Thermal condition of Surtsey

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ABSTRACT

The results of temperature measurements performed in a borehole drilled on Surtsey in 1979 are presented. These results are used as the basis for a discussion of the thermal condition of Surtsey. The hypothesis that intrusions rather than pillow lavas are responsible for the excess heat content of Surtsey is favored, but it is concluded that the 13 meter thick dike complex found in the drill core is not sufficient to explain the thermal condition of the island. An average thickness of intrusions of at least 20 meters is needed. It is demonstrated that the heat transfer in Surtsey has been dominated by hydrothermal convection and that the system is vapor dominated above sea level. The permeability of the altered tuff in a 40 meter thick section below sea level is estimated to be 2.5×10^{-13} m^2. The permeability of the unaltered tuff above sea level is estimated to be about 1.4×10^{-10} m^2.

INTRODUCTION

During the summer of 1979 a 181 m deep, continuously cored, borehole was drilled on the newly formed island of Surtsey (Jakobsson & Moore 1980). The drill site is located about 150 m east of the center of the tephra crater Surtur I, as shown on Figure 1, at 58 m above sea level. The drilling was a joint project of the Icelandic Museum of Natural History and the United States Geological Survey. The drilling was performed by the Icelandic State Drilling Contractors. It is assumed that the hole bottom is within a few meters of the old sea floor, but the drilling had to be terminated at a depth of 181 m because of very loose material encountered at that depth.

The purpose of the drilling was to obtain a continous core (4.7 cm diameter) for the investigation of the structure of the island and the hydrothermal alteration of the tuff formed during the initial phase of the Surtsey eruption. The core has been described by Jakobsson & Moore (1982) and a simplified presentation of the lithology observed in the core is given in Fig. 2.

The drill hole makes it possible to study the thermal conditions within the island. The results of temperature logging performed by the Icelandic National Energy Authority (NEA) in

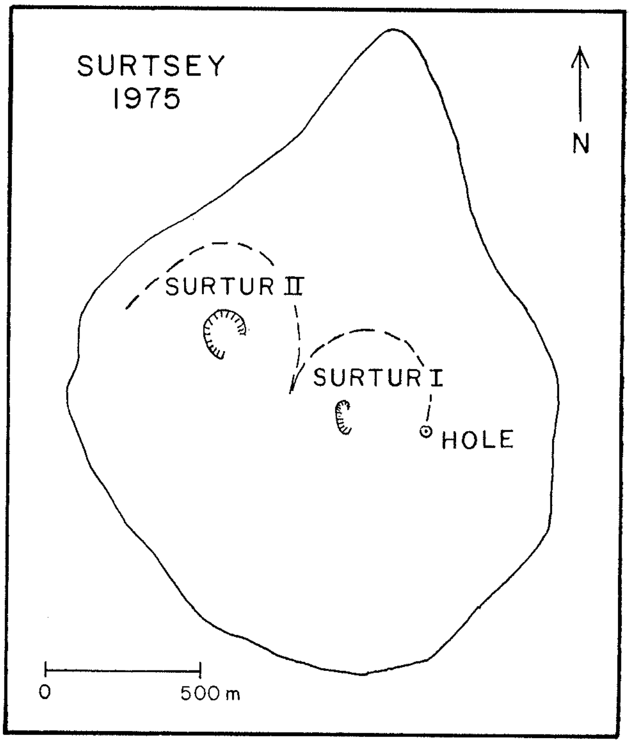

Fig. 1. A map of Surtsey showing the location of the borehole.

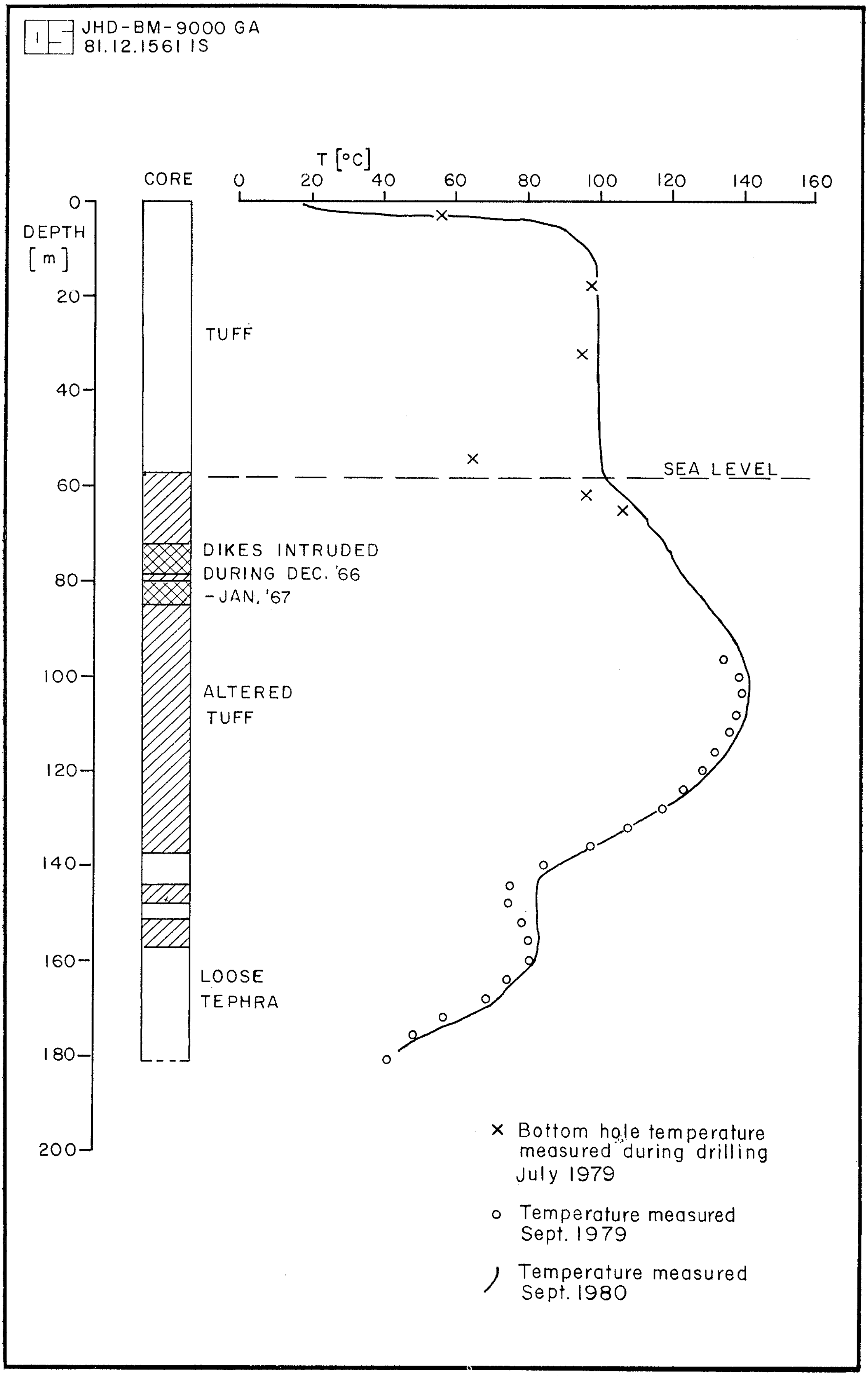

Fig. 2. The results of the temperature measurements of July and September 1979 and of September 1980, along with a simplified representation of the core lithology.

1979 and 1980 are reported in this paper along with attempts at interpretation.

MEASUREMENTS

Temperature logging was performed in the Surtsey borehole, by the NEA, at two different periods.

On the 26th of September 1979, 40 days after the drilling was completed, two temperature measurements were attempted. The first measurement, which was done with a thermistor mounted on an electrical cable, has been disregarded due to technical difficulties during the measurement. The second measurement of September 1979 was done by using a Kuster temperature gauge, and the temperature was measured every 4 m below 90 m depth. The results are shown in Figure 2.

A later temperature measurement was run on the 9th of September 1980. This measurement was performed with a platinum sensor mounted on a logging cable with a TEFZEL insulation. The resistivity of the platinum sensor was measured with a high impedance ohmmeter (Fluke 8022A Multimeter). The accuracy of the measurement is within ±0.5°C, and uncertainties in the calibration are less than 0.02°C. The temperature profile of September 1980 is shown in Fig. 2. Most of the following interpreations are based on this profile.

INTERPRETATION

General aspects

The temperature profile from the Surtsey borehole immediately shows several interesting features.

- The temperature is relatively high, having a mean value of 105°C.
- The absolute temperature and the temperature gradient vary substantially between different intervals in the hole.
- The maximum temperature, 141.3°C, is observed at 105 m depth, well below sea level, whereas the temperature decreases from that depth to the bottom of the hole, where the temperature is 40°C.

In the interpretation of the temperature profile observed in the hole the shape of the profile as well as the absolute temperature can be utilized.

An almost constant temperature of 100°C is measured between 15 m depth in the hole and mean sea level at 58 m. This results from boiling conditions at sea level. Since the observed temperature might only reflect the temperature inside the borehole it can not be concluded, from the temperature log alone, whether 100°C is the characteristic temperature of the tuff formation in this interval (Stefánsson & Steingrímsson 1980). However, bottom hole temperatures were measured (with a thermistor) intermittently during drilling. These measurements indicate a steep increase in temperature from the surface down to 15-20 m depth (Fig. 2), where a temperature of approximately 100°C is observed. Furthermore the temperature at 1 m depth at a site approximately 100 m from the site of the drillhole was 100°C in August 1970 according to Jóhannesson (1972). The above observations indicate that the interval between 15 m and 58 m is characterized by boiling. Thus the heat transport in that interval is dominated by one-dimensional convection, where the steam phase is rising and the condensate moving downwards. Convective heat transfer has previously been suggested by Jakobsson (1972 and 1978).

A zero temperature gradient is also observed in the interval between 142 and 159 m depths. As the thermal gradient is negative in adjacent regions, a convective zone is not possible. It is considered likely that this results from heat advection through a highly permeable layer in connection with the ocean.

Furthermore, the temperature decreases from 160 m depth down to the contact between the island and the old sea floor. It seems likely that there is another highly permeable layer at the

TABLE I

Estimates of the changes in temperature with depth, for various intervals in the borehole.

Interval	ΔT/ /ΔZ	Comments
0—20 m	5—15°C/m	Bottom hole temperature during drilling
0—58	1.5	Temperature log of September 1980
15—58	0.06	Temperature log of September 1980, constant gradient
58—72	1.4	Temperature log of September 1980, constant gradient
130—140	—2.6	Temperature log of September 1980, constant gradient
170—180	—2.8	Temperature log of September 1980, constant gradient

contact cooling Surtsey from below. This hypothesis is supported by the loose material encountered when drilling below 176 m depth. At the present the maximum temperature in the Surtsey borehole is observed at 105 m depth which is near the center of the tuff/tephra pile.

Two measurements of the thermal conductivity of the Surtsey tuff have been performed yielding values of about 1 J/ms °C for the wet tuff (Lachenbruch, personal communication). Based on the fact that the conductivity of steam is more than an order of magnitude lower than that of water we will assume a value of 0.5 J/ms °C for the material above sea level, whereas the value 1 J/ms°C will be used below sea level. Oddsson (1982) estimates the porosity of the Surtsey tuff and obtains values between 30 and 50% and an average value of 40%. Oddsson also estimates the dry density of the tuff to be 1600 kg/m^3 on the average.

The heat source

Since it is virtually impossible that the present heat content of Surtsey is the heat leftover from the phreatic phase of the Surtsey eruption, stored in the tephra created during that phase, two hypotheses on the heat source of Surtsey have been proposed:

A. The surface thermal anomaly (Friedman & Williams 1970, Jakobsson 1972, Jóhannesson 1972) observed in Surtsey is the result of considerable amounts of pillow lava, from the initial phase of the Surtsey eruption, at the base of the island (Sigvaldason 1968, Jóhannesson 1978).

B. The thermal evolution of Surtsey results from intrusive activity during a late stage of the volcanic activity (December 1966 to January 1967) of the island (Jakobsson 1978, Jakobsson & Moore 1980).

No pillow lavas were cored in the borehole. However, a 13 m thick discontinuous dike complex was found at about 80 m depth (see Fig. 2).

We cannot exclude the possible presence of pillow lava in Surtsey on the basis of either the drill hole core or the temperature log, but the highly conspicuous cooling at the base of the island and the lack of pillow lava in the core indicate that a large body of pillow lava, on the old sea floor, is highly unlikely.

Based on these considerations we are tempted to propose intrusions as the main source of heat for the present temperature distribution in the vicinity of the Surtsey borehole. These intrusions were probably formed during the period of effusive activity of the crater Surtur I, from August 19th, 1966 to June 5th, 1967. During December 1966 to January 1967 several fissures opened inside and north of the crater Surtur I, a few of them erupting small amounts of lava (Thorarinsson 1968). It is believed that the intrusive activity occurred at the same time. In late 1968 heat was observed in the tephra north of Surtur I (Friedman & Williams 1970), and this heat flow has continued up to the present (Friedman et al. 1976, Jakobsson 1978, Jóhannesson 1978).

We can introduce a very simple one dimensional model to estimate the effects of the intrusions found in the core. In this model the following parameters are used:

h_t = the thickness of the tuff = 170 m
h_i = the thickness of the intrusions = 10 m
T_i = the initial temperature of the intrusions = 1100°C
C_i = the heat capacity of the intrusions = 1000 J/kg°C
ϱ_i = the density of the intrusions = 3000 kg/m^3
Φ = the average water content of the tuff 0.3 m^3/m^3
C_t = the average heat capacity of the tuff = $4200\Phi + 800(1-\Phi) = 1800$ J/kg°C
ϱ_t = the density of the tuff = 1900 kg/m^3

If we assume the system to be closed (no heat loss) we can estimate the equilibrium temperature change of the tuff by

$$\Delta T = \frac{h_i C_i \varrho_i T_i}{h_t C_t \varrho_t} \tag{1}$$

This equation gives a temperature change of approximately 60°C, an upper limit since all heat loss is neglected. The fact that this estimate is much lower than the present average temperature of the tuff, indicates that a greater total thickness of intrusive material is needed to explain the heat content of the island, in the vicinity of the borehole, or that the initial temperature of the tuff was at least 45°C.

We can use the same simple approach to estimate the volume of intrusions needed to explain the average temperature, assuming the initial temperature to have been 5°C. Before we do that the heat lost from the island (in the vicinity of the hole) should be estimated. This can be done by the equation for heat conduction

$$Q = k\,dT/dz \tag{2}$$

where

Q = heat flow per unit area, per unit time
k = thermal conductivity
dT/dz = temperature gradient

and by utilizing the data in Table I.

We estimate the heat loss through the surface by assuming the near surface heat transport to be mainly conductive, even though convection is clearly important at other depths as can be seen later, and by using the temperature gradient of the uppermost 20 m (Table I) measured during drilling.

$$dT/dz = 15°C/m$$

and

$$k = 0.5 \text{ J/ms°C}$$

We obtain the present value

$$Q = 7.5 \text{ W/m}^2$$

Several observation (Friedman et.al. 1976, Jakobsson 1978, Jóhannesson 1978) inticate that this heat flow has been decreasing for the last 9 years. We will therefore assume the average conductive heat flux to have been twice this value, or 15 W/m^2, for the last 13 years.

The above assumption of pure conduction in the uppermost meters may not be valid since the annual precipitation in the Vestmannaeyjar area amounts to 1400 mm (Einarsson 1978). Less than 700 mm of the precipitation will evaporate (Einarsson 1972) and some of it will flow to the ocean. If we assume that 25% of the annual rainfall in the vicinity of the hole is vaporized we can account for this in the energy balance by raising the above heat flow estimate to about 30W/m^2. The present estimate of 7.5 W/m^2 is however an approximate lower limit which will be used later. It is noteworthy that the deuterium content of four samples of water vapor from Surtsey (Jakobsson 1978) is indicative of both sea water and meteoric origin. We estimate the heat lost by advection between 140 and 160 m by using

$$dT/dz = -2.6°C/m \text{ (Table I, 130–140m)}$$

and

$$k = 1.0 \text{ J/ms°C}$$

and obtain

$$Q = 2.6 \text{ W/m}^2$$

And the heat lost at the base of the island is similarily estimated to be

$$Q = 2.8 \text{ W/m}^2$$

Consequently we estimate the total heat loss to have been

$$Q \simeq 35 \text{ W/m}^2$$

on the average for the last 13 years, in the vicinity of the borehole. Or a total heat loss of

$$35 \text{ W/m}^2 \cdot 13 \text{ years} = 1.4 \times 10^{10} \text{ J/m}^2.$$

This value is only about 25% of the present heat stored in the tuff formation. This paradoxical result indicates that the considerable heat flow of 35 W/m^2 has not significantly influenced the thermal conditions of the formation around the hole.

Taking this heat loss into account we can now estimate approximately the volume fraction (χ) of intrusions needed to explain the average temperature observed in the hole. We obtain

$$\chi \simeq \frac{C_t \Delta T \varrho_t + Qt/h_t}{C_i T_i \varrho_i + C_t \Delta T \varrho_t} \qquad (3)$$

with the same notations as before and

$$\Delta T = 100°C$$

$$t = 13 \text{ years}$$

Equation (3) gives $\chi = 0.12$, or $h_i = 21$ m compared with the 10 m observed in the borehole. Since the heat loss estimated is only about 25% of the heat content, χ is not very sensitive to uncertainties in Q.

Thus the results of the above estimate are that the excess heat content of Surtsey can be explained if about 12% of the volume of the formation, in the vicinity of the borehole, is intrusive material. Or in other words intrusions having a mean total thickness of about 20 m. If we take the area of the surface thermal anomaly around Surtur I in 1976 (0.2 km^2 based on Jakobsson 1978) to be the surface area of the intrusions we obtain a volume of very roughly 0.004 km^3.

So far the results have been based only on the observed mean temperature. The location of the temperature maximum is also of interest. It is located about 25 m below the intrusions found in the hole. This could result if the temperature is constant in time at the top and the bottom of the system. In Surtsey the temperature is constant at 58 m depth (sea level) and most likely at 144 m depth (see Fig. 2 and p. 104).

Consider a simple heat conduction model (for the theory of heat conduction see (Carslaw &

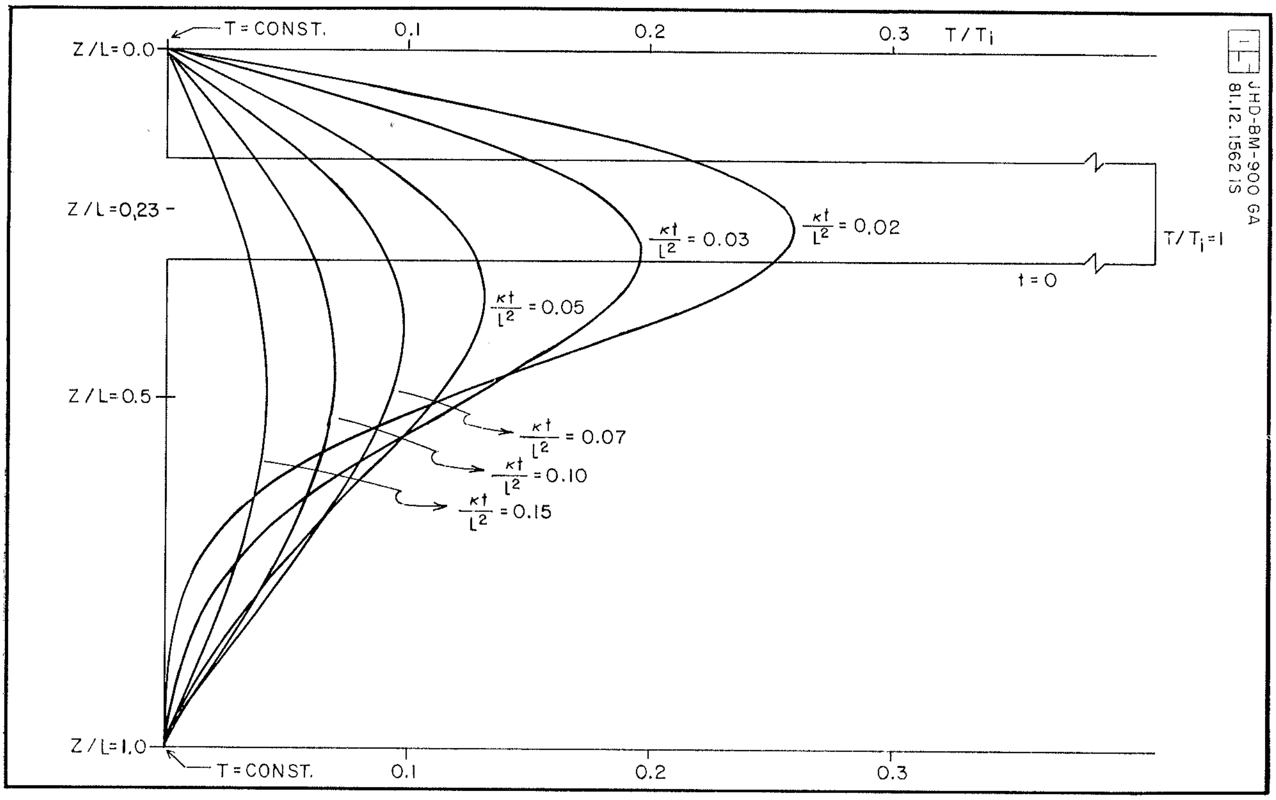

Fig. 3. The temperature distribution around an intrusion according to a simple heat conduction model.

Jaeger 1947) where a 1100°C hot intrusion of thickness d is emplaced asymmetrically in a layer of cold tuff of thickness l, at the time t = 0. The temperature is kept constant at the upper and lower boundaries of the tuff. Figure 3 shows the time evolution of the temperature distribution. It can be seen that the temperature maximum will migrate, by thermal conduction, to the center of the interval, regardless of the distribution of intrusions.

According to this model the temperature maximum in Surtsey should end up at 101 m depth. In 1979 and 1980 it is actually observed at 105 m depth. If the distribution of intrusions with depth in the formation near the hole is irregular the temperature distribution observed should be obtained when

$$\frac{\varkappa t}{l^2} \simeq 0.15 \qquad (4)$$

where

$\varkappa$ = thermal diffusivity = $k/\varrho c$
t = time since intrusive activity
l = thickness of tuff,

according to the above heat conduction model (Fig. 3).

Equation (4) can be used to estimate the effective diffusivity for the heat transport from the intrusions to the tuff formation. Using t = 13.5 years and l = 90 m we obtain $\varkappa_{\mathrm{eff}} \simeq 3 \times 10^{-6}$ m^2/s. In the case of pure heat conduction the diffusivity for the tuff equals $\varkappa_{\mathrm{cond}} = 3 \times 10^{-7}$ m^2/s. This indicates that conduction has not been the only mode of heat transfer below sea level in Surtsey, but that convection has been far more important.

Mode of heat transfer

The so-called Nusselt number is often employed in discussions of heat transfer. It is defined as the ratio between the total heat flux and the heat transferred by conduction alone (Elíasson 1973), that is

$$\mathrm{Nu} = \frac{Q_{\mathrm{total}}}{Q_{\mathrm{conduction}}} \qquad (5)$$

We can now use the above estimate of the effective diffusivity (p. 106) to estimate roughly the average Nu number over the last 13½ years, for the interval between 58 and 144 m. As an approximation.

$$\mathrm{Nu} \simeq \frac{\varkappa_{\mathrm{eff}}}{\varkappa_{\mathrm{cond}}} = 10.$$

We estimated previously that the minimum heat flux to the surface, in the vicinity of the Surtsey borehole, was presently of the order 7.5 W/m^2. Using the temperature gradient between 58 and

72 m in Table I, $k = 1.0$ J/ms°C and equation (2) we estimate the heat flux by conduction to be 1.4 W/m² in that interval. Assuming the heat flux in this interval to be the same as through the surface we can estimate the corresponding Nusselt number to be

$$\mathrm{Nu} \simeq \frac{7.5\ \mathrm{W/m^2}}{1.4\ \mathrm{W/m^2}} = 5$$

at the present. This present value is in good agreement with the value of 10 obtained above, as that value represents an average for the 13.5 year thermal history, whereas the value $\mathrm{Nu} = 5$ is valid for the present thermal conditions in the interval just below sea level. In a similar way we can use the estimated heat flux through the surface of 7.5 W/m² to estimate the Nusselt number in the zone above sea level, by estimating the conductive heat flux in the interval 0—58 m to be

$$Q = k\Delta T/\Delta Z$$

with

$$k = 0.5\ \mathrm{J/ms^\circ C}$$

and

$\Delta T/\Delta Z$ from Table I

we obtain

$$\mathrm{Nu} \simeq 10$$

This value should represent the present thermal conditions above sea level and corresponds to the value $\mathrm{Nu} \simeq 5$ for the interval 58—72 m below sea level. Note that the thermal conductivity is assumed higher below sea level than above by a factor of 2.

The surface heat flux estimate was raised earlier to 30 W/m² in an attept to account for the energy lost in heating and vaporizing some of the precipitation. If we use this value instead of the minimum value of 7.5 W/m² we obtain $\mathrm{Nu} = 40$ for the interval 0—58 m. This value is very high compared to most values presented elsewhere (Elder 1966, Elíasson 1973, Sondergeld & Turcotte 1977, Garg and Kassoy 1981) and not in agreement with the Nusselt number obtained from the effective diffusivity above. This seems to indicate that the precipitation does not influence the vertical heat transfer in the vicinity of the Surtsey borehole significantly.

Permeability of the Surtsey tuff

It has been argued above that convection is the most important mode of heat transfer in Surtsey. Thermal convenction in a water saturated porous layer is initiated when a critical Rayleigh number is exceeded. In a horizontal layer of thickness h and with a temperature difference ΔT, the Rayleigh number is given by

$$\mathrm{Ra} = \frac{\alpha g\ \Delta T\ h\varrho^2\ C_p\ K}{\mu k} \tag{6}$$

where

α = coefficient of thermal expansion of fluid
g = acceleration of gravity
ϱ = fluid density
C_p = specific heat of the fluid at constant pressure
K = permeability of the rock
μ = dynamic viscosity of the fluid
k = thermal conductivity of the saturated rock

The critical value for a layer containing a single phase fluid having constant thermal properties equals $4\pi^2$. However, it has been shown that the critical Rayleigh number ($\mathrm{Ra_c}$) is lowered substantially when the variations of the thermal properties of water with temperature are taken into account (Straus & Schubert 1977). Figure 4 shows the results of Straus & Schubert (1977) on the relationship between $\mathrm{Ra_c}$ and the relative temperature difference, as presented by Garg & Kassoy (1981).

A relationship, for liquid water, between the Rayleigh and Nusselt numbers has been found empirically (Combarnous 1978) as well as theoretically (Garg & Kassoy 1981). Combining these results, the relationship can be expressed approximately

$$\mathrm{Ra} \simeq \mathrm{Nu} \cdot \mathrm{Ra_c} \tag{7}$$

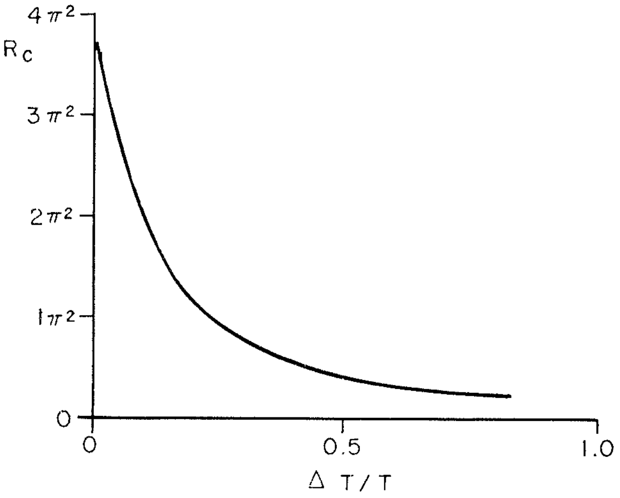

Fig. 4. The critical Rayleigh number as a function of the relative temperature difference (Garg & Kassoy 1981).

By using the previous estimate of the Nusselt number (p. 108), Fig. 4 and equations (6) and (7) we can estimate the permeability of the altered Surtsey tuff. Between the sea level at 58 m and 100 m depth, where we have estimated $\mathrm{Nu} \simeq 5$, there is a temperature difference of 40°C. By using Figure 4 we obtain $\mathrm{Ra}_c \simeq 10$ and by equation (7) we estimate the Rayleigh number to be approximately 50. Using the following parameters

$\alpha = 8 \times 10^{-4}\,{}^\circ\mathrm{C}^{-1}$
$\varrho = 940\ \mathrm{kg/m^3}$
$C_p = 4200\ \mathrm{J/kg^\circ C}$
$\mu = 2.4 \times 10^{-4}\ \mathrm{kg/ms}$
$k = 1.0\ \mathrm{J/ms^\circ C}$

and equation (6) we obtain

$K \simeq 2.5 \times 10^{-13}\ \mathrm{m^2} = 250$ milli darcy as an estimate for the permeability between 58 and 100 m depths in 1980.

This method can not be employed to estimate the permeability above sea level in Surtsey, since a relationship between the Ra and Nu numbers for two phase convenction is not known to us. If the interval between 15 and 58 m contained liquid water instead of a steam-water mixture we would expect (based on different temperature gradients and Nu numbers) the permeability there to be about 100 times higher (i.e. 25 darcy) than below sea level. However, the results of Schubert & Straus (1977) indicate that porous layers with steam water mixtures are more susceptible to convection than are those containing only liquid water.

An alternative method to estimate the permeability above sea level is to assume the convection to be purely one-dimensional. We assume that the heat flux to the surface is carried by rising steam which condenses near the surface, where a liquid cap is formed (Schubert & Straus 1979, Sheu et.al. 1979, Straus & Schubert 1981). By using the minimum heat flux estimate $Q = 7.5\ \mathrm{W/m^2}$ we can estimate the mean vertical velocity of the steam

$$V_s = \frac{Q}{l\,\varrho_s} \simeq 5.5 \times 10^{-6}\ \mathrm{m/s}$$

where

l = latent heat of vaporization of water $= 2.26 \times 10^6\ \mathrm{J/kg}$
ϱ = density of the steam $= 0.6\ \mathrm{kg/m^3}$

According to Darcy's law the velocity of the rising steam equals

$$V_s = \frac{\chi\,K}{\mu_s}\left(\frac{dp}{dz} - \varrho_s g\right) \tag{8}$$

where

χ = relative permeability of rising steam $\simeq 1$
K = permeability
μ_s = dynamic viscosity of steam
p = pressure

If we assume the pressure to be controlled by the steam phase we have

$$p = \varrho_s g z$$

and

$$\frac{dp}{dz} \simeq \varrho_s g - g\varrho_s\alpha_s\Delta T$$

And using equation (8) we can derive

$$K = \frac{V_s\,\mu_s}{\chi g \varrho_s \alpha_s \Delta T} \tag{9}$$

Now using

$V_s = 5.5 \times 10^{-6}\ \mathrm{m/s}$
$\mu_s = 1.2 \times 10^{-5}\ \mathrm{kg/ms}$
$g = 9.8\ \mathrm{m/s^2}$
$\varrho_s = 0.6\ \mathrm{kg/m^3}$
$\alpha_s = 3.3 \times 10^{-2}\ {}^\circ\mathrm{C}^{-1}$
$\Delta T = 2.5\ {}^\circ\mathrm{C}$

we obtain

$K = 1.4 \times 10^{-10}\mathrm{m^2} = 140$ darcy

for the permeability of the unaltered tuff above sea level in Surtsey. Whether the difference estimated between the permeabilities of the altered and unaltered tuff, by a factor of more than 500, is the cause for the different degree of alteration or the result thereof can not be confirmed at this point.

CONCLUSIONS

1. The fact that no pillow lava was found in the drill core of the Surtsey borehole and that substantial cooling is taking place at the base of the island favor the hypothesis that intrusions are responsible for the excess heat content of the formation around the hole rather than the hypothesis that the heat is the remainder of the initial heat in a hypothetical pillow lava.
2. The present heat content of the Surtsey tuff, in the vicinity of the borehole, can originate from intrusions with an average total thickness of roughly 20 m, compared to the 10 m of intrusions cored in the hole.

3. The heat transfer in Surtsey is dominated by hydrothermal convection, both above and below sea level. The interval above sea level is in fact considered to be a vapour dominated hydrothermal system. The heat transfer by convection is estimated to be up to ten times the heat flow by thermal conduction. The island is presumably cooled from below by advection.
4. The permeability of the altered Surtsey tuff between 58 and 100 m is estimated to be about 2.5x10^{-13} m^2 whereas the permeability of the unaltered tuff above sea level is estimated to be 1.4x10^{-10} m^2.
5. The observation that a large part of the original heat content of about 20 m of intrusions is still available in Surtsey, 13 years after the intrusive activity, puts a favorable perspective on the utilization of magmatic heat on Heimaey (Björnsson and Sigurgeirsson 1979) and elsewhere.

ACKNOWLEDGEMENTS

We thank Sveinbjörn Björnsson and Gudmundur Pálmason for critically reviewing the manuscript. Dr. A. H. Lachenbruch, at the U. S. Geological Survey, Menlo Park, is thanked for carrying out two thermal conductivity measurements of the drill core.

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