NATIONAL ENERGY AUTHORITY
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APPLICATION OF THE SILICA GEOTHERMOMETER IN LOW TEMPERATURE HYDROTHERMAL AREAS IN ICELAND

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ABSTRACT

It has been established from measured temperatures in drillholes that the amount of dissolved silica in thermal waters at depth in the low temperature hydrothermal areas in Iceland is governed by the solubility of chalcedony when temperatures are below about 110°C. At higher temperatures the solubility of quartz appears to govern the amount of dissolved silica in the water. Equilibrium with chalcedony appears in some instances to be established at temperatures as low as 20°C but most commonly cold ground water is silica supersaturated with respect to chalcedony solubility. Provided silica is the only varying component in the system silica temperatures are minimum temperatures and represent temperatures of last equilibrium with quartz or chalcedony. If mixing with cold ground water takes place and originally high pH is lowered, the estimated silica temperatures are likely to be high compared with the temperature of the mixture. Because of the frequently high pH of waters from the low temperature areas in Iceland (9-10 at 20°C) estimation of temperatures of last equilibrium with quartz or chalcedony in relatively low pH waters (7-8 at 20°C) must be done with special care since the low pH may have resulted from near surface chemical reactions or mixing with cold ground water. There is a clear relationship between intensity of low temperature hydrothermal activity and the age of the rocks in which the activity is located. There is, however, no distinct variation in highest silica temperatues of individual areas with distance from the active volcanic belts .

INTRODUCTION

Low temperature thermal activity is widely distributed in the Tertiary and Early Quaternary basalt formations of Iceland. (Fig.1). Surface manifestations are isolated springs and spring clusters with temperatures ranging from little above the mean annual temperature to boiling. Present drillhole data indicate that temperatures are less than 15o°C in the uppermost 1ooo meters of these areas. Most of the springs are located on relatively low ground in valleys and lowlands by the coast. Total flow from thermal springs is estimated to be 12oo liters/sec and exploitable from drillholes roughly 16oo liters/sec. The flow rate from individual spring clusters and isolated springs is highly variable (1-15o liters/sec). Distance between isolated springs may be as much as several tens of kilometers and generally there are no surface manifestations in the area inbetween. This scattered low temperature activity is to be contrasted with the high temperature hydrothermal activity in Iceland, which is concentrated and intense in relatively small areas of 1-1oo km^2. Besides, the 16 high temperature areas which have been identified, are all located in the active volcanic belts. Temperature variations in thermal springs within the low temperature areas are often observed from "hot centres", but it may be difficult to define the boundaries between individual areas.

Underground temperatures have been mapped out in some detail in the low temperature areas in Iceland by geochemical analyses of the waters and application of the silica geothermometer supplemented by inspection of the overall composition of the water. The data on which this mapping is based are of different and sometimes unknown quality so it is to be expected that details in the map (see Fig. 6) will change as further data accumulate.

The study of low termperature thermal areas in Iceland has much economic significance since these waters with temperatures as low as 56°C are used extensively for house heating and greenhouse farming (Pálmason and Zöega, 197o). Hydrogeochemistry plays an important role in surface exploration of thermal manifestations in these areas. Judgement of the probability of economic subsurface recovery of thermal water by drilling is based on this exploration. Drilling may be performed for individuals, towns, villages, and other communities.

COMPOSITIONAL CHARACTERISTICS OF THE WATERS

Thermal waters of the low temperature areas in Iceland are notable for their low content of dissolved solids and high pH. Analyses of selective samples of different types of waters from most of the areas are given in table 1. The most abundant dissolved ions in springs and drillholes are sodium, sulphate, and chloride. Silica amounts to 25-50% of the dissolved solids except for few waters with relatively high sodium chloride or sodium carbonate content. In most of the waters the chloride concentrations are less than those of sulphate but in many of the springs and drillholes located near the coast, chloride concentrations exceed those of sulphate.

It is generally accepted that the dissolved chemical components in the low temperature waters have been derived from the wall rock by leaching (Einarsson, 1942, Sigvaldason, 1966). It seems, however, possible that the carbonate in the sodium carbonate waters of the Snaefellsnes peninsula in western Iceland are of juvenile origin, derived from shallow level intrusions. Temperature appears to be the main factor influencing the bulk composition of the waters. The concentrations of many of the dissolved solids are governed by the solubility of hydrothermal minerals or ionic exchange reactions with such minerals. These include sodium, potassium, calcium, magnesium, carbon dioxide, and sometimes sulphate. The concentrations of other components such as chloride, fluoride, boron and sometimes sulphate appear on the other hand to be governed by their rate of leaching from the wall rock. It is considered that the high pH so characteristic of the low temperature waters has resulted from ion exchange reactions which accompany early dissolution of silica from volcanic glass and alteration of magnesium silicates such as olivine and pyroxene. It is known that hydrogen ions are easily removed from solution into magnesium silicates upon dissolution of magnesium (Luce et al., 1972). Preliminary studies indicate that the oxidation potential of the water is controlled by equilibrium between sulphide and elemental sulphur. If insignificant sulphide is present which is usually the case for warm waters, the oxidation potential may be influenced by the atmospherically derived oxygen content of the water.

Sigvaldason (1966) suggested that the chemical variation within the low temperature areas in Iceland were best explained by dilution and water-rock interaction in upflow zones from a deep, apparently homogeneous water reservoir. This explanation is considered to be valid for a few low temperature systems but is not accepted as the fundamental process which causes chemical variations in thermal waters within the low temperature areas. As can be seen from Fig. 4 the warm waters (7o$^{\circ}$C) are often in equilibrium with chalcedony whereas the hotter waters are generally supersaturated. Since mixing leads to chalcedony and quartz supersaturation, it seems likely that the warm waters have not reached much higher temperatures than indicated by chalcedony equilibrium. This is further supported by the very high pH of these waters but mixing would lead to pH-lowering. The positive relation between sulphate concentrations and silica temperatures (Fig. 3) is taken to indicate that the warm waters have not received their temperature by conductive cooling of hotter waters.

If measured temperatures or temperatures of last equilibrium with quartz or chalcedony are less than about 5o$^{\circ}$C, the chloride concentrations tend to be of the same order of magnitude as in rain water (5-1o ppm) but they are higher in waters with higher silica temperatures. There is, however, no observable gradual rise in the chloride content with rising silica temperatures. Since the low temperature waters are considered to be of meteoric origin as indicated by isotopic studies (Bödvarsson, 1962, Árnason and Tómasson, 197o), it appears that temperatures of more than about 5o°C are required before significant leaching of chloride takes place from basaltic rocks and their differentiated products.

The increased chloride content in some thermal waters near the coast is little doubt due to percolation of sea water into the rock and mixing with water of meteoric origin. This mechanism is, however, not acceptable for many of these waters. Sigvaldason (1966) has proposed that the increased chloride content is due to leaching from chloride rich clastic sediments deposited under marine conditions in Quaternary times but these sediments tend to located near the present coast. In at least one low temperature area such chloride rich water issues from Tertiary basalts and the only marine sediments known are thin layers of post-glacial age in glacially eroded depressions of the Tertiary basement. This area and many others were probably below sea level during glaciations of the Quaternary and certainly submerged at times during interglacial periods and at the beginning of post-glacial times. At such times more sea water may have percolated into the rocks than is possible under present hydrological conditions. Because of the presumed long convection cycle of thermal waters their present chloride content may be due to percolation of sea water into the rocks during times of higher position of sea level and simultaneous or subsequent mixing with water of meteoric origin. The present magnitude of this marine component in the thermal water will depend on porosity and flow rates in individual thermal systems.

The content of sulphate in fresh cold ground water in Iceland is generally less than about 5 ppm. Thermal waters with silica temperatures of less than about 5o°C contain sulphate in concentrations similar to those of cold ground waters but there is an increase in the sulphate concentrations with rising silica temperatures (Fig. 3). This relationship is very distinct for waters with silica temperatures of less than about 100°C but waters with higher silica temperatures are comparatively lower in sulphate. It seems likely that the sulphate content of waters with silica temperatures of less than about 100°C is governed by the rate of leaching from the wall rock. According to solubility data (Blount and Dickson, 1969 and Helgeson, 1969) anhydrite saturation exists rarely and only in the highest temperature waters (120°C). The low content of sulphate in the waters with highest silica temperature relative to the rest of the low temperature waters cannot, therefore, be considered to be generally limited by the solubility of anhydrite. It is possible that equilibrium with chalcedony instead of quartz exists even in the hottest low temperature areas. If so the relatively low sulphate content of highest silica temperature waters is due to the erraneous assumption of equilibrium with quartz instead of chalcedony.

SILICA TEMPERATURES

It has been established from measured temperatures in deep drillholes (300-2200 meters) in Iceland that the dissolved silica in the thermal water at depth is in equilibrium with chalcedony provided temperatures are below about 110°C. (Arnórsson, 1970). At higher temperatures present data indicate that the dissolved silica is in equilibrium with quartz but additional drillhole data are required before this equilibrium can be considered firmly established. The solubility data on chalcedony and quartz on which these results are based have been obtained from Fournier (1969) and Morey et al.(1962). It appears that equilibrium with chalcedony exists when temperatures are as low as 20°C but near surface cold ground water (5-10°C) in Iceland is generally somewhat supersaturated and at these very low temperatures the silica content of the water is probably controlled by the rate of leaching, which may be rapid, especially in the case of glassy volcanic rocks.

Ascending thermal water entering shallow drillholes or emerging in thermal springs may contain dissolved silica in excess of saturation, i.e. equilibrium with chalcedony or quartz. This supersaturation may have resulted from cooling by conduction in the upflow zone without precipitation of silica to retain equilibrium that existed at depth. Experimental work has shown that precipitation of silica upon cooling is a slow process especially at low temperatures, but above about 150°C equilibrium is attained rapidly (Morey et.al., 1962). It is this slow precipitation which forms the basis of the usefulness to apply the dissolved silica in thermal springs and shallow drillholes to predict what water temperatures would be recovered by drilling by eliminating the effects of cooling by conduction in the upflow zone. As will be discussed later silica supersaturation in thermal waters near the surface may not have resulted from cooling of the water by conduction but lowering of pH in the upflow zone or mixing with cold ground water.

Measured temperatures in thermal springs of the low temperature areas vary from about 15°C to 100°C but silica temperatures, i.e. temperatures calculated from the silica content of the water assuming equilibrium with quartz or chalcedony are between 15°C and 178°C. Comparison between measured temperatures and silica temperatures in springs show that the amount of dissolved silica corresponds to equilibrium at the measured temperature for about 25% of the selected but representative samples, but the other 75% are supersaturated and by as much as 130°C (Fig. 4). Supersaturation by 10-40°C is common. Significant undersaturation is not observed. On the basis of drillhole data Arnórsson (1970) found that equilibrium with chalcedony or quartz exists in aquifers below about 300 meters depth (Fig. 5) and the temperatures of these aquifers correspond well with silica temperatures in surface springs or shallow drillholes in few areas where deep drillholes have been located by thermal springs. This empirical observation may be used as a crude rule to decide minimum depths of drillholes that are to penetrate aquifers with temperatures predicted by the silica geothermometer from surface data.

Available data support the idea that the silica geothermometer can be successfully applied on high pH waters in springs or shallow drillholes of the low temperature areas and also on somewhat lower pH waters provided the lowering of the pH is due to higher content of sodium and calcium chlorides. Sodium carbonate waters which have low temperatures (50°C) are generally highly supersaturated with respect to chalcedony and quartz solubilities. These waters are characteristic for the Snaefellsnes peninsula in western Iceland but they are also known in other areas. This supersaturation may well reflect high temperature conditions at depth but since no drillhole data are available to support this the application of the silica geothermometer on these waters should be done with the greatest care. It is possible that the pH of these waters may have been lowered near the surface by the addition of carbon dioxide and that the water at greater depths had such a high pH that significant part of the total dissolved silica was dissociated.

Some warm spring waters of relatively low pH (8-9 at 2o°C) have little doubt originated by mixing of hot water with cold ground water near the surface. Mixing itself invariably leads to supersaturation so the silica geothermometer is not applicable on these waters unless the proportion and the composition of the hot and cold water components can be evaluated by other means.

Temperatures of equilibrium with quartz or chalcedony, i.e. silica temperatures, vary considerably between individual low temperature areas (Fig. 6). There is also much variation within some of these areas. As indicated in Fig. 1 there is insignificant low temperature activity within the belt of active volcanism and late Quaternary volcanism. The high temperature activity is on the hand located within these belts. In older rocks the low temperature activity is widespread although some areas are almost devoid of any surface thermal manifestations, particularly eastern Iceland. There is no strong variation in highest silica temperatures of individual areas with distance from the youngest volcanic rocks nor the age of the rocks from which the waters issue. Indeed, Sigvaldason (1966) considered that the temperature and composition of the low temperature waters were the same everywhere at depths below the upflow zones (1-2 km?) and that the variations in surface springs were due to mixing with cold ground water at shallower depths.

A good impression of the distribution and intensity of the low temperature activity is obtained from Figs. 1 and 7. The activity is very widespread as indicated in Fig. 1 but its intensity, temperature and flow rate, shows a clear relation with the age of the rocks from which the waters issue. In the Tertiary rocks the major quantity of water issued at the surface has silica temperatures of less than 90°C but in the lower Quaternary rocks more than 50% of the water has silica temperatures greater than 130°C and almost all of it has silica temperatures in excess of 90°C. The quantity of water issued from the lower Quaternary rocks is roughly 60% of the total despite the fact that these rocks cover much smaller areas than the Tertiary rocks. Thus there is a clear relationship between intensity of low temperature activity and the age of rocks in which it is located.

The most active low temperature area, Reykholtsdalur in western Iceland is located in rocks of uppermost Tertiary age but in the foregoing it was assumed that the water has been derived from Quaternary rocks. The reason for its emergence at the surface in the Tertiary rocks is due to structural control of dykes and abundant faults, vertical channelways almost absent in the Quaternary rocks just east of the thermal area.

The most common question which relates to economy and exploitation of low temperature waters demands an answer for silica temperatures for individual springs or an isolated spring. In order to produce the most reliable answer, it is important to have studied the relevant area on a regional basis to see whether the spring in question fits into the regional picture. Secondly it is important to evaluate the probability of mixing and change in pH in the upflow zone but the influence of these factors may cause erraneous silica temperatures.

MIXING EFFECTS

Mixing of cold ground water with thermal water leads always to silica supersaturation in the mixture whether the original thermal water was in equilibrium with chalcedony or quartz. This is so because the solubilities of chalcedony and quartz increase more rapidly as temperatures increase in the range relevent for the low temperature waters. Cold ground water in Iceland contains silica which for its temperature corresponds either to equilibrium with chalcedony (5-10 ppm) or, as is more frequent, it is supersaturated, contains up to 40 ppm silica. This leads to further supersaturation by mixing. If thermal water in equilibrium with quartz at 124°C would mix in equal volumes with cold ground water (10°C) containing 10 ppm dissolved silica, the temperature corresponding to quartz equilibrium would be 95°C whereas the actual temperature of the mixture would be 67°C. If equilibrium with chalcedony had been assumed for the mixture instead of quartz a silica temperature of 67°C would have been obtained. If the temperature of the original thermal water component had been lower, the chalcedony derived temperature would have been a little lower than the actual temperature of the mixture. Had the original thermal water on the other hand had a temperature higher than 124°C, the chalcedony temperature would have been higher than the temperature of the mixture, about 15°C for the hottest low temperature waters in Iceland (180°C).

Mixing which lowers the temperature of the thermal water below about 100°C may upset equilibrium with quartz and establish equilibrium with chalcedony. In such instances mixing will only lead to significant supersaturation and precipitation of silica if the thermal water had a temperature of about 150°C or more before mixing. The degree of supersaturation at the temperature of the mixture relative to chalcedony solubility depends though on the ratio in which thermal water and cold water mix and will increase with decreasing fraction of the thermal water.

Warm and hot (30-100°C) waters from the low temperature areas have as a rule very high pH (9.5-10 at 20°C). Hot water with substantial content of calcium and sodium chlorides possess though lower pH (8-9 at 20°C). Some warm waters low in total dissolved ions have also rather low value of pH (<8.5) relative to the characteristic waters. It is believed that many of these last mentioned warm waters have originated by mixing of hotter water and cold ground water.

It is not sufficient to evaluate the effect of mixing alone for these waters in estimation of their silica temperatures. It is also necessary to evaluate the effect of pH lowering which will occur during the mixing if the original thermal water has such a high pH that a significant part of the silica is dissociated. It is very important to know if mixing takes place during vertical movement of the water or during horizontal movement. If mixing takes place during horizontal movement the temperature of the thermal water aquifer penetrated by a drillhole will be at the most equal to the mixing temperature but as much as several tens of degrees lower than the silica temperature of that water or waters in surface springs. If, on the other hand, mixing takes place during vertical movement of the thermal water, a drillhole will penetrate the zone of mixing and subsequently strike aquifers hotter than indicated by silica temperatures of surface data. It is thus of much importance to reveal the hydrogeology of a thermal area or a part of it, if it is suspected that the silica temperature estimates are unreliable due to mixing. The hydrogeology can be revealed by geological mapping, magnetic and resistivity surveys. Scorious tops and bottoms of lava flows in the basaltic volcanic piles in Iceland provide permeable and near horizontal channelways suggesting that mixing during horizontal flow of thermal water is likely to take place, at least locally.

In the high pH waters the dissolved silica is the main buffer but it is well known that silica in solution behaves like a weak acid. The first dissociation constant of this acid is about $1o^{-1o}$ at $2o^{o}C$ and the variation in its value with temperature is known from experimental data (Pitzer, 1937, Rizhenko, 1967). Contrary to thermal water cold ground water has a pH not far from 7 and the dominant buffer in these waters is carbon dioxide and its concentrations vary from few tens of ppm. to about 2oo ppm. When hot and cold waters mix, the pH of the mixture will depend on the original content of silica and carbon dioxide in the hot and cold waters respectively, their pH, and the ratio in which these waters mix. Other weak acids might exert a buffer action on the pH of thermal waters, such as boric acid, bicarbonate, and hydrogen sulphide but they are not relevant for the low temperature waters in Iceland because of the low concentrations of their dissociated products in these waters. Calculation of the pH of water of mixed hot and cold water origin is possible if the composition of these hot and cold water components is known and their ratio in the mixture. For these calculations it is assumed that the equivalent sum of the anions of weak acids in the mixture is equal to their sum in the two water components multiplied by their fraction in the mixture. This assumption is correct as long as no precipitation takes place during the mixing that will change the total content of dissolved silica and carbon dioxide. The pH is most conveniently found by trial and error, i.e. repeated estimation of its value and subsequent calculation of dissociated silica ($H_3SiO_4^-$) and bicarbonate (HCO_3^-) from the known dissociation constants of silicic and carbonic acids and their concentrations in the mixture until the calculated sum of the anions is equal to their measured sum in the hot and cold water components of the mixture. the pH may be calculated at the temperature of the mixture or at a fixed temperature.

In table 2 the influence of mixing and simultaneous lowering of pH has been calculated for thermal water of three different original temperatures. The cold water of the mixtures is assumed to have a silica content of 1o ppm., total carbon dioxide content of 66 ppm., and a pH of 7 at 2o°C. The thermal water is assumed to be in equilibrium with chalcedony at the lowest temperature but in equilibrium with quartz at the two higher temperatures. The pH of the thermal water is taken to be 9.5o at 2o°C and total carbon dioxide 22 ppm. These compositions for hot and cold waters are commonly observed in the low temperature areas of Iceland. The calculations in table 2 are only approximate since concentrations are assumed to be equal to activities. The difference in temperature between the first and third columns for each original hot water temperature of table 2 is the difference between the actual temperature of the mixture and the silica temperature, when the combined effects of mixing and pH lowering have been taken into account. The difference between columns one and two represents the effect of mixing alone whereas the difference between columns two and three represents the effect of pH lowering alone. The degree of supersaturation due to mixing increases with increasing temperature difference of the hot and cold water components in the mixture, the fraction of cold water and its silica content. This effect is larger for quartz than chalcedony and reaches a maximum of about 5o°C for the temperatures and compositions selected in table 2. By contrast the same maximum for chalcedony equilibrium is about 15°C. The effect of pH lowering is less than that of mixing and reaches a maximum of about 1o°C for all cases in table 2. The pH effects will increase with increasing carbon dioxide content and decreasing pH of the cold water component of the mixture but decrease with increasing pH, silica (therefore temperature) and carbon dioxide of the hot water component of the mixture. This effect reaches a maximum in the pH range of about 7.5-9.o when the buffering effects of both silica and carbon dioxide is small.

If cold water with the assumed composition in table 2 mixes with water at 80°C in equilibrium with chalcedony the effect of supersaturation is already significant in the presence of a small fraction of the cold water in the mixture even when the pH is above 9. This is particularly serious when the silica geothermometer is being applied on such waters with exploitation for house heating in mind. For such exploitation a temperature of 60-70°C is needed and a positive result is obtained if the silica geothermometer indicates such a temperature. Exploratory drilling may be carried out on the basis of such results.

Equilibrium with chalcedony may be assumed for waters which were in equilibrium with quartz if mixing led to sufficient lowering of the original silica content of this hot water. This assumption will still yield too high temperatures if the pH of the mixture is less than about 9 and also at higher pH values when the original hot water temperature is above about 150°C.

Dissolved elements or components in thermal waters can be used as indicators of mixing if they occur in high concentrations in the thermal water compared with cold ground waters and if they are not involved in water-rock reactions during and after mixing. For the low temperature waters in Iceland sulphate and chloride fulfil often these requirements, particularly in the case of the hottest waters. If the concentrations of the indicator component is known in the hot and cold water components of the mixture, the fraction of each of these components in the mixture can be derived easily. It is considered to be a reasonable assumption for individual low temperature areas in Iceland to take waters from the hottest thermal springs to represent the hot water component of the mixture and the local ground water to represent the cold water component. The pH for any mixture can be calculated from the silica and carbon dioxide contents of the hot and cold waters and their mixing ratio. If this calculated pH compares well with the measured pH of the thermal water that was suspected to be a mixture, this can be taken to be a good evidence for the suspected mixed origin. If the evaluated mixing ratio is valid the concentration of undissociated silica in the suspected mixed water must not exceed the calculated silica concentrations. If the measured and calculated silica concentrations are similar, this may be taken to indicate insignificant precipitation of silica from the water during and after mixing. If the measured silica content is, on the other hand, lower, this suggests some precipitation after mixing.

Some warm springs in the Southern Lowlands low temperature area which are located few kilometers or less from boiling hot springs are considered to have originated by the mixing of thermal water with composition similar to that of the boiling hot springs and cold ground water. Calculated chaledony temperatures assuming mixing to an extent indicated by the chloride content of the warm springs are rather similar to those derived from their silica content. Temperatures of the warm waters calculated in the same way are similar or higher than their measured temperatures. The above comparison fits the explanation of mixed origin of the warm waters if it is assumed that they have cooled somewhat by conduction which seems quite reasonable, especially when the low flow rates of <1 liter per sec. are taken into consideration.

During hydrothermal alteration of basaltic rocks, primary minerals are replaced by less dense hydrothermal minerals. Typical hydrothermal minerals of the low temperature areas include montmorillonite, chlorite, quartz, calcite, various zeolites and a variety of other minerals in minor concentrations. The hydrothermal alteration appears to be mostly isochemical recrystallisation on the spot and will therefore reduce porosity and permeability of thermal water aquifers. A decrease in porosity by 1o-15% seems likely during complete replacement of primary minerals by the hydrothermal minerals. Some dissolved components may be transported for some distances and deposited where changes in temperature or mixing takes place. This transport is thought to be most significant in upflow zones where water movement is relatively rapid. In this relation deposition of silica in upflow zones as a result of mixing is emphazised. This deposition may play an important role in reducing permeability at the boundaries of upflow zones and thus seal the hot water from the surrounding cold ground water. Near surface deposition may bring about extinction of surface hydrothermal activity as has been pointed out before (Facca and Tonani, 1967), but such sealing is thought to be important only for high temperature activity.

Hot springs of the low temperature areas with high flow rates (few tens of liters per sec.) have silica temperatures well above 100°C. There is no gradual increase in flow rates observable with rising silica temperatures. It seems, however, certain that springs with high flow rates tend to have higher silica temperatures than springs with lower flow rates. Of course, decreasing density of thermal water, which accompanies increasing temperatures will tend to increase flow rates to the surface. The precipitation of silica on the boundaries of upflow zones is particularly significant when thermal water temperatures are above about 150°C. Such precipitation leads to the formation of an impervious layer and increases pressure differences between hot and cold ground water systems on either side of this layer. A precipitation of this kind may thus exert an influence upon flow rates of thermal waters to the surface and the magnitude of this influence depends on water temperatures. This may also cause upflow zones to be narrower or more confined when water temperatures above about 150°C than at lower temperatures. It is worth considering these effects upon location of drillholes in the low temperature areas.

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CAPTION TO TABLES

Table 1 Analyses of representative samples of thermal water from the low temperature areas. Concentrations in ppm.

Table 2 Comparison of silica temperatures of thermal waters waters with their actual temperatures when the silica temperature has been influenced by mixing with cold ground water.

<u>TABLE 1</u>

	Temp. °C	pH/°C	SiO_2	Na^+	K^+	Ca^{++}	Mg^{++}	CO_2 total	SO_4^{--}	H_2S	Cl^-	F^-	Diss. solids	Silica temp. °C
1 Reykjavík, drillhole G.4	146	9.2/99	183	62.2	2.5	1.9	0.03	9.4	36.3	0.3	32.7	1.4	369	123
2 Seltjarnarnes, drillh.1	92	8.9/83	110	271.5	5.9	60.8	0.04	4.5	105.6	<0.1	426.0	0.8	1111	92
3 Deildartunga	99	9.70/13	143	75.3	2.2	3.4	0.03	13.5	71.0	1.7	32.7	2.5	358	140
4 Varmaland	82	9.51/13	113	88.8	2.5	9.0	0.07	5.4	73.4	<0.1	85.6	2.0	404	104
5 Lýsuhóll, drillhole 1	40	6.5/40	187	414.0	31.1	46.0	26.6	1518	27.4	<0.1	101.0	4.0	1670	174
6 Saelingsdalur	62	9.50/25	79	57.5	1.3	4.0	<0.01	21.5	62.1	0.7	9.5	1.2	222	78
7 Reykhólar, drillhole 1	96	9.63/25	135	69.5	1.9	3.6	0.02	24.7	42.7	0.8	31.5	1.1	325	130
8 Reykir in Hrútafjördur	98	7.98/70	123	224.0	8.6	68.0	0.04	19.0	219.6	0.3	307.0	2.4	1020	120
9 Reykjarhóll, Bökkum	75	9.00/75	144	73.0	2.4	2.4	0.09	21.5	50.2	0.7	32.9	0.6	356	108
10 Varmahlíd	88	8.90/80	126	73.5	1.9	1.6	0.04	26.5	50.4	<0.1	27.6	2.2	339	103
11 Stekkjarflatir	35	10.12/12	43	30.0	0.6	1.6	0.03	17.0	5.6	<0.1	6.3	0.3	115	35
12 Ólafsfjördur	56	9.70/55	58	39.0	0.8	1.8	0.06	11.5	5.3	<0.1	2.9	0.1	150	53
13 Laugaland	88	8.96/80	130	55.5	1.6	2.0	0.02	24.0	31.3	0.2	13.7	0.6	288	97
14 Hveravellir, Reykjahverfi	98	9.41/25	179	56.0	2.2	1.7	0.01	31.4	60.5	1.2	10.0	1.6	345	152
15 Flúdir	100	8.4/99	156	76.2	2.2	2.0	0.04	43.1	61.3	1.3	15.6	1.6	398	151
16 Sydri-Reykir	99	8.6/99	206	88.0	4.7	2.6	0.03	22.4	53.2	0.9	51.8	2.6	437	162
17 Eyvík	51	7.5/51	155	181.7	12.3	7.2	13.2	389.1	41.9	<0.1	79.2	1.7	726	162
18 Selfoss	92	8.2/79	81	172.0	5.1	31.4	0.10	19.3	56.4	0.2	272.8	0.8	667	93

TABLE 2

	Temp. of hot water 80°C. Eq. with chal.					Temp. of hot water 120°C. Eq. with qtz.					Temp. of hot water 160°C. Eq. with qtz.				
Fraction of hot water with mixture	t_1	t_2	t_3	SiO_2	pH	t_1	t_2	t_3	SiO_2	pH	t_1	t_2	t_3	SiO_2	pH
1.0	80	80	80	78	9.50	120	120	120	98	9.50	160	160	160	196	9.50
0.8	65	71	74	65	9.35	97	109	112	81	9.38	129	143	148	159	9.45
0.6	50	61	68	51	9.02	74	99	105	63	9.15	98	132	136	122	9.35
0.4	35	48	58	37	7.80	51	85	95	45	8.12	67	113	121	84	9.08
0.3	28	41	50	31	7.38	40	75	86	37	7.54	52	100	112	66	8.68
0.2	20	34	40	24	7.23	28	66	74	28	7.28	36	87	97	47	7.75
0.0	5	15	16	10	7.00	5	16	16	10	7.00	5	16	16	10	7.00

t_1 temperature of water after mixing

t_2 silica temperature assuming no influence of dissociated silica

t_3 silica temperature derived from the pH and the silica content of the mixture

The following assumptions were made for compositions before mixing:

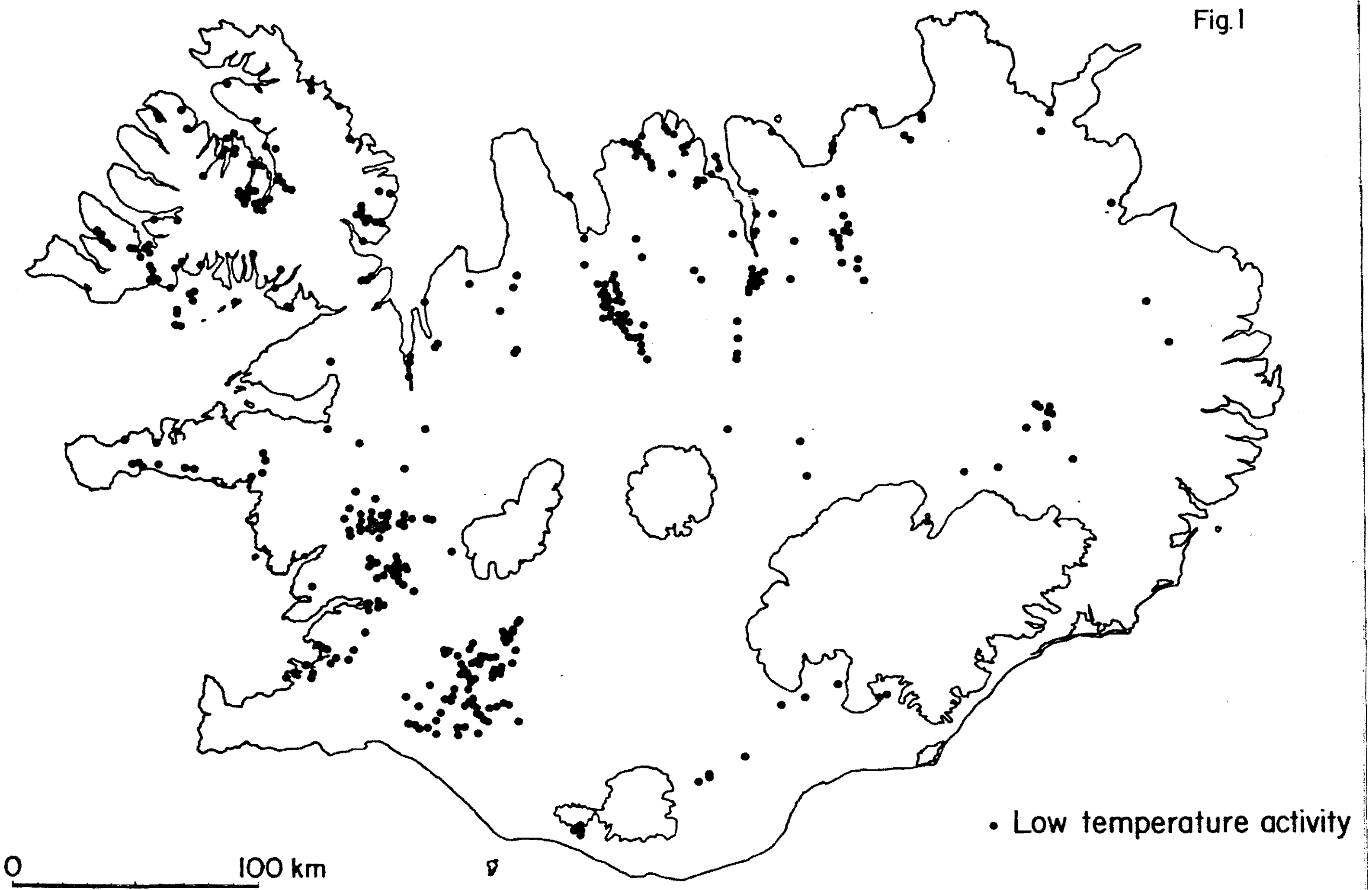
Cold water: 10 ppm SiO_2, 66 ppm CO_2 (total), pH 7.0 at 20°C.

Hot water: silica corresponding to chalcedony or quartz equilibrium, 22 ppm CO_2 (total), pH 9.5 at 20°C. All calculations refer to temperatures of 20°C.

CAPTION TO FIGURES

Fig. 1	Distribution of Low Temperature Activity in Iceland.
Fig. 2	Location of Sample Points of Selective Analyses in Table 1.
Fig. 3	Relation Between Sulphate Concentrations and Silica Temperatures.
Fig. 4	Comparison Between Measured Temperatures in Springs and Silica Temperatures.
Fig. 5	Comparison Between Measured Temperatures and Silica Temperatures in Deep Drillholes.
Fig. 6	Silica Temperatures in Selected Springs and Drillholes of the Low Temperature Areas.
Fig. 7	Relation Between Silica Temperatures, Flow Rates from Springs, and Age of Rocks.

Fig.1



J-ým Tnr 383 Fnr 11398

Fig.2

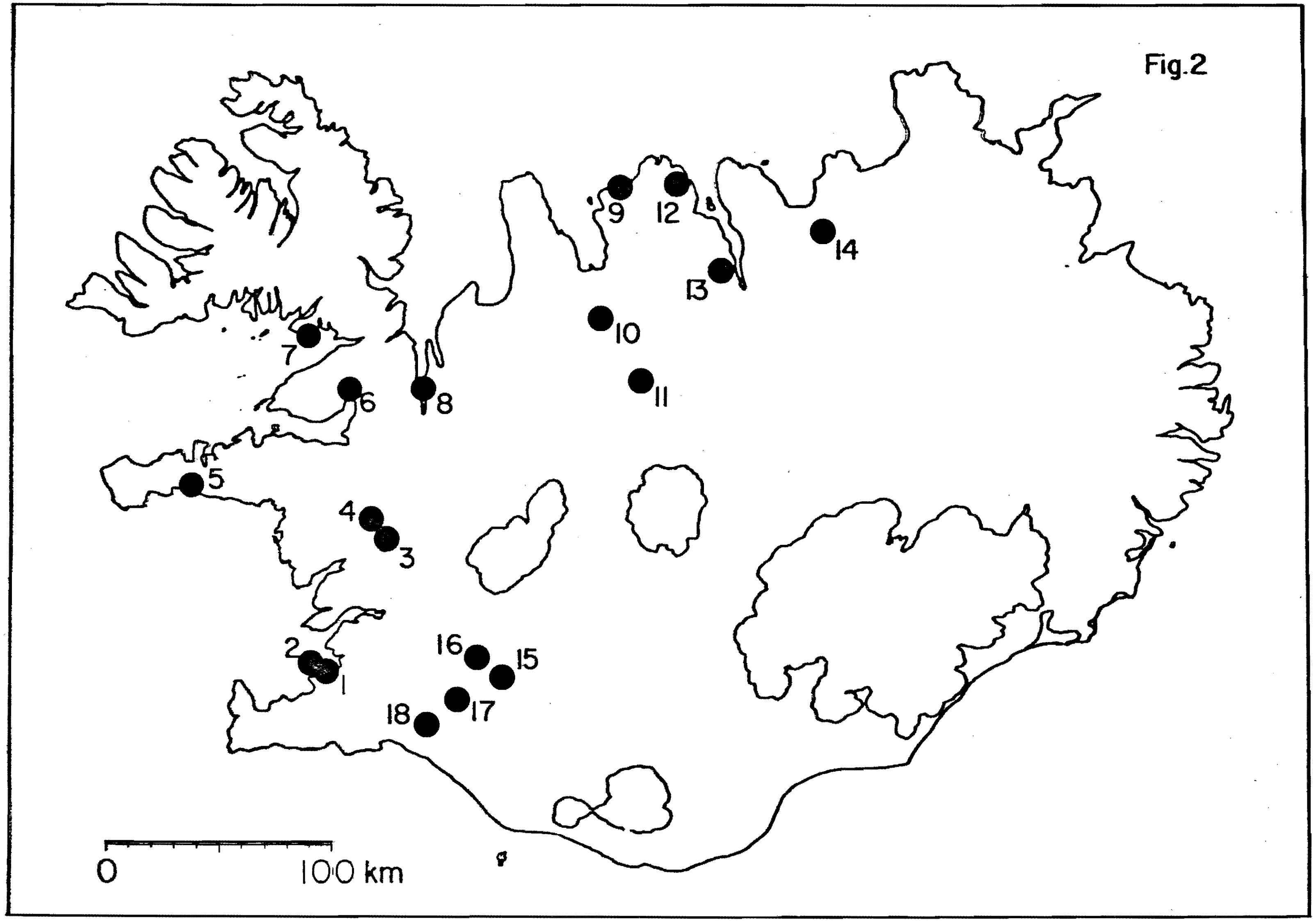
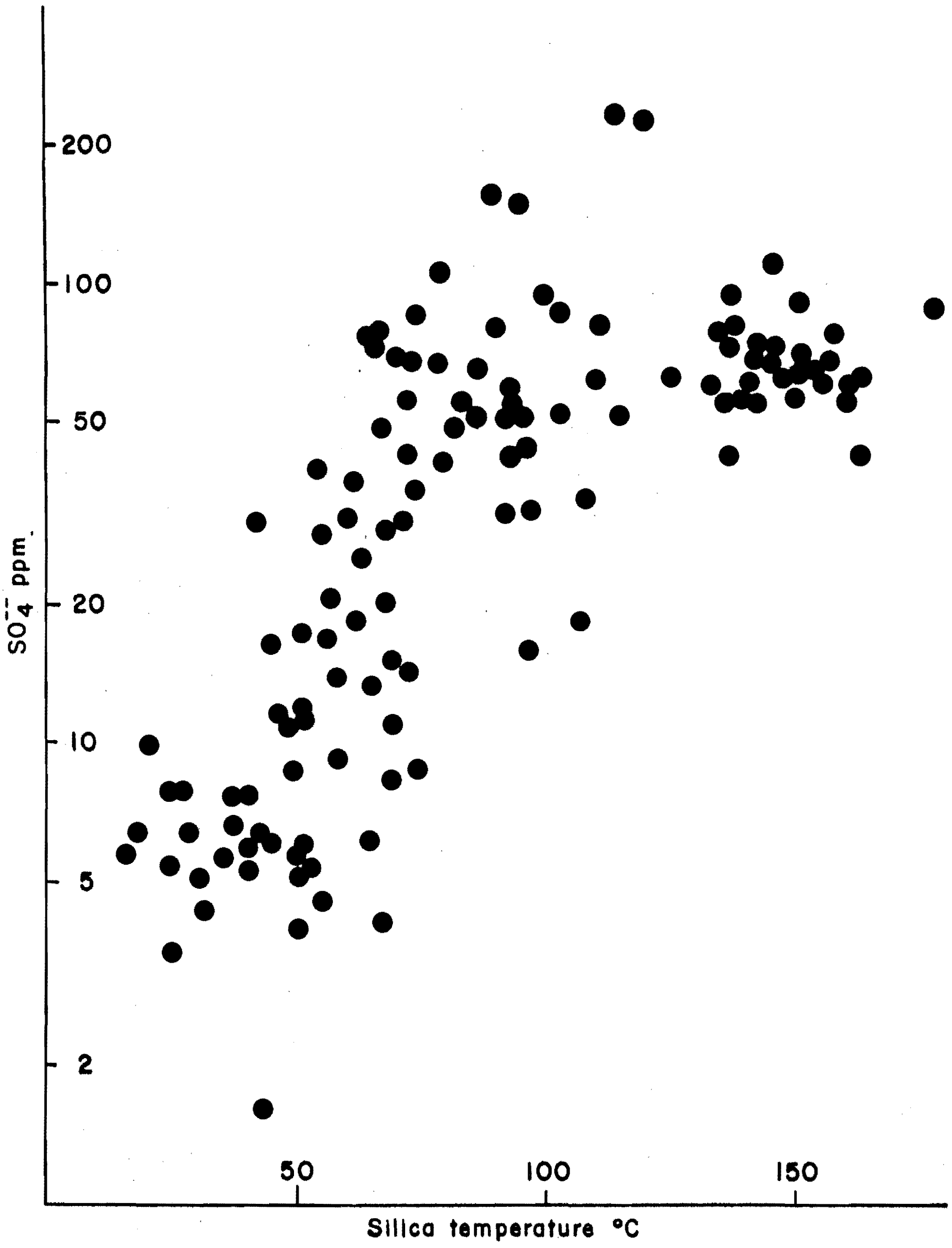


Fig. 3



J-Ým. Tnr.388, Fnr.11400

Fig. 4

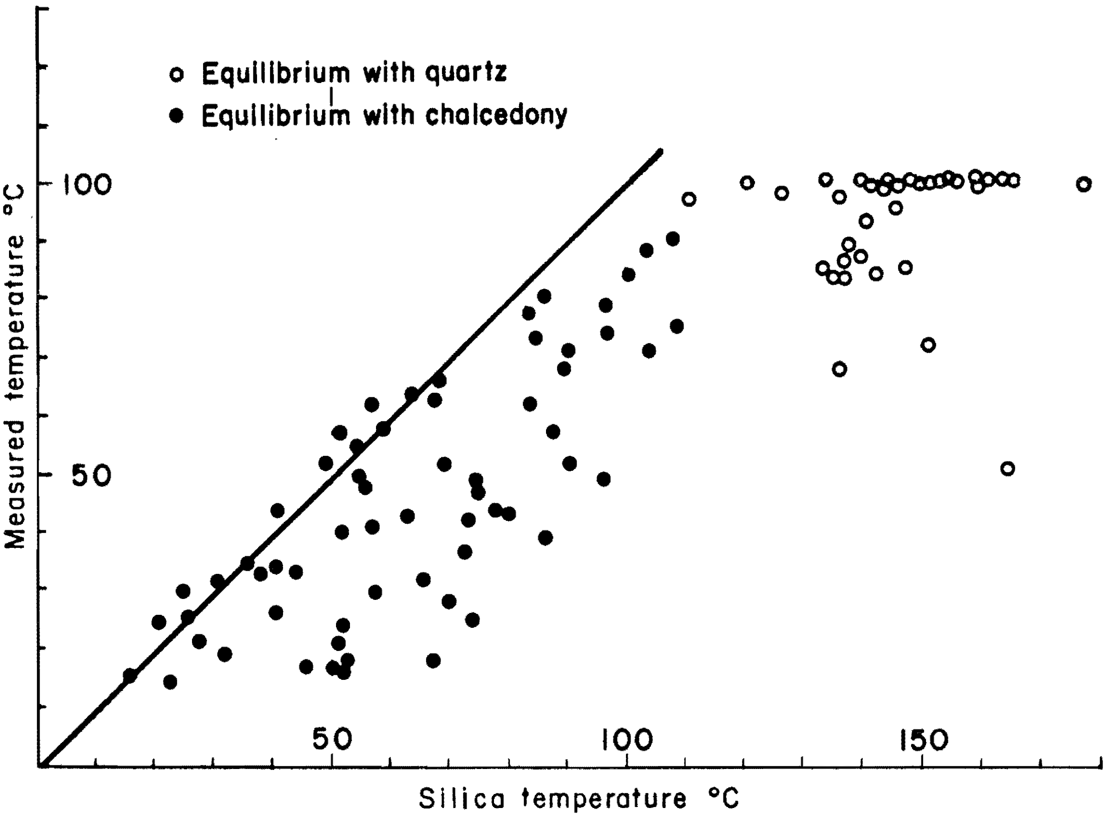


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Fig. 5

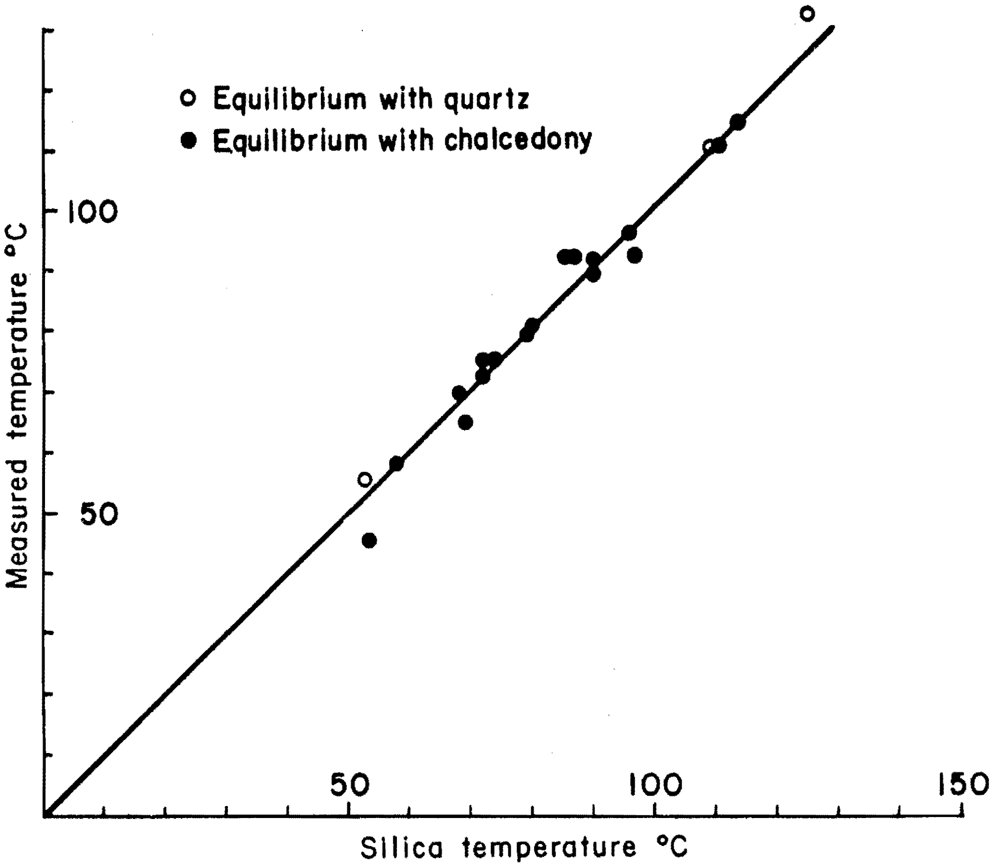

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Fig. 6

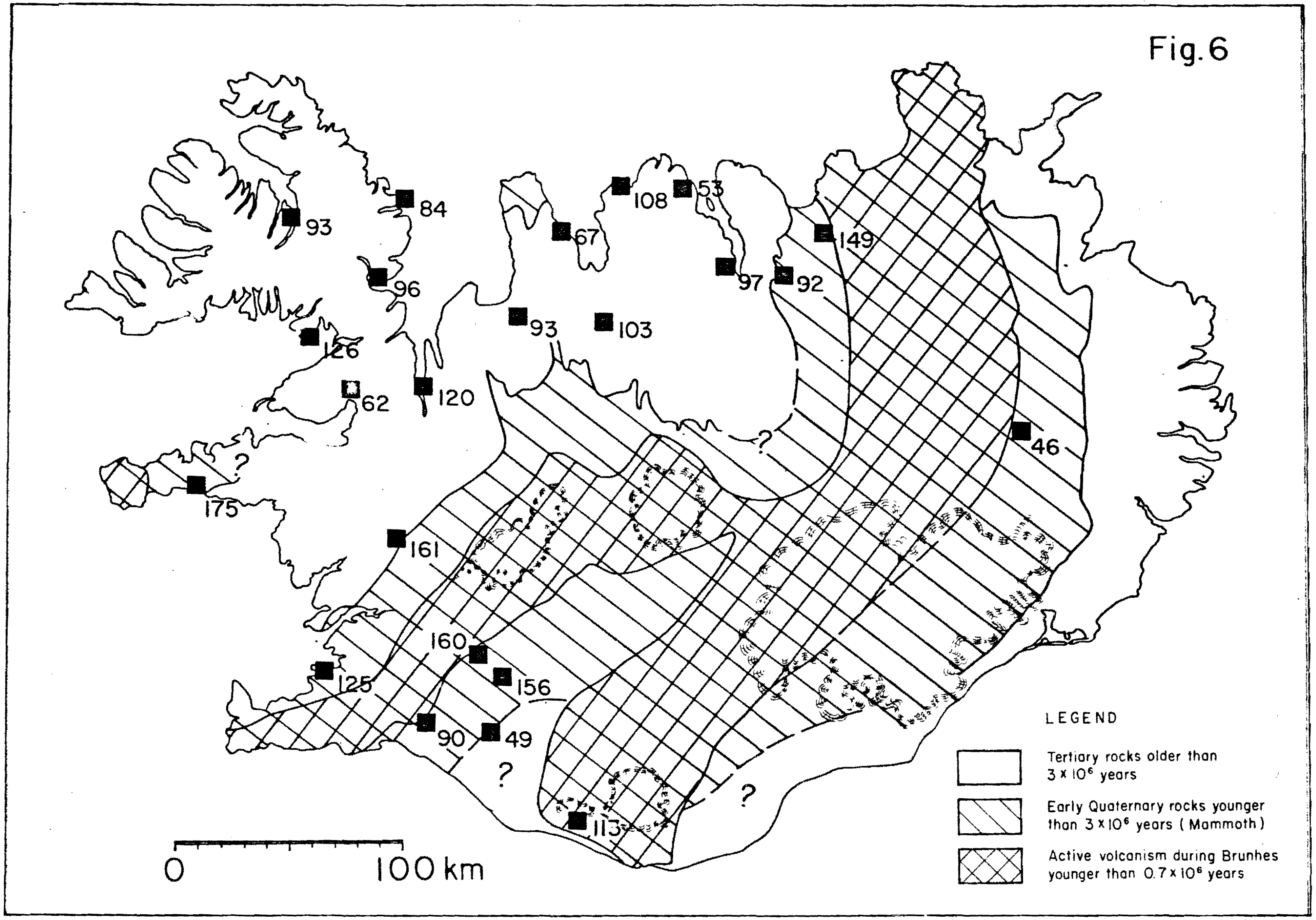
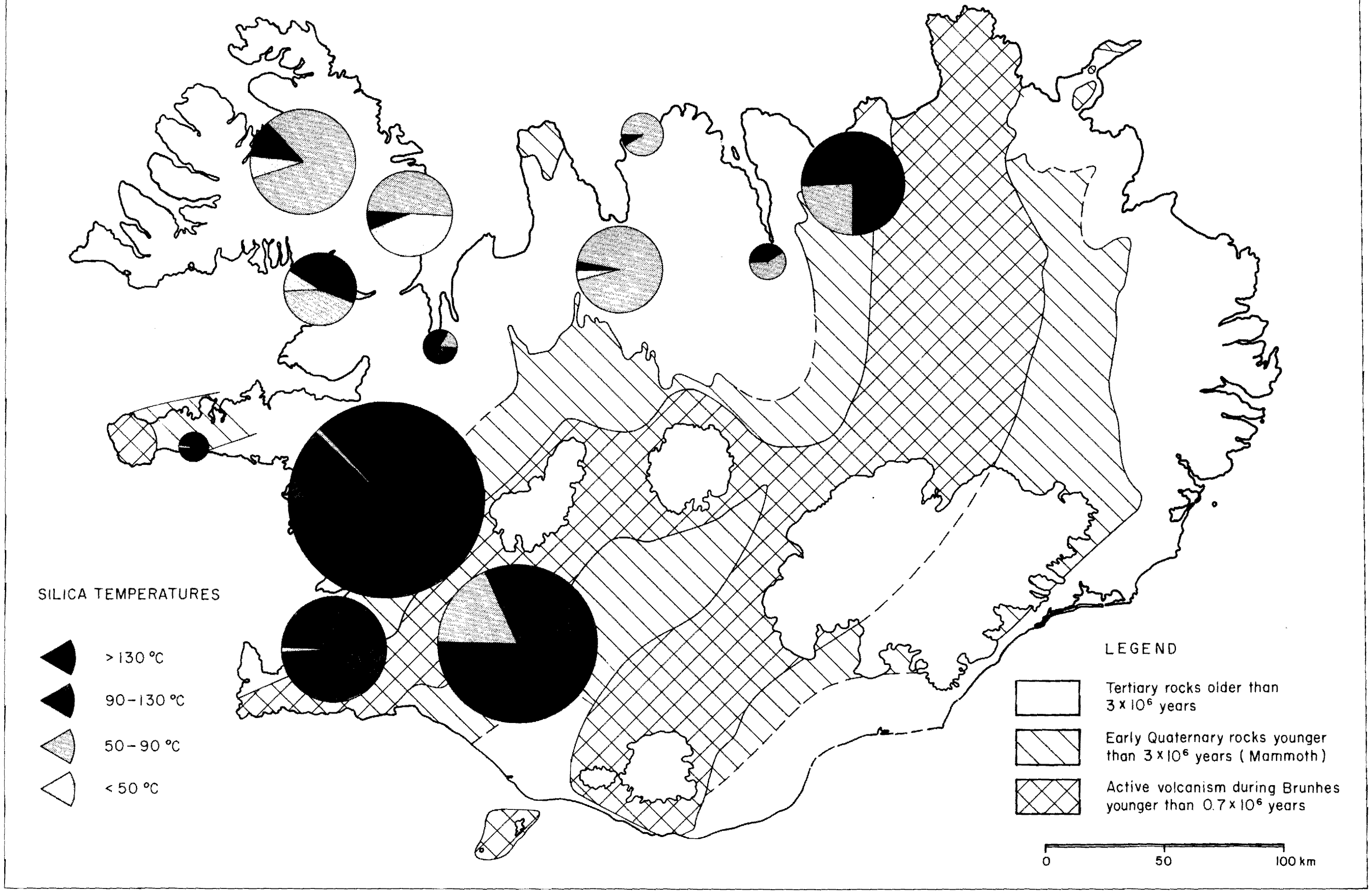

84
93
96
126
62
120
93
67
108
53
103
97
92
149
46
175
?
161
160
125
156
90
49
?
113
?
?
0
100 km
LEGEND
Tertiary rocks older than 3 x 10⁶ years
Early Quaternary rocks younger than 3 x 10⁶ years (Mammoth)
Active volcanism during Brunhes younger than 0.7 x 10⁶ years

Fig. 7



J-ým. Tnr. 335 Fnr. 10853

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