General Aspects of Thermal Activity in Iceland

S. ARNORSSON, J. JONSSON and J. TOMASSON

Iceland

Summary — Thermal areas in Iceland have been classified into high and low temperature areas. The high temperature areas are confined to the active volcanic belt, frequently associated with acid volcanic rocks. The low temperature areas are mainly situated in the Tertiary flood basalt areas. The total flow from thermal springs and drillholes is estimated at the present as some 2700 l/sec with an average temperature of roughly 120 °C. With few exceptions the Icelandic thermal waters are low in total dissolved solids in particular those elements not influenced by mineral equilibria with the wall rock. Most of the utilized thermal energy is used for domestic heating purposes.

General geology

Iceland is almost exclusively built up of volcanic rocks, mainly flood basalts with subordinate andesitic and rhyolitic rocks and minor intrusions of gabbro and granophyre. The oldest rocks exposed are basaltic lava flows of Tertiary age. These Tertiary rocks are confined to two areas: a) W. Iceland, the NW. Peninsula and the Middle N. Iceland and b) E. and SE. Iceland. (Fig. 1.)

The Tertiary rocks are separated by a zone of younger volcanics of Quaternary and Recent age, mainly basaltic tuffs, palagonite breccias, lava flows and pillow lavas. Within this area a zone of active volcanism crosses the country from NE. to SW. This volcanic belt forms the continuation of the rift zone of the Mid Atlantic Ridge. Another subordinate active volcanic area is situated on the Snaefellsnes Peninsula.

The volcanic zone is characterized by several central volcanoes, many linear volcanoes, and numerous faults and tectonic fissures. In S. Iceland they trend SW-NE. but in N. Iceland nearly N-S. The dominant type of volcano, the eruptive fissure, is as a rule closely connected with the tectonic fractures. The tectonic active zone is, however, much wider than the active volcanic zone (Stefansson, 1967).

In Quaternary and Recent times there appears to have been a certain periodicity in the volcanic and tectonic activity. (Jonsson, 1967).

Thermal activity

Thermal activity in Iceland is very widespread. Fig. 1 gives an impression of the distribution of the thermal activity. It should though be pointed out that it is impossible to map every spring or spring group on such a small scale map so the density of points gives no picture of the intensity of the activity in each area. For the energy output in each area the reader is referred to tables 1 and 2.

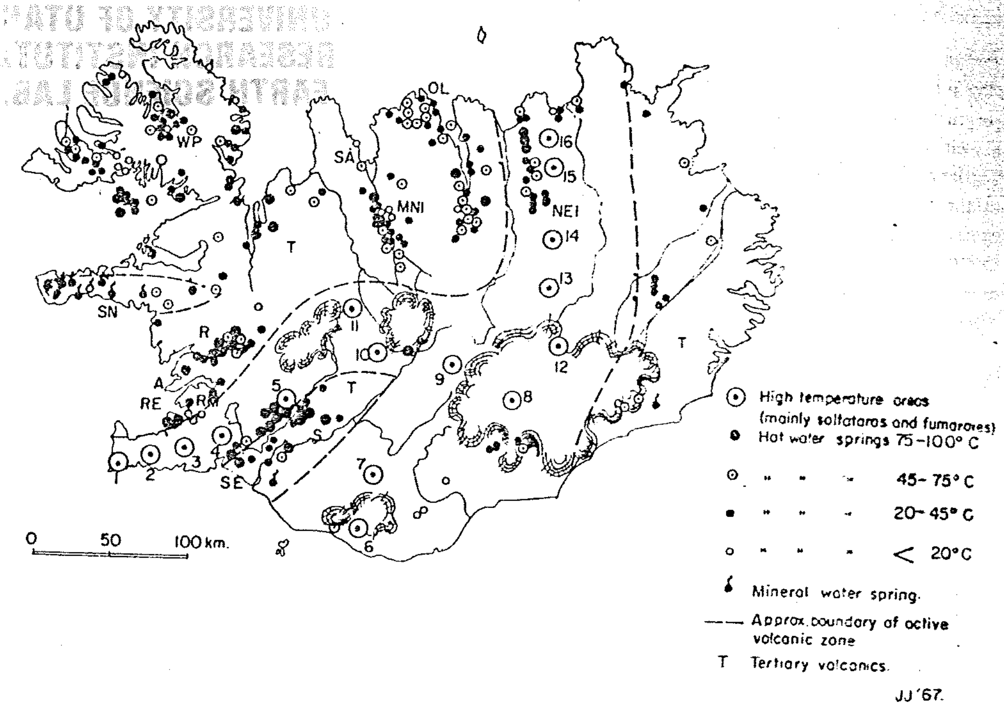

Fig. 1 — Mineral and thermal springs of Iceland 1 — Reykjanes-Eldvörp; 2 — Krysuvik--Trölladyngja; 3 — Brennisteinsfjöll; 4 — Hengill; 5 — Geysir Area; 6 — Solheimajökull (sub-glacial); 7 — Torfajökull; 8 — Grimsvötn (sub-glacial); 9 — Vonarskard; 10 — Kerlingarfjöll; 11 — Hveravellir; 12 — Kverkfjöll; 13 — Askja; 14 — Ketildyngja; 15 — Namafjall-Krafla; 16 — Theistareyikir
RE — Reykjavik; A — Akranes; R — Reykholtsdalur; SN — Snaefellsnes Peninsula; WP NW — Peninsula; SA — Saudarkrokur; OL — Olafsfjördur; MNI — Middle N. Iceland; NEI — NE Iceland; SE — Selfoss; RM —Reykir Mosfellssveit

Two types of thermal areas have been recognised in Iceland (Bödvarsson, 1961); hig temperature areas and low temperature areas. It is relatively easy to define geographically a high temperature area but this is difficult and sometimes impossible for the low temperature thermal activity. In this article four geographically distinct high temperature areas two and two of which are closely connected are considered at two (areas 3 and 15 on Fig. 1) although previously considered as four (Bödvarsson, 1961). Furthermore one area (5, Fig. 1) classified by Bödvarsson (1961) as borderline case between high and low temperatures areas is here considered as truly high temperature on the basis of the high silica content in the surface springs waters.

The present authors agree with Bödvarsson (1961) that no well defined limits exist between high and low temperature activity although area 5 on Fig. 1 is not considered as borderline case between the two. On the other hand the northwesternmost part of the Southern Lowland presents probably such a borderline case.

Bödvarsson (1961) favoured to distinguish high and low temperature areas on the basis of base temperature. The concept of base temperature is based on a hydrothermal model where all the thermal water is considered to be of meteoric origin and that it becomes heated by contact with hot rock. The highest temperature reached by the water during its deep circulation is defined as its base temperature. Present data suggest that subsurface temperatures exceed 200 °C at depths of less than 1000 m in high temperature areas but are generally less than 150 °C at similar depths in low temperature areas.

Table 1 — Natural surface discharge in the main low temperature areas

Area	Total flow l/s	Max. surface temp. °C	Remarks
Southern Lowland	330	100	Many shallow drillholes Total discharge 35 l/s
Reykholtsdalur	300	100	
NW. Peninsula	250	100	One drillhole in the largest group of springs issues 20 l/s
Middle N. Iceland	130	89	One deep drillhole at Laugaland (1080 m), issues 8 l/s, temp. 93° C
NE. Iceland	145*	100	
Other areas	50+		
Total	1205		

* Source: Bödvarsson (1961)
+ Rough estimate

Table 2 — Total discharge from drillholes in thermal areas in Iceland

Area	Total flow l/sec	Max. temp. ° C	Surface manifestation of thermal activity	Remarks
Reykir, Mosfellssveit	290	88	Many surface springs, flow substantial, temp. 83° C	70 drillholes, max. depth 1200 m, mostly natural flow.
Reykjavik	360	146	Surface springs, flow 11 l/sec., temp. 88° C	23 deep drillholes, max. depth 2200 m, numerous shallow drillholes. Most of the water is recovered by pumping.
Saudárkrökur	35	70	Insignificant springs, temp. 35° C	12 drillholes, max. depth 480 m, natural flow.
Olafsfjàrdur	35	57	A single surface spring, small flow, temp. 50° C	13 drillholes, max. depth 590 m, natural flow.
Námafjall	60	>260	Intense fumarolic activity, temp. 100° C	3 drillholes, max. depth 680 m, natural flow.
Selfoss	80	94	Insignificant warm spring that disappeared at the beginning of the century	8 drillholes, max. depth 500 m. Practically all the water is recovered by pumping.
Hengill	600	>260	Springs and fumarolic activity, temp. 100° C	18 deep drillholes, max. depth 1200 m, many shallow wells. Natural flow.
Krysuvik	20	220	Intense fumarolic activity, temp. 100° C	4 deep drillholes, max. depth 1200 m, many shallow wells, natural flow.
Total	1480			

The high temperature areas are characterized by large area of hot ground, fumaroles, mud pools, and sometimes solfataras. Near the surface the rocks are intensely altered. Water issued at the surface is in most cases negligible. All the high temperature areas are situated within the zone of active volcanism often emerging at high altitudes, 300—1500 meters above sea level. Most of them are closely connected with acid volcanism (Jonsson, 1961, Arnason et al., 1968). At the surface the thermal activity is frequently concentrated along permeable faults and fissures but drilling in few areas has shown that the hydrothermal reservoir at depth is more or less continuous and more extensive.

The low temperature areas are characterized by hot water springs often with high flow rates and surface temperatures ranging from 15°—100 °C. Hydrothermal alteration around the springs is as a rule insignificant. Most of the low temperature areas are situated in valleys and stretches of lowland along the coast, mainly in the Tertiary flood basalt areas. Frequently the hot springs are lined up along permeable dykes and faults. The very high natural rates of discharge in some of the low temperature areas has been attributed to high permeability of contacts between lava flows, i.e. their vesicular tops and bottoms, and occasionally sedimentary intercalations.

A separate low temperature area on Snaefellsnes is characterized by spring waters high in total carbonate.

Bödvarsson (1961) has estimated the total heat output in high temperature areas as roughly of the order of 10^9 cal/sec and the total sensible heat output (above 4 °C) of springs as roughly 18^8 cal/sec. The integrated flow from surface springs and drillholes is estimated as some 2700 l/sec at the present with an average temperature of roughly 120 °C. Drilling has increased the total flow greatly.

Table 1 gives the integrad flow of natural springs in the various low temperature areas and table 2 the flow from drillholes in most of the well drilled thermal areas.

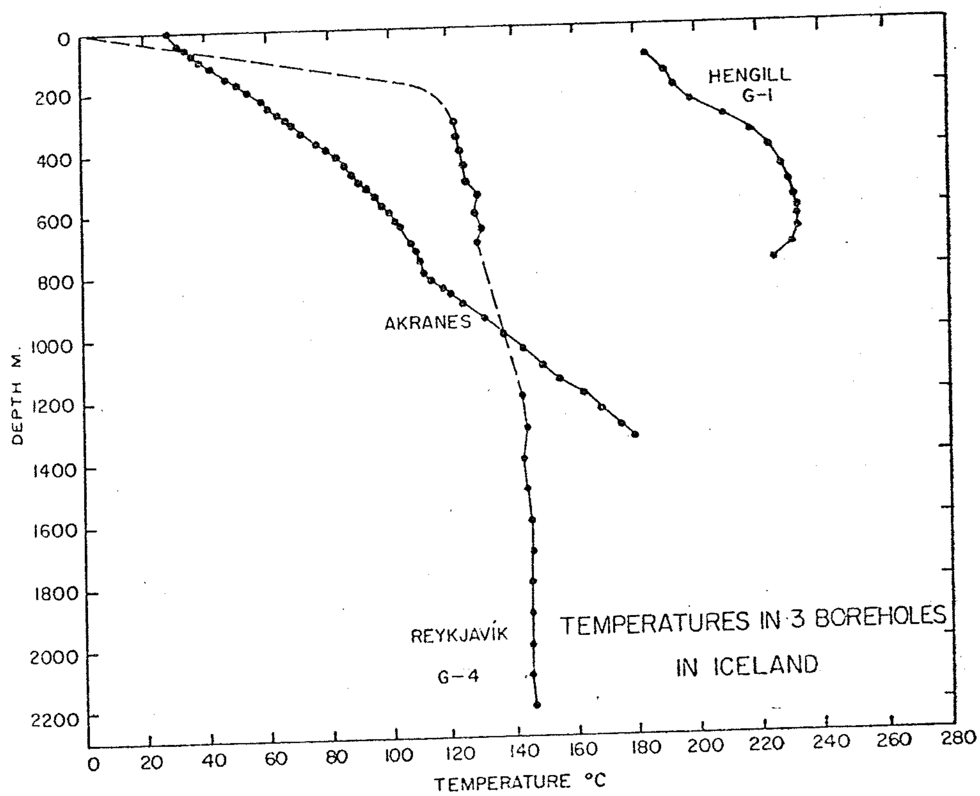

Fig. 2

Fig. 2 gives the subsurface temperature in 3 drillholes: a) from the Hengill high temperature area, b) from Reykjavik, a low temperature area, and c) Akranes, where there is no surface manifestation of thermal activity. Drilling in various parts of the country outside thermal areas has established a near surface thermal gradient of 34-165 °C/km. In many areas the surface thermal gradient has been observed to be controlled by movement of hot water at depth (Palmason, 1967). This fact has lead to the conclusion that shallow drilling to establish the local thermal gradient is an effective method in the exploration for natural sources of thermal energy.

Regarding theories on the origin of the thermal energy the reader is referred to Bödvarsson (1961) and Einarsson (1942).

Extensive deuterium analysis support that the thermal waters are of meteoric origin. (Bödvarsson, 1962, Arnason, 1967).

Chemistry of the thermal water

When the chemical composition of thermal waters in Iceland is compared with thermal waters in other parts of the world, e.g. New Zealand, U. S. A., and Japan it becomes evident that the Icelandic thermal waters are lower in total dissolved solids, in particular those elements whose concentration is not influenced by solution equilibria with the wall rock (See Ellis and Mahon, 1964, 1967, Sigvaldason, 1966).

Analysis of representative thermal waters is given in table 3 together with an analysis of a thermal brine from Reykjanes (analysis 3). Waters from the low temperature areas are lower in total dissolved solids (analysis 4—5) than waters from the high temperature areas (analysis 6—8).

The hot spring water in the low temperature areas is on the whole alkaline (pH 8.0—9.5) as well as the deep water tapped from drillholes in both low and high temperature areas. Alkaline springs occur in some of the high temperature areas but acid sulphate springs and occasional carbonate springs are more typical (analysis 9—10). Evidence from deuterium analysis suggests that the water in the sulphate and carbonate springs is of local meteoric origin.

The alkaline water in the high temperature areas is strongly reducing whereas the sulphate water is oxidising and the carbonate water oxidising or reducing. In the low temperature areas the water is generally weakly reducing.

Drilling in recent years for thermal water in low temperature areas and outside thermal areas has revealed hot water of the connate type scarcely known in surface springs. This type of water is higher in total dissolved solids than other thermal waters, in particular Cl^- and Ca^{2+} (analysis 1—2). This type of water is often but not always connected with marine sediments. At any rate

Table 3 — Chemical analyses of representative thermal waters in Iceland (values in ppm)

Location	Akranes drillhole IV	Solfoss drillhole VI	Reykjanes (1) drillhole I	Eyjafjördur Reykhús drillhole I	Reykholtsdalur, Skrifta	Namafjall drillhole III	Geysir Geysir-Area	Torfajökull Eyrarhver	Torfajökull Raudihver	Torfajökull Gilshver
	1	2	3	4	5	6	7	8	9	10
Temp. °C	26.6	76	100	76	100	>260	88	94	94	75
pH	7.1	8.2	6.7	9.8	9.4	9.8	9.0	9.6	2.5	7.2
Eh (volts 25° C)	+0.12	+0.04			−0.04		−0.13	−0.20		+0.33
SiO_2	60	65	543	106	178	823	501	259	102	177
Na^+	1360	215	13800	57.5	70.8	177.0	250.0	370.0	3.8	87.5
K^+	17	4.5	1920	0.8	3.8	25.5	25.0	19.2	2.9	18.5
Ca^{2+}	560	37.2	2200	3.2	1.42	1.2	0.9	0.0	11.9	60.3
Mg^{2+}	12	2.8	45	0.5	0.13	0.0	0.0	0.02	6.6	16.0
Cl^-	3017	363.0	27400	13.3	34.2	18.2	127.0	360.0	15.2	5.1
F^-	0.1	0.8	0.4	0.6	2.2	1.1	9.5	25.0	0.4	0.3
OH^-	0.0	0.0	0.0	8.7	0.0	28.2	0.0	1.0	0.0	0.0
CO_3^{2-}	0.0	3.0	0.0	26.4	46.6	93.0	70.0	148.2	0.0	0.0
HCO_3^-	12.0	18.0	5.0	0.0	0.0	0.0	133.0	12.8	0.0	503.3
SO_4^{2-}	600.0	65.9	1280.0	48.5	57.4	78.5	108.0	54.8	443.3	5.9
H_2S	< 0.05	0.14	0.2		1.6		0.7	24.9		< 0.05
Diss. solids	6120	720	47500	272	429	1397	1152	1351	718	599

all the drillholes are situated close to the present level so percolation of sea water into the hydrothermal system cannot be excluded.

In Reykjanes a notable brine issues from several surface springs and one shallow drillhole (analysis 3). The brine is considered to have been formed by circulation of sea water through the hydrothermal systema with subsequent rock/water interactions. Deuterium analysis favours this hypothesis.

Gas analyses show that CO_2, H_2S and H_2 are the dominant gases in the high temperature areas whereas N_2 is dominant in the low temperature areas (Sigvaldason 1966).

Recent drilling in two high temperature areas has revealed deep water very low in chloride (see analysis 6). The temperature at the bottom of the drillholes (600—800 m) is 260—270 °C. At this temperature and pressure corresponding to 600—800 m water column the water will be close to its boiling point. Boiling of the water at greater depths with the separation of a vapour phase ascending to higher levels and condensing there could explain this low chloride concentration. In other high temperature areas explored by drilling to date, the deep water is always well below its boiling point for the corresponding pressure.

Exploitation

Geothermal energy is one of the most valuable natural resourcs in Iceland. About 20% of the energy consumption in the country comes from thermal energy. Most of it is used for domestic heating purposes. This utilization which is unique for Iceland makes thermal water with temperatures as low as 50 °C a valuable source of energy. Today about half of the population in the country lives in houses heated by natural hot water and this figure is increasing every year. The Reykjavik Municipal District Heating Service (Hitaveita Reykjavikur) is the largest heating service installation and serves about 75 000 inhabitants of the city. Four smaller communities have also installed such heating services together with many farms in the vicinity of the thermal springs.

Greenhouse heating by natural hot water was initiated in the 1920's and has since been of ever increasing importance. Fig. 3 shows haw the greenhouse farming has developed since it was initiated.

The use of geothermal energy for industrial purposes has been small indeed up to the present time. It appears though that the utilization of geothermal fluids for the idustries will increase much in the near future.

This year the production of diatomaceous earth from an underwater deposit in lake Myvatn in Ne. Iceland was initiated. Due to the high water content of this deposit (80—85%) a low cost energy is required to dry it and this energy is provided by natural hot steam from the nearby high temperature area at Namafjall.

evel so percolation of sea
ed.
surface springs and one
d to have been formed by
systema with subsequent
this hypothesis.
ominant gases in the high
v temperature areas (Sig-

revealed deep water very
he bottom of the drillholes
nd pressure corresponding
o its boiling point. Boiling
a vapour phase ascending
n this low chloride con-
y drilling to date, the deep
responding pressure.

tural resourcs in Iceland.
ntry comes from thermal
urposes. This utilization
h temperatures as low as
of the population in the
d this figure is increasing
eating Service (Hitaveita
and serves about 75 000
have also installed such
ty of the thermal springs.
iated in the 1920's and
hows haw the greenhouse

es has been small indeed
utilization of geothermal
r future.
n an underwater deposit
he high water content of
to dry it and this energy
high temperature area at

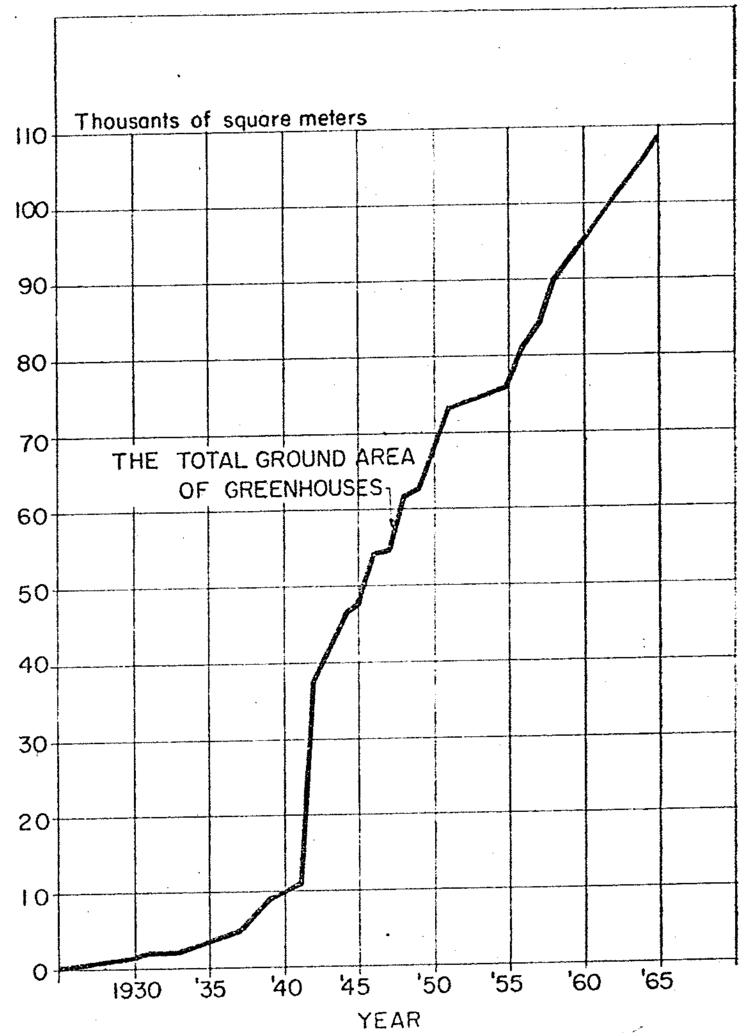

Fig. 3 — The development of greenhouse farming in Iceland (Lindal, 1961, modified)

Experiments on drying seaweeds by natural hot water at Reykholar in the NW. Peninsula have been carried out. It is intended to start production in 1969. Research on erecting a small geothermal power station at Namafjall is in progress and the possibility of extracting salt from sea water and the thermal brine at Reykjanes by flash evaporation using natural steam is being studied.

References

Arnason, B. (1967): Hydrogen Isotopes in Hydrological Studies in Iceland. IAEA. Proceedings of the Symposium Isotopes in Hydrology, Vienna pp. 35—47.

Arnason, B., Theodorsson, P., Björnsson, S. and Saemundsson, K. (1968): Hengill, a High Temperature Thermal Area in Iceland, Bull. Volcanologique, in press.

Bödvarsson, G. (1961): Physical Characteristics of Natural Heat Resources in Iceland. U. N. Conference on New Sources of Energy, Vol. 2, Rome.

Bödvarsson, G. (1962): The Use of Isotopes of Hydrogen and Oxygen for Hydrological Purposes in Iceland. Jökull, 12, pp. 49—54.

Einarsson, T. (1942): Ueber das Wesen der Heissen Quellen Islands. Societas Scientiarum Islandica, 38.

Ellis, A. J. and Mahon, W. A. J. (1964): Natural Hydrothermal Systems and Experimental Hot-water/Rock Interactions. Geochim. et Cosmochim. Acta, 28, pp. 1323—1358.

Ellis, A. J. and Mahon, W. A. J (1967): Natural Hydrothermal Systems and Experimental Hot-water/Rock Interactions. (Part II). Geochim. et Cosmochim. Acta, 31, pp. 519—538.

Jonsson, J. (1961): Nattura Islands, pp. 95—119, Almenna bókafelagid, Reykjavik (in Icelandic).

Jonsson, J. (1967): The Rift Zone and the Reykjanes Peninsula. In Iceland and Mid-Ocean Ridges, pp. 142—150. Societas Scientiarum Islandica, 38.

Lindal, B. (1961): Greenhouses by Geothermal Heating in Iceland. U. N. Conference on New Sources of Energy, Vol. 3, Rome.

Palmason, G. (1967): On Heat Flow in Iceland in Relation to the Mid-Atlantic Ridge. In: Iceland and Mid-Ocean Ridges, pp. 111—127. Societas Scientiarum Islandica, 38

Sigvaldason, G. E. (1966): Chemistry of Thermal Waters and Gases in Iceland. Bull. Volcanologique, XXIX, pp. 589—604.

Stefansson, R. (1967): Some Problems of Seismological Studies on the Mid-Atlantci Ridge. In: Iceland and Mid-Ocean Ridges, pp. 80—89, Societas Scientiarum Islandica, 38.