these gases is not higher than that it is possible to explain their wholly coming from surface water. The geological distrubution of the springs shows no connection with volcanism. Finally the heat transfer calculations show that it will be possible to explain the entire heat contents of the water by means of the normal heat current through the surface provided that the surface water can reach a depth of 1.000 to 2.000 meters. he heat flow to the subsurface channels of the average alkaline spring is steady and the springs can continue until the circulation channels become closed through deposits. Only in the case of the few very volumous springs, an unsteady heat flow and that these springs be using a certain heat reservoir which will only last for a comparatively short period must be assumed. After this period, springs of only moderate discharge will remain. (Intrusives, a few million years old can in some localities have a slight effect on the temperature gradient and thus contribute to the maintenance of alkaline springs ( see page )

## THE ACID SPRINGS.

Of the acid springs, those in the Hengill area previously mentioned and described have received by far the best attention of research and this group will be taken as a prototype and the discussion will be conducted with reference to it.

The gases which accompany the steam in the acid springs are, as previously stated, of a composition entirely different from the gases of the alkaline springs. Here one meets components such as carbon dioxide, hydrogen sulphide, free hydrogen and methane. These components are mostly regarded as magmatic. It does, however, appear to be doubtful whether these gases need to be derived from magma.

All surface water, especially water from moors, contain an amount of bicarbonate. When this water is heated it will give off some carbon dioxide. Secondly ignious rocks can contain small amounts of carbon dioxide which is given off when the rocks are heated and circulation water can also dissolve this. Finally deep-seated limestone is also a possible scource of carbon dioxide. At the present stage it is difficult to say whether these three cases can explain the existence of all the carbon dioxide in the steam, but yet it is obvious that carbon dioxide can be derived from other sources than magmatic intrusions.

Pyrite consists of two strongly reducing agents, viz., iron and sulphur. It appears probable that pyrite can, under certain circumstances, have a reducing action on carbon dioxide and water so that carbon mono-oxide free hydrogen and hydrogen sulphide be formed (Einarsson 4). But if free hydrogen, carbon mono-oxide and carbon dioxide are present it is not difficult to explain the presence of methane as this is known to be formed by the action of the free hydrogen on carbon mono-oxide and carbon dioxide. The amount of hydrogen sulphide, free hydrogen and methane in the steam is in all cases very small so that the presence of these components can easily be explained by assuming that small amounts of pyrite be in the rocks through which the hot water flows. The gas contents of the steam thus does not compel one to reckon the acid springs as being in direct contact with magmatic intrusive.

As previously stated the total heat flow from the Hengill area is estamated to be 150 million kcal per hour, which is approximately the same as that of the alkaline springs in Borgarfjord.

Great deposits of silica-sinter are showing that the thermal activity in the Hengill has been going on for a considerable part of the Postglacial period. If one therefore provides for the unaltered existence of this thermal activity for 5000 years, the total heat flow during this period will be 7 $10^{15}$ kcal, but it must also be noted that drilling has shown that the Hengill area has a very high thermal gradient near to the surface so that one must not only reckon with the heat which has flown from the place, but it must also be taken into account that a considerable amount of heat is accumulated in the rock.

The temperature measurements in the deepest well drilled in the Hengill area, show that the temperature in the vicinity of this well is at a depth of 100 meters $150^{\circ}$ C and at 200 meters it is

220 to 225 °C. It must be assumed that this high temperature gradient near to the surface is caused by an upward diffusion of superheated water. According to the calculations shown in appendix VII it seems probable that the initial temperature of this water is about 300°C, and as this circulation starts in the lower parts of the plateau, this water must come from a depth of about 2.000 meters. This enables us to estimate the total heat accumulated in the rocks. The temperature distribution described above seems to be valid for the Southern part of the area but in order to prevent an exaggeration it will here be assumed that these conditions are only valid for an area of 35 square kilometers or half of the whole Hengill area. Calculating only the heat accumulated in the rock down to a depth of 2.000 meters one /finds that this amount is about $10^{16}$ kilogram calories. The total output of the heat source during the last 5.000 years is therefore $1,5 \cdot 10^{16}$ to $2 \cdot 10^{16}$ kilogram calories.

It seems impossible to explain this thermal activity as being caused by a general deep circulation of ground water which Einarsson thinks is the cause of the alkaline activity. The amount of heat steadily flowing from the Hengill is assumed to be about the same as in the case of the springs in Borgarfjord. But the necessary contact area for the heat flow was calculated in that case/and it is therefore possible to use the same figure here, but this area is about 2.000 square kilometers. There is however a great difference in the necessary depth of the porous layer as the temperatures are much higher in the case of the Hengill. Temperatures of 220°C have already been measured and one can at least say that a temperature of 250°C will be measured at a greater depth, but the maximum temperature of the water was above assumed to be about $300^{\circ}C$. If a gradient of $1^{\circ}C$ per 15 meters is assumed to be an average for Iceland than the depth of the layer in the case of the Hengill must be about 5 kilometers. The possibilities of a porous layer at this depth seem to be most remote. It is therefore obvious that an abnormal temperature gradient is necessary.

The duration of the thermal activity and the high temperatures, seem to prohibit any explanation based on the same principle as was assumed in the case of the alkaline springs in Borgarfjord, without taking an intrusive into account. The necessary temperatures at the depth of 2.000 meters would in the case of the Hengill be about $400^{\circ}C$. This temperature could only be caused by an intrusive near to the surface as will be shown later.

The necessity of an intrusive makes it probable that at least a part of the heat be carried to the place by magmatic water, in the form of steam. The role of magmatic or juvenile water in thermal activity is a very important but difficult question.

Very little is known about the mechanism of water expulsion from magma, but the question cannot be solved without fundamental information about this process.

The experiments of Goranson (13), however, are throwing some light on this mechanism, and based on their results the author considers the following picture likely. Magmatic masses derived from great depths and placing themselves in the crust near to the surface will give off their water contents for two reasons. Firstly, a part of the water is given off because of the sudden release of pressure. The time during which the masses give off this part, is of the same order as the time which the magma takes to flow from down under.

When the magmatic masses have aquired a balance with the surrounding rock pressure, they will no longer give off water until crystallization commences. The pressure on the masses is now constant and the cooling down to the crystallization point does according to the experiments, not expel water. There is even a possibility for that the magma may within a certain temperature interval absorb some water again. The pressure of the water is increased when crystallization commences and magma under constant pressure will give off water while crystallizing. But this process is entirely dependant on the heat transmission from the magma and is therefore very slow. A large basic sill or dike having an initial temperature of 1100°C and a thickness of 1.000 meters will require about 10.000 years for cooling down to 750°C where crystallization should be finished. As the water expulsion by crystallization is dependant on the heat conduction from the intrusive, one can include the latent heat of the water into the total heat contents of the rock and treat this process just as the heat conduction. It seems probable that the water expelled during the crystallization is not in excess of 2% by weight of the rock and the latent heat of the water, which is in the form steam, is therefore about 14 kilogram calories per kilogram of rock. The total heat contents of molten rock is around 400 kilogram calories per kilofram, which shows that the water expulsion during crystallization will not be of any importance for thermal activity.

The total water contents of intrusives is limited by the pressure of the steam, as intrusives with high water contents will be able to blow off their cap rock. Taking the figures of Goranson for acid rock, one finds that the minimum depth of an intrusive having a water content of 5,75% by weight, is 3,8 kilometers and for 8% it is 7,6 kilometers. The figures for basic rock are unknown, but these have a higher melting temperature and therefore a lower water content for the same pressure, so that the figures above are also minimum figures for basic rock. There is a good reason to assume that intrusives actually are unsaturated,i.e., they have a lower water content than the saturation content corresponding to the depth, so the author in inclined to assume that the maximum water content for intrusives is around 5% by weight.

As intrusives are crystallizing under pressure they will not expel all the water, so that a part of it will remain in the rock after crystallization. A low figure for this part is 1% by weight. If the water expelled during the crystallization is 2% by weight, there remain only 2% as the maximum weight of water expelled during the flow of the magma from down under. It is this part of the water content which is of great importance for volcanism as it furnishes the magma with the power to ascend. But it is very unlikely that it is of any importance for thermal activity.

The water expelled during the magmatic injection will flow into the country rock and heat the surroundings of the intrusive and this occurs before any counting quantity of heat is conducted from the intrusive. As the amount of water expelled will hardly exceed 2% by weight of the intrusive an easy calculation shows that this water is only able to raise the temperature of a mass of country rock equal to the mass of the intrusive by about 70°C.

Summing up the aforesaid, one obtaines the following picture: The total water contents of intrusives is hardly in excess of 5% by weight. About 2/5 of the water is expelled during the injection of the magma, flows into the country rock and causes a slight elevation in the temperature of the surroundings. The intrusive magma is subsequently cooled down to the point where crystallization commences and will during the period of cooling not expel any water. During crystallization it will slowly expel about 2/5 of the water, but 1/5 will remain in the intrusive rock. The maximum latent heat of the total amount of water expelled is only about 28 kilogram calories per kilogram of the magma which is about 7% of the total heat content per kilogram of the molten rock. The latent heat of the water is therefore only of minor importance compared with the heat content of the magma itself. The only possible explanation of the acid thermal activity seems therefore to be that the heat be conducted from a local intrusive. In order to find the size and depth necessary for an intrusive maintaining the thermal activity in the Hengill the author will assume the following picture. Within the upper part of the basalt plateau there is an intense local water ciculation. Water of a temperature about 300°C (see appendix VII) is ascending from a depth of about 2.000 meters. The specific weight of water at this temperature is about 0,7 so that an intense circulation is possible even without a hydrostatic head. The heat is only conducted up to the basement of the circulation i.e. only up to a depth of about 2.000 meters but is carried by superheated water from this depth up to the surface. The circulation covers an area of about 100 square kilometers which is somewhat larger than the area of the thermal activity at the surface. The total heat flow to the circulation is about 150 million kilogram calories per hour or about 1,5 kilogram calories per hour and square meter. The total amount of heat accumulated within the zone of circulation is about $10^{16}$ kilogram calories.

The first problem of interest is to find the maximum depth to an intrusive under the whole area of 100 square kilometers. This is found by assuming that the intrusive/ be a horizontal stock, as this is the largest intrusive possible. The heat flow through the earth's surface per unit time and unit area by the presence of a stock at a depth h , is expressed in appendix VIII. It is shown that the heat flow has a maximum $Q_m$ at a certain time $t_m$, measured from the birth of the stock. By assuming that the diffusivity $a^2$ is 15 $m^2$/year and the conductivity c is 1,5 kcal/m, °C,h , and the normal temperature gradient g is 1°C per 15 meters , and that the initial temperature of the stock is 1100°C one obtaines the following $Q_m$ $t_m$ and $g_m$ for the various h where $g_m$ is the maximum gradient:

| | | | | | |
|---|---|---|---|---|---|
| h | 500 | 1.000 | 2.500 | 5.000 | meters |
| $t_m$ | 8.000 | 32.000 | 180.000 | 630.000 | years |
| $g_m$ | 1,27 | 0,64 | 0,27 | 0,14 | °C/meter |
| $Q_m$ | 1,9 | 0,95 | 0,40 | 0,20 | kcal/$m^2$ ,h |

| | | | |
|---|---|---|---|
| h | 7.500 | 10.000 | meters |
| $t_m$ | 1150.000 | 1.600.000 | years |
| $g_m$ | 0,10 | 0,082 | °C/meter |
| $Q_m$ | 0,15 | 0,12 | kcal/$m^2$ ,h |

By using $t_m$ as a time unit one is able to express the heat flow Q at the time t as a fraction of $Q_m$, and the following values are valid for the lower h:

| $t/t_m$ | 0,5 | 1,0 | 2,0 | 3,0 | 4,0 | 5,0 | 1,0 |
|---|---|---|---|---|---|---|---|
| $Q/Q_m$ | 0,89 | 1,0 | 0,91 | 0,82 | 0,73 | 0,68 | 0,51 |

The values for the greater h are slightly higher than those in the table.

The first table shows that the thickness of the conducting layer can hardly exceed 500 meters i.e. the total depth to a stock is hardly in excess of 2.500 meters. By reviewing the second table one finds that $Q_m$ is a very weak maximum so that the age of the stock can be 30,000 to 40,000 years.

The tables furthermore disclose some interesting facts in connection with deepseated intrusives. Stocks or small batholiths having a cap rock thicker than 10.000 meters have only a negligible influence on the temperature gradient at the surface, and are only doubling the gradient when the cap rock is 5.000 meters. The effect will however last a long time e.g. by a cap rock of 5.000 meters it will last for nearly 2 million years. One must however note that large batholiths can have a greater influence as convection currents within the magma can in this case not be excluded. It must furthermore be kept in mind that the author has assumed a high average gradient for Iceland but this is decreasing the effect of the intrusives.

In the case of Hengill it is furthermore possible to calculate the smallest intrusive necessary to maintain the thermal activity. Here it will be assumed that the thermal activity started 5.000 years ago, which seems to be the shortest duration. It is easy to convince oneself that the smallest intrusive is a sill situated just at the basement of the water circulation. Assuming that this sill has an area of 70 square kilometers one has to find the least thickness to maintain the thermal activity. The heat flow from a horizontal sill is expressed in appendix VIII and an easy calculation shows that the thickness has to be 500 meters in order to account for both the heat flow today, and the heat accumulated in the circulation zone. Its total volume is therefore 35 cubic kilometers, and the depth about 2.000 meters.

The only way of explaining the thermal activity in the Hengill therefore seems to be as follows: An activity starting within the second half of the Postglacial period can be caused by heat conduction from an intrusive situated at a depth not exceeding 2.000 meters, and having a total volume not less than 30 to 40 cubic kilometers. The smallest intrusive is a concordant sill having a thickness not less than 500 meters and covering an area approximately equal to the area of the thermal activity at the surface.

A thermal activity going on for the whole Postglacial period would require a much thicker sill. The author is therefore inclined to assume that the intrusive be in this case a stock under the whole area of thermal activity. The depth to the roof of the stock can hardly be much in excess of 2.500 meters, and its age only a few score thousand years. Magmatic or juvenile water does in both cases only play an unimportant role. No signs of Postglacial intrusives have been observed , so the latter case is, as yet more likely.

The views expressed in this report are largly based on quantitative calculations regarding the heat balance of the thermal springs, meanwhile pure geological observations have received less attention. The calculations are made by the means of assumptions many of which are very inaccurate, and one has therefore to regard them only as an experiment to find a likely model for the thermal phenomena. The last proofs can only come through geological and geophysical observations. But the geologists cannot observe the heat balance and the temperature field, so the problem must be treated in this way. The objects of further study are first and foremost the local geology and the age of the thermal activity in the Hengill. The history of the basic tuffs is not fully known, as yet, and one tends to consider the solution of this problem to be essential for that of the geothermal problems. Parallel herewith it must be attempted to find whether there really be a stock under the Hengill. There seem to be 3 ways of treating this problem. It is not impossible that a stock causes a gravity or a magnetic anomaly. The temperature field near the surface in and around the Hengill could also give important information.

## PROSPECTING FOR HOT WATER AND STEAM.

The drilling in Mosfellssveit near to Reykjavík has particularly shown that it it possible to multiply the flow of hot water by the drilling of holes. The same applies to the natural steam as the drilling in the Hengill and at Krísuvík has shown. The question of where drilling should be performed, i.e., where the best results may be expected, arises in this connection.

The solving of this problem is naturally closely connected with the entire geothermal problem, but it is, at this stage possible to get a partial answer without considering the fundamental cause of the thermal activity.

In the case of the alkaline springs the first thing one will note is that these are a very localized phenomenon and are confined to certain fissures in the plateau. It is a prime necessity for those attempting to increase the flow by drilling to obtain concise information on the location of the fissures. It has been stated above that the rising of hot water in and at the side-walls of dikes appears to be a frequent occurrance. In many places there are outcrops of these dikes and one can also decide their incline. In such cases the near-surface geological problems are, practically speaking, solved. In other places the dikes are covered by soil over a large area. But a great number of them are accompanied by strong magnetic anomalies and magnetic exploration can, therefore, grant a precise idea of the location of a magnetic dikes. Many dikes of a thickness of 6 to 10 meters have shown positive anomalies upto 11.000 gamma. It is worth while mentioning that some

dikes have shown negative anomalies of upto 7.000 gamma. These dikes may side with those showing positive anomalies.
Although one can thus gain a concise idea of the location of the dikes, the question remains as to where in the dike it would be most suitable to perform the drilling. The presence of springs on the surface can, in many cases grant a good idea of the location of channels issuing hot water, but surface springs can also grant misleading information.

During the last two years the earth resistivity method has been widely used for the location of the hot water channels. Through the high contents of solids and the elevated temperature, the hot spring water has much lower electric resistivity than normal surface water. While surface water has a contents of solids of 60 to 150 p. p. m. the hot spring water contains from 150 and upto 1500 p. p. m. Although a part of the solids be silica which has hardly any influence on the conductivity of the water, it may be said that the average resistivity at 25 degrees C., of the alkaline water is from 2000 upto 5000 Ohmcm but resistirities as low as 300 Ohmcm have been measured. The average resistivity of surface water at 25 degrees C., is 10.000 to 15.000 Ohmcm, yet water from moores can, in some cases, come down to 4000 Ohmcm.
As the resistivity of water decreases rapidly by increasing temperature, or about 2% for each °C., it is obvious that the resistivity of the hot spring water in the earth is, in most cases, less than one tenth of the resistivity of the surface water. This great difference in resistivity makes it possible to use the earth resistivity method in the prospecting for hot water and steam. The

/h
tecnique is in this case by no means different from that of using this method for other purposes.

The normal resistivity of surface rocks in Iceland is 15.000 to 25.000 Ohmcm. This resistivity is greatly diminished by the presence of hot alkaline water in the rock but the water flowing through the channels always infiltratesan area around them. For the basalt it appears that figures of 10.000 to 15.000 Ohmcm., be common, but for sediments much smaller values can be obtained and as low as 2000 Ohmcm., have been measured. It does not seem to be beyond possibility to estimate the temperature gradient near hot springs through earth resistivity data. This is further dealt with in appendix IX.

In the case of the acid springs much lower resistivity values are encountered near to the springs owing to the higher ground temperature and the higher contents of electrolytes in the ground. Values as far down as 200 Ohmcm., have been measured, but hitherto the resistivity conditions in the case of the acid springs have not been studied in such a measure that it be possible to deliberate further, but the conclusions seem to be such as to make it most difficult to use them for calculating the temperature distribution.

For further explanation an interesting example of the use of the earth resistivity method in the alkaline area will be given.

In one place in Northern Iceland it was noted that at the shore of a small lake there was a pool which usually did not freeze in wintertime and this fact was taken as an indication of the presence of thermal activity. This place, which is situated much to the fore in Skagafjord, lies near to the small community of Saudarkrokur. Owing to the interest existing in this community for obtaining hot water for the heating of houses, a resistivity survey was undertaken in the place around the pool. The drawings no. 4 and 5 show the result.

The first drawing shows the variation in the resistivity with increasing electrode spacing. From this curve one will note that close to the pool at a depth of approximately 30 to 50 meters there is a layer of low resistivity. When one considers that the basement in this place is plateau basalt, covered with a layer of gravel and clay, one would be inclined to reckon with a hot water layer on top of the basalt. Further resistivity measurements with constant electrode spacing shown in the drawing 5 gave a good idea of the size of this layer. The measurements were performed, as will be seen also in the surface of the lake. From the resistivity values it appeared possible to calculate that the temperature in the layer were 50 - 60 degrees C., although this calculation be fairly uncertain.

On the basis of this information, drilling was commenced as near to the center of the layer as possible as there was strong belief that water would issue. The drilling has now shown that the assumption based on the earth resistivity survey was correctly interpreted. On the top of the plateau basalt there was a hot water layer at a depth of 40 meters and this had a temperature of 52 degrees C. By deeper drilling higher temperatures were encountered and the drilling of two holes has now been completed. One of these issues 20 litres per second at 70 degrees C., but most of this water is derived from a depth of 110 to 120 meters.

The question of the quantity of water expected after drilling is considerably more difficult than the matter of locating the channels from which the water issues. It is, however, possible to acquaint oneself with this problem in Various ways. As stated in the Chapter (2) on alkaline springs, the flow of the springs increases with increasing temperature. This is a most important fact for in places where springs with a small flow but a high temperature are located one may be certain that all the water does not reach the surface. Through the chemical analysis of the water one may also ascertain whether it be mixed with cold water, but this is an important point in this connection. By earth resistivity methods it is possible to decide on the size of the areas near to the surface which are infiltrated by hot water, but the size of the area grants information about the quantity of water flowing from below. In this connection it should be mentioned that great volumes of hot rock can act as heat reservoir. One cubic kilometer of rock at the temperature of 100 degrees C., is a storage for $1,5 \times 10^{13}$ kcal above the temperature of 75 degrees C., and this is sufficient for the heating of $2 \times 10^{8}$ metric tons of water upto a temperature of 75 degrees C. This quantity of wate suffices for the maintenence of a spring of 100 litres per second for a period of 65years. These calculations prove the importance of reckoning with heat stored in rocks. It is less important how this heat enters, but it will in most cases have been issued with hot water.

It is still unknown, and presents one of the major problems in this connection, whether the increase in the flow of hot water obtained by drilling, e.g., in Mosfellssveit, be derived from a steady flow of hot water from below or whether it be obtained from a local heat or water reservoir which will only last for a certain period. In the first case one would assume that the actual volume of hot water streaming from below be at least 400 litres per second, but that a mere 100 litres have reached the surface prior to drilling being commenced. The remaining 300 litres per second will then have been absorbed into the cold ground water and lost heat both through mixture and conduction.

In the latter case one would assume that the increase of 300 litres per second has been caused by the better communication of the hot rock with the surface obtained through the wells. If one assumes that a local mass of rock has been heated up, there are possibilities for that the thermal area becomes unstable and the heavier cold water flows into the hot rock, but is heated and thus formed into new hot water. This then continues until a certain part of the heat accumulated in the rock has been used up.

A third possibility of the drilling really having increased the entire flow of the hot water from below might be mentioned, but as one must provide for the water having flown long distances at considerable depth prior to its coming up in this place, it appears hardly possible that boreholes of 500 metres' depth can bring any effect to bear on the entire circulation. One does, unfortunately, not know anything about the thermal activity in Mosfellssveit prior to drilling being commenced, but this makes it very difficult for one to take a stand toward the above problems.

The increase of the steam flow of the acid springs through drilling is a question not unrelated to the above discussion although there is a variation in details. It has been stated that the acid springs be grouped as, e.g., in the Hengill area. These groups are characterized through a very high temperature gradient in the surface. This gradient has, in the Hengill area, been measured as I degree C., per meter near the surface.

The expected temperature field is calculated in appendix VII.

The total amount of heat steadily flowing from the Hengill area has been estimated at 150 million kcal/h and this heat issues at an area of 70 square kilometers, but this represents nearly 4 tons of steam per hour and square kilometer. This heatflow is distributed in such a manner that it does not seem to promise that it be possible to work it with the drilling of holes in the area as numerous wells scattered over the whole area would have to be drilled.

The vast amount of heat accumulated in the place, however, helps matters out. It has been seen that a mere 200 meters' depth need be reached in order to encounter a rock of 200 degrees C., and no doubt remains that at least 250 degrees C., will be encountered at greater depth. If one considers a well drilled into a rock with this temperature distribution, the vapour pressure of the water at a depth of about 200 meters in the walls of the well will become larger than the weight of the water column in the well which will become instable and blow off the water as a geysir. When this has occurred there has been a sudden and great pressure-drop in the well and all super-heated water in the walls of the well enters it, partially evaporates and brings the well to issuing a mixture of steam and water. If the permeability of the rock is great enough to secure a steady supply of super-heated water, the well will issue a steady flow of steam and water. As the pressure in the well is less than at its surroundings, this may occur without any other heat supply than the heat accumulated in the rock. The great gravity difference between super-heated water and cold water will cause the cold surface water to thrust out the hot water. When the cold water enters the hot rock, the rock gives heat to the water and thus forms new hot water. This process may continue until the greatest part of the heat accumulated in the rock has been used. The heat accumalated within a depth of 2 kilometers has in the case of the Hengill been estimated to be about $10^{16}$ kilogram calories, and the temperature of the rock near to 300 °C. This heat suffices for the production of nearly $10^{10}$ metric tons of steam at 150 degrees C., and a pressure of 5 atmosphere absolute. If one provides for only 10% of this heat being worked by drilling, this does, however, suffice for a production of 1000 tons per hour of steam during a period about 100 years. Although these figures are uncertain the author maintains that this be a low estimate.

At certain conditions there seem to be possibilities for the accumulation of steam and water within structures and even for the seperation of water and steam by their difference in specific weight. This process should be of the same type as the accumulation of oil and gas within structures as is known from oilfields. The essential for this is e.g., an anticline with an impermeable cap-rock. It is, therefore, not only the heat in the rock which is important but a direct accumulation of steam and superheated water can be of importance.

This does, however, not seem to be of any major importance here in Iceland as the plateau basalt which is the main formation of the first 2000 to 3000 meters has very low porosity and permits no formation of structures. Although the greatest emphasis is laid on the accumulated heat and water in the place, the water and steam flowing from below from channels in the rock is, of course, of some importance, but, as previously stated, these channels appear to be highly distributed over the entire area and each channel conveys only a small amount of steam and water.

Summing up, one finds that there are good prospects of securing steam if the well is drilled in a place where there are sufficient masses of hot rock with the requisite permeability and porosity. The latter is of special interest if there are possibilities for the accumulation of steam within structures. Fissures and contacts are, of course, of importance as these mean a local increase in permeability.

Drilling for natural steam in Iceland is still so little advanced that one can hardly speak of experience or evidence to support the views expressed here. It may, however, be expected that the explorations in the Hengill and Krisuvik will be increased in the coming few years and this will augment the knowledge on this phenomenon.

The drilling of the basalt will present difficulties in the development of these explorations. The basalt is hard, fine grained and often badly fractured. It is true that diamond bits are making good progress, but as steam wells have to be of a size of not less than 10" the use of diamond bits is rendered impossible. Besides diamond drills, both percussion and calyx drills have been used. Both of the latter have given rather poor results. Modern rotary machinery employing rock-bits is now being introduced, but it is doubtful whether this method be economic owing to the heavy wear of bits. Loss of circulation has proved to be a great obstacle.

## THE ECONOMIC POSSIBILITIES OF THE NATURAL HEAT RESOURCES IN ICELAND.

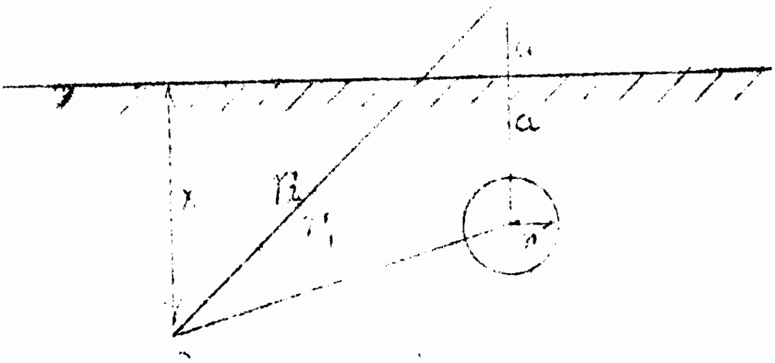
The natural hot water already plays an important role in the fuel economy in Iceland. Some 35.000 people in the city of Reykjavik are now living in apartments heated by natural hot water from the wells in Mosfellssveit. It is estimated that this decreases the imported quantity of coal by 35.000 tons annually, but Iceland has practically no fuel resources. At this stage it is somewhat difficult to predict the economic possibilities of the natural steam resources. These can be used, as the Italians have so brilliantly succeeded in doing, for the generation of electric power. It seems to be possible, without entailing great difficulties, to erect power plants having a total capacity of 100.000 kws.

In Iceland there is a abundance of hydro-power and the total undeveloped capacity is estimated to be about two million kws. It must, however, be admitted that a large part of the hydro-power resources is such that one might encounter difficulties in utilizing it because of the water being glacial. The cost of constructing natural steam power plants does not seem to promise to be less than that of the larger hydro-electric plants and as it is obvious that the hydro-power plant has greater reliability one could not venture into the construction of natural steam plants except under extraordinary conditions. The natural steam resources seem to be of greater importance for the chemical industry. Particular branches of chemical industry as e.g., electrolytic caustic soda plants greatly depend upon inexpensive heat and power. Certain difficulties are entailed in the use of by-products of these industris, but the possibilities are being studied closer.

## APPENDIX.

### 1. Steady Heat Transfer to a Long Horizontal Pipe in the Earth's Crust.

Suppose a long narrow, horizontal pipe being at the depth h and the diameter of which be 2r.



The gradient is g degrees per meter and the inside of the pipe is colder than the surrounding rock, i.e., that heat is flowing to the pipe. In order to find out how much heat flows into a unit length of this pipe, one must find the temperature distribution around it, and it must then be noted that the temperature at the surface of the earth is zero. To solve the problem the pipe will be subsituted by a line sink. The boundary condition at the surface will be fulfilled if we place, at a distance h from the surface, a heat source of the same capacity as the line sink. If Q is the capacity per unit length of the line source, one gets the temperature at the point p which is at the depth z where c is the coefficient of heat conduction for the rock.

$$T = g\,x - \frac{Q}{2\pi c}\ln {}^{r_2}/_{r_1}$$

This formula is self explanatory as the temperature distribution around a line source is proportional to ln (r) where r is the distance from the line. If the diameter of the pipe is 2r and the heat at its surface is T, one finds 0 by fulfilling this boundary condition

$$r_1 = d/2 \qquad r_2 = 2h \qquad T = 0$$

as it is being provided that r be very small as compared with h. From this formula one can calculate the heat transfer coefficient k

$$k = \frac{2\pi c}{\ln \frac{4h}{d}} \qquad \text{kcal/m, } {}^{\circ}\text{C, h}$$

If h and r are to be considered in meters and c in kcal/m, °C, h it is found that k is in koal/m, °C,h.

$$k = \frac{Q}{g a - T} = \frac{2\pi C}{\ln \frac{4h}{d}}$$

## II. The Distance which Water must flow in a Narrow, Horizontal Pipe in order to attain a certain Temperature.

It is here being provided that water flows through a certain length of the above pipe and that the initial temperature be zero. In order to find the distance x from the origin which this water must flow to attain the temperature T one must may use the above coefficient k in Appendix I. As rocks are very poor heat conductors, any counting quantity of water will have to flow a distance which is very long when compared with the diameter of the pipe. The temperature gradient along the axis of the pipe is, therefore, very small and this may be negligible when compared with the radial gradient. If the distance along the axis of the pipe is x and $T_o = g \cdot a$, the normal temperature of the rock at the depth of the pipe, q the water flow and s the specific heat of the water, the differential equation for the temperature of the water will be:-

$$s \cdot q \frac{dT}{dx} = k\,(T_o - T)$$

This equation is easily solved and the solution is:-

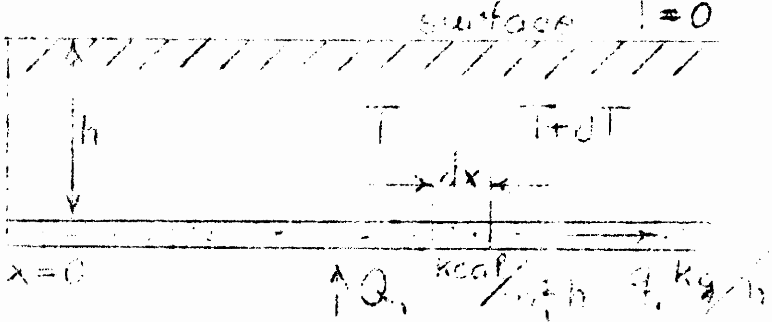
$$T = A\, e^{-s\frac{k}{q}\cdot x}\ x\ T_o$$

Where A is an arbitrary constant. This constant is found by the boundary condition that where x = o, T = o and one finds

$$T = T_o \left( 1 - e^{-\frac{k}{s\,q} x} \right)$$

## III. The Heating of Water flowing through an Extensive, Thin, Horizontal Porous Layer.

It is provided that, at the depth h, there is a thin, horizontal porous layer, the horizontal dimensions of which are large when compared with the depth.



It is then being provided that the water flows at an even speed over the entire width of the layer, which is b. If q is the heat current from the interior of the earth, i.e.,q = c • g where g is the temperature gradient, q the water flow and s the specific heat of the water, we find the differential equation for the temperature of the water as a function of x :

$$s \cdot q \frac{d\,T}{d\,x} = b\,q - c\,b\,\frac{T}{h}$$

Here it is being provided that, as the horizontal dimensions of this layer were large compared with its depth, the heat current both above and below the layer is practically vertical, i.e. $\frac{dT}{dx}$ is a very small quantity compared with the gradient g.

The solution of the equation is:

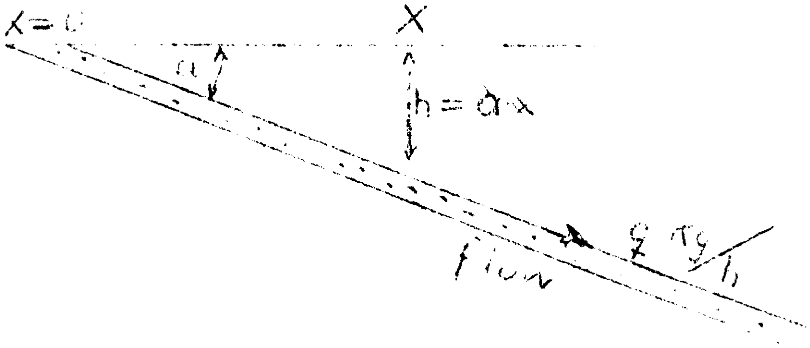
$$T = A \cdot e^{-\frac{c \cdot b}{h \cdot q\ s} \cdot x} \times \frac{h}{c} Q$$

Where A is an arbitrary constant. This constant is found with the boundary condition x = o, T = o. The solution of the equation is, therefore,

$$T = T_o \left( 1 - e^{-\frac{e\ b}{h\ q\ s} x} \right)$$

Where $T_o$ is the normal temperature at the depth h, i.e., $T_o = g \cdot h$ and $q = g \cdot c$.

If the layer is sloping it is easy to calculate the temperature e.g., in the case of the layer commencing at the surface:-



and if the slope a is small one finds the differential equation:-

$$s \cdot q \frac{dT}{dx} + \frac{c \cdot b}{a} \frac{T}{x} = Q \cdot b$$

The solution of this equation for the boundary condition x = o, T = o is:-

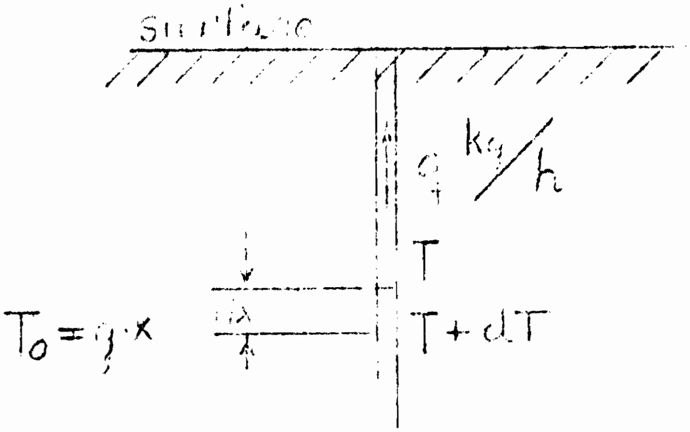
$$T = \frac{g \cdot h}{1 + a \frac{q}{c} \frac{s}{b}}$$

## IV. The Cooling of Water flowing to the Surface through a vertical Pipe, assuming a constant Co-efficient of Heat Transfer.

Here it is being provided that the heat transferred per unit length Q between the pipe and its surroundings be:-

$$Q = k\,(T - g \cdot x)\ ,\ \text{kcal/m, h}$$

Where k is the co-efficient of the heat transfer, T the temperature within the pipe and g • x the normal temperature of the surroundings of the pipe at the depth x, i.e., g is the temperature gradient



The differential equation for the temperature of the water as a function of the depth x is then:-

$$s \cdot q\,\frac{dT}{dx} = k\,(T - g \cdot x)$$

and the solution of this equation is:-

$$T = A \cdot e^{\frac{k}{s\,q}x} + g \cdot x + g \cdot \frac{s.q}{k}$$

Wherein A is an arbitrary constant. This will be found with the boundary condition that the water starts off with the temperature

$T_o$ at the depth h, i.e., $x = h$, $T = T_o$. We find the solution

$$T = \left( T_o - g\,h - g\,\frac{s\,q}{k} \right) e^{-\frac{k}{sq}\,h\,-x)} + g\cdot x + g\,\frac{s\,q}{k}$$

and the temperature of the water at the surface is by putting $x = o$:

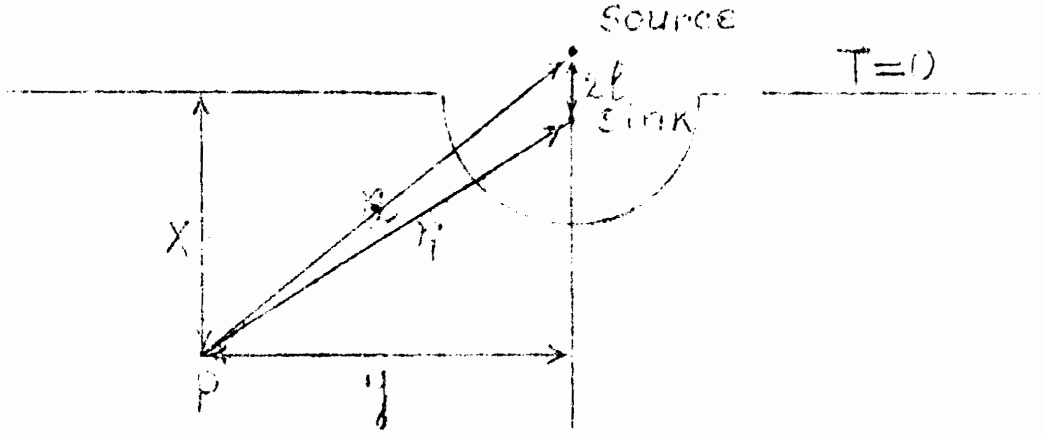
$$T = g\cdot\frac{s\cdot q}{k}\left(1 - e^{-\frac{k\cdot h}{s\cdot q}}\right) + (T_o - g\,h)\,e^{-\frac{k\cdot h}{s\cdot q}}$$

## V. Influence of Topographic Conditions and Erosion on the Temperature Gradient in the Surface.

Topographic conditions, i.e., irregularities in the surface exert influence on the heat flow through it so that at the bottom of valleys and under large, vertical walls there is a larger heat flow than on the top of hills. The speed of the erosion of the surface also has a noticable influence on the heat flow. This comes of the fact that the heat flow in normal rocks is an extremely slow process owing to the low co-efficient of conductivity. This means that when a part of the surface is taken away, the temperature field requires a long time to accord to the new conditions. If the erosion is rapid it can constantly hinder the temperature field in attaining balance with the alrerations of the surface.

The influence of topography on the temperature gradient has been studied by many authors. This matter will, therefore, not be discussed in detail, but two examples will be given in order to show the order of the influence.

Firstly, assume a long, circular valley having the diameter 2R and supposes that the temperature be zero everywhere on the surface. In order to find the temperature distribution near to the valley, one need only place a pair of line heat source and line heat sink very close together at the center of the valley. The source-sink pair is called a line doublet and its axis is placed perpendicular to the surface.



The distance between the source and the sink is 2·l. Because of the symmetry of this doublet the temperature on the flat surface will be zero so that this boundary condition is fulfilled. The temperature in the point p is, through the effect of the doublet,

$$T_p = A \cdot \ln {}^{r_1}/_{r_2}$$

wherein A is an arbitrary constant. Calling the co-ordinates of the point p, x and y one finds:-

$$T_p = A \cdot \ln \frac{(x-l)^2 + y^2}{(x+l)^2 + y^2}$$

As the distance l is had very small, this may be simplified thus:-

$$T_p = A \ln \left( 1 - \frac{4xl}{r^2} \right) = - C \frac{x}{r^2}$$

where $r^2 = x^2 + y^2$ , and C is an arbitrary constant. This constant is selected so that the temperature at the surface of the valley be zero and then the temperature distribution is found where g is the normal gradient in the surface.

$$T = g \cdot x \ ( 1- R^2/r^2 )$$

and the temperature gradient, therefore, is

$$\frac{dT}{dx} = g \ ( 1- \frac{R^2}{r^2} ) + 2g \ \frac{x^2 R^2}{r^4}$$

For the bottom of the valley where x = R and y = o, one then finds the gradient to be just 2 · g, i.e., the temperature gradient at the bottom of a circular valley is just double the normal gradient and is independent of the size of the valley. This is, of course, only for the steady flow of heat.

Similarly to this one can calculate the temperature distribution around a hollow in the surface having the form of a semi-sphere of a radius R. In this case one does not have to deal with line doublets, but with a point doublet. In other respects the calculations are practically the same. One finds in this case the temperature at the depth x and the distance r from the center of the hollow

$$T = g \cdot x \ ( 1- R^3/r^3 )$$

The temperature gradient at the bottom of the hollow is 3g or three times the normal gradient in the surface. It is interesting to note that if one calculates the heat which flows from the hollow, this is three times as great as the heat which passes through the area $\pi R^2$ of the normal surface.

The case of the valley's radius being on a constant increase through an erosional affect will now receive attention. The temperature field around the valley is, in this case, unsteady and in order to find this, one must reckon with a variable doublet for as may be noted from the above calculations the line doublet fulfills the boundary conditions required in this case. It is, in this instance, sufficiently concise to calculate with a constant doublet starting at the time t = o, i.e., as will be seen from the following caculation, that the formation of the valley commences at the time t = o. It is found in the literature (14) that the temperature distribution around a constant line source starting at the time t = o:-

$$T = \frac{S}{4\pi a^2} \int_{o}^{t} e^{-\frac{r^2}{4a^2(t-\tau)}} (t-\tau)^{-1} \, d\tau$$

wherein S is the strength per unit length, $a^2$ is the diffusivity of the rock and r the distance from the line. It is an easy matter to find from this formula the temperature field around a line double starting at the time t = o. One finds:

$$T = -\frac{S \cdot \ell \cdot x}{4\pi a^4} \int_{o}^{t} e^{-\frac{r^2}{4a^2(t-\tau)}} (t-\tau)^{-2} \, d\tau$$

wherein x is the distance from the doublet measured on the axis of the doublet and 2·1 is the distance between the two components. This integral can be evaluated and one finds, by placing S, 1,$\pi$ and $a^2$ into one arbitrary constant.

A:-

$$T = A\cdot \frac{x}{r^2} \cdot e^{-\frac{r^2}{4a^2t}}$$

This constant is found with the consideration that the radius of the valley is at the time $t_o$ of the size R:

$$T = g\cdot x\left(1 - \frac{R^2}{r^2}\, e^{\frac{R^2}{4a^2t_o} - \frac{r^2}{4a^2t}}\right)$$

This formula is, of course, not much different from the one outlined above for the steady heat flow and one finds that the expential factor takes the erosion into account. Having regard to actual conditions, one finds that the erosion speed it, however, small when compared with the speed of the temperature field to accord with the erosion. It is, therefore possible to simplify the above formula, as the exponent in the exponential factor is very small and one finds that

$$T = g\cdot x\left(1- \frac{R^2}{r^2}\left(1 + \frac{R^2}{4a^2T_o} - \frac{r^2}{4a^2t_o}\right)\right)$$

As the consideration centers on the temperature field below the valley where r is larger than R, and the time which is of interest is just $t = t_o$ then it is possible to simplify the formula still further:-

$$T = g \cdot x \left( 1 - \frac{R^2}{r^2} + \frac{R^2}{4a^2 t_o} \right)$$

which shows that the temperature gradient is increased by the factor $\frac{R^2}{4a^2 t}$ through the erosion. In these calculations one has provided for a rate of erosion proportional to the square of the time as will be seen from the formulaes. This law of erosion seems to be more likely than that the erosion rate be a constant.

## VI. Temperature Variations in Springs caused by variation in the Temperature of Surface Water.

The annual variation of the temperature of surface water in Iceland is at least 10 degrees C. The question to be looked into here is whether this variation may have any effect on the temperature variation of the alkaline springs. It is provided that the water flows through a certain channel within the rock and that the distance from the beginning at the surface be x. It is also provided that the annual variation be simple-harmonic

$$T = A_o \cdot \cos(wt)$$

wherein $A_o$ is the amplitude. As all problems of heat conduction are linear, one may superpose the annual variation in temperature of the water over the mean temperature of the water at different places in the rock and hence one need not take the mean temperature of the water into account. This has been found in appendix III.

Furthermore, as the the problem is linear, the temperature variations within the channel in the rock will also be harmonic. The temperature at the distance x in the channel from the point where the water starts at the surface, can therefore be assumed.

$$T(x) = A(x) \cos(wt + p)$$

where $A(x)$ is the amplitude which varies with the distance x, and the p represents the lag which is also dependent on the distance x. It is known that if the temperature ( 14 ) varies thus simple-harmonically on the surface of a semi-infinite solid, having the diffusivity $a^2$ and the conductivity c, the heat flow from the surface Q per unit area is:-

$$Q = -\frac{c}{a}\sqrt{w} \cdot A(x) \cos(wt + p + \pi/4)$$

It is, therefore, known how great a heat exchange occurs between the water and the rock if the temperature amplitude is known. The differential equation for the heat variation within the channel may, therefore, be written thus:-

$$s \cdot q \frac{d}{dx} A \cos(wt + p) = -\frac{c \cdot b}{a}\sqrt{w}\, A \cos(wt+p+\pi/4)$$

wherein s is the specific heat of the water, q the flow in litres per hour and b the surface per unit length of the channel. The above equation will become:-

$$s \cdot q \frac{dA}{dx} \cdot \cos (wt + p) - s \cdot q \cdot A \sin (wt + p) \frac{dp}{dx}$$

$$= - \frac{c . b}{a} \sqrt{w} \; A \left( \text{cas} (wt + p) \cdot \frac{1}{\sqrt{2}} - \sin (wt + p) \cdot \frac{1}{\sqrt{2}} \right)$$

and thus one finds two equations for A(x) and p

$$s \cdot q \cdot \frac{dA}{dx} + \frac{c . b}{a} A \sqrt{\frac{w}{2}} = 0$$

$$s \cdot q \cdot \frac{dp}{dx} A + \frac{c . b}{a} \sqrt{\frac{w}{2}} \cdot A = 0$$

These equations are easily solved and with the boundary conditions

$$x = o; \quad A = A_o ; \quad p = o$$

one finds $A = A_o e^{- \frac{c . b . x}{a . s . q} \sqrt{\frac{w}{2}}}$

$$p = - \frac{c . b . x}{a . s . q} \sqrt{\frac{w}{2}}$$

then the solution of the differential equation is:-

$$T = A_o e^{- k x} \cdot \cos (wt - k \cdot x)$$

$$k = \frac{c . b}{a . s . q} \sqrt{\frac{w}{2}}$$

This solution represents a damped harmonis vibration and which goes to prove the influence of the heat capacity of the rock on the temperature variation within the channels. At closer observation it is seen that the numerical value of k is such that the annual variation is highly damped and that it be not possible to expect any measureable variation in the temperature of the hot springs due to the annual variation in the temperature of the surface water. Only cold springs flowing a short distance are likely to show easily measurable variations. As an example there follows a calculation of the amplitude for a spring of 2 litres per second where it is reckoned with that the contact surface within the channel be 20 square meters per meterlength and the amplitude of the annual variation be 5 degrees C., One finds if

$a^2 = 0.00\,25\ m^2/h$

| | | | | | |
|---|---|---|---|---|---|
| $x =$ | 500 | 1000 | 2000 | 3000 | meters |
| $A(x) =$ | $2.3^\circ$ | $1.0^\circ$ | $0.21^\circ$ | $0.04^\circ$ | |
| Time-lag = | $1\frac{1}{2}$ | 3 | 6 | 9 | months |

This table shows, in particular when one accounts for the small contact area, that easily measurable variations are only obtainable at springs not flowing a longer distance than 1000 to 2000 meters. Although less variations in temperature than 1/4 degree C., be easily measurable, it will, in this case, hardly be possible to discuss less variations as mixture with new surface water at the outlet always has a disturbing effect on all measurements. If one looks at the time-lag it will be seen that one may, in many cases, expect the springs to have the highest temperature in wintertime.

In the above calculations mixture of the spring water with other water en route was excluded and it was assumed that the annual variation in the temperature of the earth's surface did not reach the channel.

## VII. The Temperature Gradient in the Surface by the Presence of Diffusion of Hot Water from Below.

Here it is being provided that, from a depth of h meters, there is over a great area a flow of water at an initial temperature $T_o$ through various small pores and fissures. If it is assumed that the pores and the fissures be very small, so that one may regard this as a case of diffusion, it is known that, if the flow of water is steady, the differential equation for the temperature T at the distance x from the surface is

$$c \cdot \frac{d^2 T}{dx^2} + s \cdot q \frac{dT}{dx} = 0$$

wherein s is the specific heat of the water, q the flow of water in kilos per hour and square meter and c the heat conductivity. The solution of this equation with the boundary conditions

$$x = o; \quad T = o$$

$$x = h; \quad T = T_o$$

is

$$T = T_o \frac{1 - e^{-\frac{s \cdot q}{c} \cdot x}}{1 - e^{-\frac{s \cdot q}{c} \cdot h}}$$

In most particular instances the factor $e^{-\frac{s \cdot q}{c} h}$ can be neglected and one finds that:-

$$T = T_o \left( 1 - e^{-\frac{s \cdot q}{c} \cdot x} \right)$$

This formula shows that in the case of diffusion from below, one may not expect a constant temperature gradient, but that this be very high at the surface, declining rapidly. The following example is considered to show in some measure conditions in one place of the Hengill area. In this it is being provided that the water starts off at a depth of 2000 meters and a temperature of 300 degrees C., and that the quantity diffused be q = 0.01 kilos /m$^2$, h.

One finds:-

| | | | | | | |
|---|---|---|---|---|---|---|
| x = | 100 | 200 | 500 | 1000 | 1500 | meters |
| T = | 150 | 225 | 291 | 300 | 300 | °C. |

The figures show out the rapid decline in the temperature gradient.

## VIII. Cooling of Intrusives.

In the following calculations, the temperature field in and near to intrusives which are cooling will be dealt with. Here it is being provided that the intrusive be formed in a short time and convectional currents within the intrusive or in the ground water body are not taken into account. Normal heat conduction through the rocks will only be reckoned with. These assumptions are certainly not correct, but to how great an extent actual conditions deviate herefrom it is difficult to say. The following calculations must, therefore, be accepted with considerable reserve and it may only be said that they grant an idea of the order of the temperature field variation.

It should also been mentioned that the heat conduction calculations do not take the latent melting heat and the water expelled during crystallization into account as this heat is given off in a small temperature interval and is then actually nothing but an increase in the specific heat within this interval. In order to take this into account, it will be best to increase the initial temperature and the mean specific heat in such a manner that the total heat contents of the rock at the initial temperature becomes equal to the total melting heat, For basalt the total melting heat is about 400 kcal/kilo and the melting point is about 1100 degrees C. Here one would reckon with the intrusive's being just melted, i.e., having a temperature of 1100 degrees C. In order to take the above into account an initial temperature of 1300 degrees C., and a mean specific heat of 0, 32kcal/°C, kilo will be assumed. As the density of basalt is about 2.9 and the heat conductivity about 1.5 kcal/m,°C,h, one finds a diffusivity of $a^2 = 0,0016\ m^2/h$ or $a^2$ x approximatly 15 $m^2$/year or 15 square kilometers per million years. In all calculations dealing with heat conduction in basalt at temperature lower than the melting point, one must use the value $a^2$ of approximatlly 20 $m^2$/year, e.g., as in calculations in appendix V and VI.

The fundamental facts in the calculation of the temperature field of bodies within a semi-in-finite solid are found in all major texts (14) on heat conduction. No reason, therefore, exists for showing these formulaes here, but the solutions for the temperature fields around bodies in two cases will be given, i.e., for a batholith and a laccolith of a great horizontal area. The laccolith has the form of a thin, horizontal plate.

A. The initial temperature condition to be fulfilled in the case of the batholith is a constant normal heat gradient, g, in the surface above it. The roof of the batholith is at the depth h then one has from this depth h to a certain depth, d, the temperature of the batholith $T_o = g \cdot d$, and therefrom a gradient which is supposed to be normal. It must be stated that the gradient at greater depth is lower than near to the surface, but this is not taken into account here as it has but slight bearing on the calculations. The boundary condition at the surface ($x = o$) is $T = o$. The solution of the heat conduction equation for this initial condition is:-

From this formula one may calculate the heat flow $Q$ through the earth's surface (x = o) at the time t from the forming of the batholith and one finds

Some factors of minor importance have been omitted in the derivation of this formula. It is easy to see that the heat flow has a certain maximum and this amximum will be found in the usaual way by differentiating Q with respect to t and make this zero. One finds that the time $t_m$ at which the maximum heat flow $Q_m$ through the earth's surface occurs is:-

$$t_m = \frac{T_o - g \cdot h}{T_o} \frac{h^2}{2\alpha^2}$$

B. The Laccolith.

Here a thin, horizontal laccolith, 2b in thickness, is provided for and also that the distance from the surface to the middle of the laccolith be h. The initial condition to be fulfilled in this case is the normal constant gradient g over all, only within the distance of b both over and below the middle plane we have the temperature of the laccolith, which is assumed to be $T_o$. The solution of the heat conduction equation in this case with the boundary condition

$$x = o, \quad T = o,$$

is:-

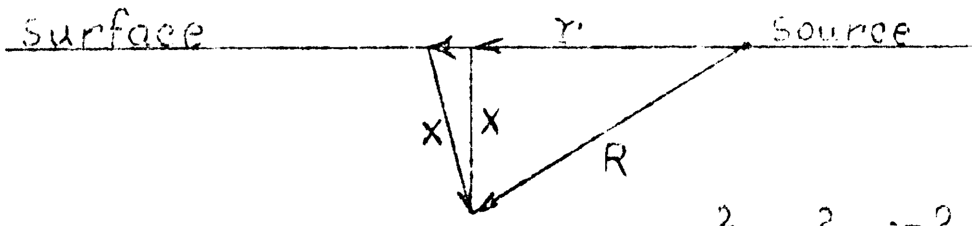
wherein some factors of minor importance ahve also been omitted
One finds the heat current through the earth's surface,

## LX. The use of Earth Resistivity Measurements in finding the Temperature Gradient near the Surface.

Here the electric field around a point source on the surface of a semi-infinite solid, the electric conductivity of which varies with the distance from the surface, will receive attention. The variation of the conductivity be such that it be constant in all planes parallel to the surface and that the conductivity function is:-

$$c = c_0 \cdot x^n$$

wherein $o_0$ and n are constants and x is the depth. If cylindrical co-ordinates, x,r, are used



$$R^2 = x^2 + r^2$$

the differential equation for the electrical potential V in the semi-infinite solid will be(15):

$$\operatorname{div}\,(c \cdot \operatorname{grad} V) = 0$$

if direct current is obtained from the source. This equation becomes:

$$\frac{\delta^2 V}{\delta r^2} + \frac{1}{r} \cdot \frac{\delta V}{\delta r} + \frac{\delta^2 V}{\delta x^2} + \frac{1}{c} \quad \frac{dc}{dx} \cdot \frac{\delta V}{\delta x} = 0$$

It is easy to show that if

$$c = c_o \cdot x^n$$

then the solution of this differential equation is:-

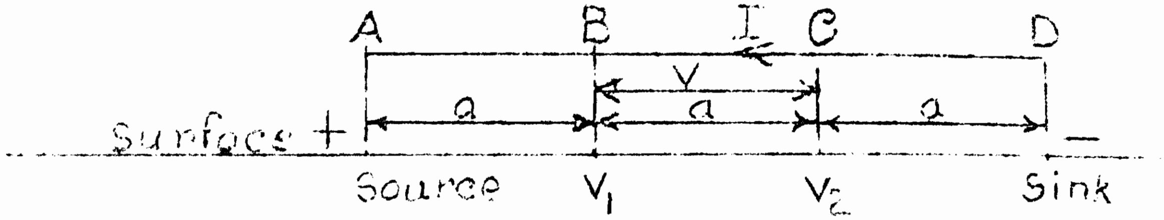
$$V = \frac{A}{R^{n+1}} = \frac{A}{(x^2 + r^2)^{\frac{n+1}{2}}}$$

wherein A is an arbitrary constant depending on the strength of the source, i.e., the equipotential surfaces are concentric spheres areound the source.

If I is the total current of the source into the semi-infinite solid, one furthermore finds, through an easy calculation, that

$$V = \frac{I}{2\pi C_o \cdot R^{\,n+1}}$$

The above calculations will now be used for the calculation of the conductivity measured with the usual equidistant electrode configuration used in ordinary earth resistivity measurements



One finds the potential of the point B due to the source-sink pair where a is the electrode distance:

$$V_1 = \frac{I}{2\pi C_0} \left( \frac{I}{a^{n+1}} - \frac{I}{(2a)^{n+1}} \right)$$

and at the point C

$$V_2 = \frac{I}{2\pi c_0} \left( \frac{I}{(2a)^{n+1}} - \frac{I}{a^{n+1}} \right)$$

If the measured potential difference is V

$$V = V_1 - V_2$$

one obtains

$$V = \frac{I}{\pi C_0 a^{n+1}} \left( 1 - \frac{1}{2^{n+1}} \right)$$

where I is the measured current.

Now the apparent conductivity is defined

$$C_m = \frac{I}{2\pi \cdot a \cdot V}$$

and as the conductivity at the depth a is

$$C\ (a) = C_o \cdot a^n$$

one finds from the formulas - above that

$$\frac{c(a)}{c_m} = 2 \left\{ 1 - \frac{1}{2\ n+1} \right\} = N$$

This formula shows out the interesting fact that if the conductivity c (a) in the ground varies in a parabolic manner $c = c_o \cdot x^n$ Then $c_m$ (a) is proportional to C (a) the factor N being 1 to 2.

Now it is possible to assume that the conductivity of water is a linear function of the temperature within a certain interval so that

$$c = c_o\ (1 + k \cdot t)$$

Without making a great error one may say that this formula be applicable in the interval 0° C to 100° C and that in this interval the constant k is about 0.025. It also seems possible to assume that the conductivity of the rock be proportional to that of the water in it and therefore this formula should also be applicable for the conductivity of rocks within the interval stated.

If g is the temperature gradient and x the depth and the porosity of the rock is constant, the above fotmula becomes:-

$$c = c_o\ (1 + k \cdot g \cdot x)$$

and hence

$$\frac{dc}{dx} = c_o \cdot k \cdot g$$

$$g = \frac{I}{c_o \cdot k} \cdot \frac{dc}{dx}$$

It was shown above that if the conductivity varies parabolic with a exponent n, the apparent resistivity $c_m$ mesured with the electrode distance a is practically $c_a$ i.e.,:-

$$\frac{dc(a)}{da} \simeq \frac{dcm(a)}{da} . N$$

It is, therefore, under these circumstances, possible to find $\frac{dc}{dx}$ from the measured graph of $c_m$ over a, and one gets

$$g = \frac{N}{c_o \cdot k} \cdot \frac{dcm}{da}$$

The factor $c_o \cdot \frac{dcm}{da}$ must be taken with a certain skill from the graph and can, of course, never be very concise.

It is essential to make it clear that although the calculations shown above display a possibility of finding the temperature gradient in the surface with earth resistivity measurements, numerous assumptions for simplification have been made and the aforesaid applies only under specific conditions. Firstly it must be possible to approximate the measured earth resistivity data with a parabola with an exponent,n. This will, in a great number of cases, be possible, but there must be a certainty for there being no great changes in the ground water, the rock and the porosity down to a certain depth, before it is possible to use the formula. There are therefore, great open chances for making errors which shows that the procedure can only be used with the utmost care. In some cases, however, the author has actually been able to calculate a temperature gradient from the earth resistivity data and measure it sucsequently in a bore-hole. In a few cases where the formula could actually be applied for geological reasons, the calculated gradient was pretty correct.

It should be stated that the gradient must be fairly high or higher than 1 degree per 15 meters in order to achieve results.

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The author is indebted to Mr. Trausti Einarsson, dr.phil. Professor of the University of Iceland, for his numerous good advise and enlightening discussions on the subject of this report.

Thanks are also due to Mr. Hilmar Foss for the translation of the manuscript and to Mr. Glumur Björnsson who has undertaken numerical calculations.

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