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Icelandic National Committee
for the Geodynamics Project

DEEP CRUSTAL DRILLING IN ICELAND

A preliminary report on the scientific aims and some necessary preparations for the project.

Prepared by a working group on deep crustal drilling.

OSJHD 7538

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1. Introduction.

The first written proposal for deep crustal drilling in Iceland was made by Dr. Gunnar Bödvarsson in the years 1960-1962. The primary aim of his proposal was to drill into the then newly discovered layer D under Reykjavík (which later was found to correspond to layer 3, Vp = 6.5 km/s), in order to obtain core samples of the layer, measure the borehole temperature, heat conductivity and the velocity of sound in the rocks. Dr. Bödvarsson had been in contact with Dr. Maurice Ewing, director of the Lamont Geological Observatory and Dr. Frank Press, director of the Seismological Laboratory, Pasadena. The latter took the matter up with the Mohole-committee, but the committee was not interested in supporting deep crustal drilling in Iceland financially. It was not possible to raise funds for the drilling elsewhere either.

Drilling into layer 3 in Iceland was recommended by Dr. S. Thorarinsson at the Ottawa symposium of the International Upper Mantle Committee in 1965.

Drilling into layer 3 was furthermore recommended by the first symposium of the Geoscience Society of Iceland, held in 1967, and the Surtsey Research Conference in Reykjavík in 1967.

The matter was next taken up formally in 1970 at a meeting in Cleveland, Ohio, between a group of Icelandic scientists and American scientists representing several research institutions in the United States, such as the Case Western Reserve University, Oklahoma University, Lamont-Doherty Geological Observatory, and the U.S. Geological Survey.

The results of that meeting were that in spite of the general interest shown by participants in the project, it was felt that time was not ripe for applying for support to the National Science Foundation.

Deep crustal drilling into layer 3 in Iceland was listed as one of five high priority field projects in a report of a special workshop held in Princeton, N.J., in January 1972 under the auspices of the Ocean Science Committee of the U.S. National Academy of Sciences. The aims of the workshop were "to identify the major geological, geophysical, and geochemical problems associated with the Mid-Atlantic Ridge and to outline an orderly approach to a comprehensive study of this important part of the earth's surface"("Understanding the Mid-Atlantic Ridge, A comprehensive program", National Academy of Sciences, Washington, D.C., 1972). The drilling project was listed in the Budget for Operating Proposed Oceanographic Studies of the Mid-Atlantic Ridge.

Working group 4 of the Inter-Union Commission on Geodynamics at its meeting in Reykjavík 1973 recommended three deep drilling projects in three distinct and seemingly very different parts of the world Rift System. These were the Iceland, Baikal and Kenya rifts. The scientific aims of each project is outlined in Report No. 5 of the Inter-Union Commission on Geodynamics (Paris, 1974).

At its 1974 meeting in Zürich the Inter-Union Commission on Geodynamics passed three general resolutions and recommendations, one of which was to urge "that the unique opportunity for studying the deeper oceanic and continental crust by land drilling in rift areas be utilized and that interested National Committees combine their efforts to take advantage of this opportunity (Report No. 7, Inter-Union Commission on Geodynamics, Paris, 1975).

At its meeting on October 3rd, 1974, the Icelandic National Committee for the Geodynamics Project set up a working group of 10 scientists to draft a preliminary research plan in which the aims of the Icelandic deep crustal drilling project (IDCDP) would be defined. This preliminary plan might subsequently serve as a basis for further discussions between interested parties in Iceland and abroad.

Several partial reports have been submitted by members of the working group and the Icelandic National Committee, and the report presented here is made from these and the results of discussions within the working group.

2. The aim of deep crustal drilling in Iceland.

The primary aim of the project is to investigate the composition and various physical, geological and chemical properties of the crust. The nature of seismic layer 3 (V_p = 6.5 km/s) is of particular interest, since contrary to the upper layers it cannot be investigated at the surface and in shallower drillholes. The working group concluded that layer 3 should be reached by continuous coring if at all possible. A hole that penetrates well into layer 3 is expected to serve the dual purpose of providing direct information on the properties of this layer and its upper boundary, and furnishing samples to test the various geophysical techniques by which the layer is presently detected.

In this connection it must be considered whether sites should be chosen within an active volcanic zone, or in Quaternary or Tertiary rocks at a distance from an active volcanic zone. The working group concluded that ideally the layer 2/layer 3 interface should be penetrated both within and outside an active volcanic zone, which would mean two or more holes. It was also concluded that a site within a region of uniform depth to layer 3 should have priority over a site of anomalously shallow depth to layer 3, although a hole on the latter type of site would be of great interest for comparison.

All possible types of measurements should be conducted on the drill site, within the hole, and on samples of core and water. Investigations on the site will be discussed in the next chapter, but investigations within the hole and on the samples should include:

a) Normal registration of drill speed, aquifers and stratigraphy.

b) Borehole-temperatures during and after drilling.

c) Thermal conductivity of core.

d) Specific heat of core.

e) Electrical conductivity of wall and core.

f) Density of core.

g) Porosity of core.

h) Permeability of core.

i) Compressional (V_p) and shear (V_s) wave velocities of core as a function of pressure.

j) Gamma-gamma density log.

k) Neutron-neutron porosity log.

l) Acoustic velocity log.

m) Caliper log.

n) Direction and deviation log of the hole.

o) Televiewer log for the determination of fractures in hole.

p) Petrology (petrography and petrochemistry), primary and secondary mineralogy of core. Major elements, trace elements and isotope chemistry of core.

q) Magnetic properties (including ore mineralogy) and polarity directions of core.

r) Chemistry (including isotopes) of water samples from various depths in hole.

s) Chemistry (including isotopes) of pore water in core.

t) Stress measurements in hole.

3. The selection of sites for deep crustal drilling.

Iceland is the largest subaerial landmass on the mid-Atlantic ridge and is in that way an anomalous segment of the ridge. This anomalous situation makes it more easily accessible to most investigations, including deep drilling. It was concluded that thorough and comprehensive geological and geophysical investigations should be conducted on the potential drill sites selected for a short list. On the basis of these investigations the final decision on the site(s) should be made. These surface investigations should include:

a) Detailed geological mapping (at least on scale 1:50000) of several tens of km^2 surrounding and stratigraphically below the potential drill site. An accurate connection of the strata with the geomagnetic time scale will be of importance, as it is rather unlikely that many samples fresh enough for K/Ar dating can be obtained from the core. The mapping should include an estimate of the dyke density, investigation of the petrology of the province and the secondary mineralogy of the vicinity of the drill site.

b) Detailed electrical sounding of the vicinity of the site with both the Schlumberger and dipole arrangements. This would serve the dual purpose of showing whether the site is of a regional or anomalous character and in providing much wanted data for a comparison of lithological stratification and stratification interpreted from electrical sounding, which is so widely used in geothermal prospecting. Magnetotelluric measurements at several sites near the proposed hole could give valuable information on the electrical structure and temperature of the lower crust and upper mantle.

c) Detailed seismic refraction survey of the site with reversed profiles both parallel to and perpendicular to the strike. This would be of great importance with respect to the primary aim of the project.

d) The drill site should be linked to a regional gravity survey in order to establish whether the site is in or close to a gravity anomaly.

e) Detailed magnetic survey on the site and its surroundings by surface measurements or/and from the air. This survey could give valuable information on the regularity of the strata on the site.

f) Recording of microearthquakes in the vicinity of the site. This could give information on tectonic movements and stress fields in the crust.

Part a) requires fairly good exposures of bed rock on a regional scale. Parts b) and c) require that the site is relatively easily accessible by jeep, preferably both approximately parallel to and perpendicular to the strike. Investigations outlined in parts b), d) and e) are more easily interpreted if the site is on a relatively flat ground, ideally with an altitude variation of less than 100 m in an area with 10 km radius from the hole.

It is clear that detailed geological and geophysical investigations such as outlined above are both very time consuming and expensive. This fact narrowed the selection of sites for the first two or three deep holes from a list of some twenty holes in all parts of Iceland to 10 sites in southwestern Iceland, where most of the above mentioned investigations have been carried out to a certain degree, and one or possibly two sites of particular interest in south-eastern and eastern Iceland, where the geological mapping has been carried out.

The list must, however, still be shortened, and to do this some detailed work is needed and a thorough comparison of the pros and cons of the individual sites. In addition to being the region most thoroughly investigated by multidisciplinary methods it was thought that southwestern Iceland had an advantage over other parts of the country in being the most direct continuation of the mid-Atlantic ridge.
It can be expected that the further inland and higher one goes some characteristics of the mid-oceanic ridge system will change.

It was concluded that there were four types of sites to choose from in southwest Iceland:

a) A high temperature area within the active volcanic zone

Localities	Depth* to seismic layer 3 km	Known ground water environment
Hengill	∿ 2.0	Fresh water
Krísuvík	∿ 2.6	" "
Svartsengi	∿ 2.8	Sea water
Reykjanes	∿ 2.6	" "

* Depth below sea level

Drilling within a high temperature area would be cheaper than drilling within a normal area in the volcanic zone, due to a higher drill speed and because much less casing is needed in the former. But the high temperature areas are anomalous parts of the active volcanic zone and analogous to the eroded central volcanoes where layer 3 is recorded at shallow depths in the Quaternary and Tertiary provinces.

All the above mentioned thermal areas have been penetrated by drilling to 1000 m or more. The chemical composition of thermal waters in Hengill and Krísuvík shows that they are basically fresh-water systems, but those of Svartsengi and Reykjanes are sea-water brines and thus probably more akin to thermal areas on the sea floor.

b) A normal part of the median active volcanic zone

Localities	Depth* to seismic layer 3 km	Known ground water environment
Stapavík at Thingvallavatn	∿ 2.0	Fresh water
The tip of the Reykjanes peninsula	∿ 2.6	Sea water

The former locality is within the active Thingvellir subsidence zone. More or less continuous stratigraphic profiles can be obtained westwards from this area through Brunhes, Matuyama, Gauss and Gilbert rocks according to K/Ar datings**. The nearest high temperature area (Nesjavellir, 6.5 km away) has been penetrated by drilling to 1800 m depth. Lower Matuyama**

* Depth below sea level

** Unpublished data.

(pre Olduvai) rocks some 20 km west of Stapavík have been penetrated by 30 holes 800 to 2043 km deep in the Reykir low-temperature thermal area. Preliminary plans are being made for 2.5 to 3 km deep holes in that area with tricone drill bits, but no provisions have been made as yet for core sampling there.

The latter locality is the closest point in Iceland to the submarine mid-Atlantic ridge. Surface stratigraphic correlation is impossible but the nearby Reykjanes high temperature thermal area has been penetrated by drilling to 1754 m depth. Sea water permeates the strata at this locality.

c) <u>An area of high thermal gradient near the boundary of Quaternary and Tertiary rocks</u>

Localities	Distance from active volc. zone km	Depth* to seismic layer 3 km	Near-surface thermal gradient °C/km
Kjalarnes	20	2.0 - 2.5	165
Akranes	30	2.5 - 3.0	130 - 150

The former locality is in rocks of Gauss age**, and some 13 km NW of the Reykir low-temperature area mentioned previously in part b). The thermal gradient has been measured in a 240 m deep drill hole.

The latter locality is some 10 km NW of the former and in rocks of Gilbert age**. The deepest drill hole in the vicinity is 1400 m showing a gradient of 129°C/km. Slightly higher gradients have been measured in shallower drill holes.

* Depth below sea level

** Unpublished data

Further surface investigations might show which of these two localities would be more suitable. Both localities have been connected to the palaeomagnetic time scale by geological mapping. The water in the strata at both localities is fresh.

d) <u>A dissected central volcano of Quaternary or Tertiary age</u>.

Localities	Depth* to layer 3 km
Stardalur	∿ 0.4
Hvalfjordur	∿ 1.5

The former central volcano is of mid-Matuyama age** and the country rock is therefore of subaerial lavas intercalated at intervals corresponding to glaciations, with thick piles of subaquatic volcanics. The centre of the volcano is characterized by a caldera with a concentric cone sheet swarm and coarse grained intrusions up to 2.3 by 1 km in size. A downward projection of the cone sheets suggests the upper margin of a continuous layer of intrusions 100 to 200 m below the seismically recorded top of layer 3. The thoroughly drilled Reykir thermal area (see p. 8) is just outside the positive gravity anomaly, which coincides with the caldera structure.
The latter central volcano is of Gauss age** and the country rock is primarily subaerial lavas, but substantial amounts of hyaloclastite are intercalated with the uppermost series. The volcano has erupted abundant acid rocks. It has a caldera and intrusive basaltic plugs in the center. An intense regional dyke swarm is associated with it. A thorough mapping of the volcano is needed before drilling is decided.

* Depth below sea level

** Unpublished data

These central volcanoes are only two of a dozen or so dissected central volcanoes in Iceland characterized by a wide range in rock composition from basalts to rhyolites, a great bulk of shallow level intrusions, positive gravity anomalies, and shallow depth to layer 3.

It is worth noticing that the localities Stapavík in b), Kjalarnes in c), Akranes in c) and Stardalur in d) are in a direct stratigraphical continuity of one another, and the thoroughly investigated and drilled Reykir area is part of the same line. The locality Hengill in a) is at a relatively short distance away from Stapavík in b) along the active volcanic zone. These localities have therefore an important advantage over the others. The localities Svartsengi and Reykjanes in a) and the tip of the Reykjanes peninsula in b) have, however, a closer similarity to the sea floor as the strata are permeated by sea water, which may be of considerable importance with respect to the secondary alteration of the rocks.

In the discussion of possible drill sites in this report attention has so far mainly been paid to SW-Iceland because of its proximity to the mid-Atlantic ridge. If, however, we want to investigate Iceland itself, it may be argued, that we should go further inland. During post-glacial time the discharge of volcanic products per unit time reaches a maximum in the center of the country. A dissected area in the fjords of eastern Iceland, i.e. in a direct continuation of the aseismic Iceland-Faeroe ridge, comes also strongly into consideration. Detailed geological mapping is completed in large areas in the eastern fjords, but an extensive geophysical surveying project would be needed before a site could be selected.

It would be of particular interest to do further research on the intrusive sheet complex in southeast Iceland which Walker (in "Geodynamics of Iceland and the North Atlantic Area", p. 189-201, ed. L. Kristjánsson, Reidel 1974) has recently proposed as being an exposed part of layer 3. It would be important to link the complex more thoroughly with the regional geology by further geological mapping. A detailed geophysical surveying program should be conducted in the vicinity of the complex before deep drilling is considered in that area. The shallowest depth to layer 3 in southeast Iceland recorded so far is 1.2 km in the Austurhorn area, and the top of the layer has been recorded at a depth of 1.8-2.0 km in the vicinity of the sheet complex in Hornafjördur.

4. Drilling equipment.

A drilling rig with a depth capacity of 3600 m has recently been purchased to Iceland. This rig would be capable of drilling a hole that should penetrate well into seismic layer 3 in many areas. The rig could be made available for deep crustal drilling. The rig is not fitted with equipment for continuous coring, but enquiries are being made into this matter.

Members of the Icelandic National Committee for the Geodynamics Project:

Ágúst Bödvarsson
Gudmundur Pálmason, chairman
Gudmundur E. Sigvaldason
Kristján Saemundsson
Leó Kristjánsson
Ragnar Stefánsson
Sigurdur Steinthorsson
Sigurdur Thorarinsson
Sveinbjörn Björnsson
Sveinn Jakobsson
Trausti Einarsson

Members of the working group on deep crustal drilling in Iceland:

Axel Björnsson
Gudmundur Pálmason, chairman
Ingvar Birgir Fridleifsson, secretary
Leó Kristjánsson
Rögnvaldur Finnbogason
Sigurdur Benediktsson
Sigurdur Steinthorsson
Stefán Arnórsson
Sveinbjörn Björnsson
Trausti Einarsson

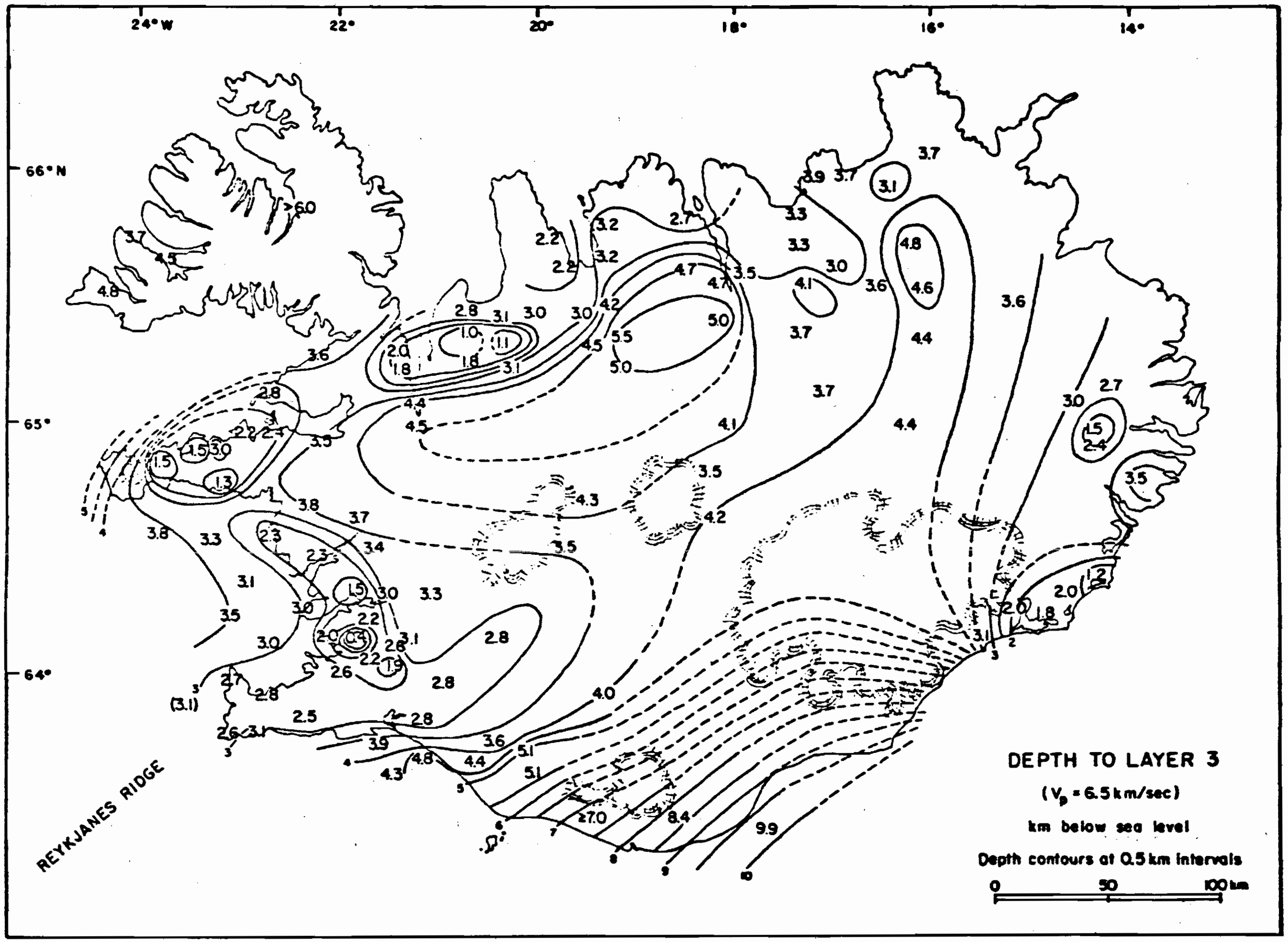

Fig. 1. Depth to layer 3 in Iceland, based on about 80 refraction profiles.

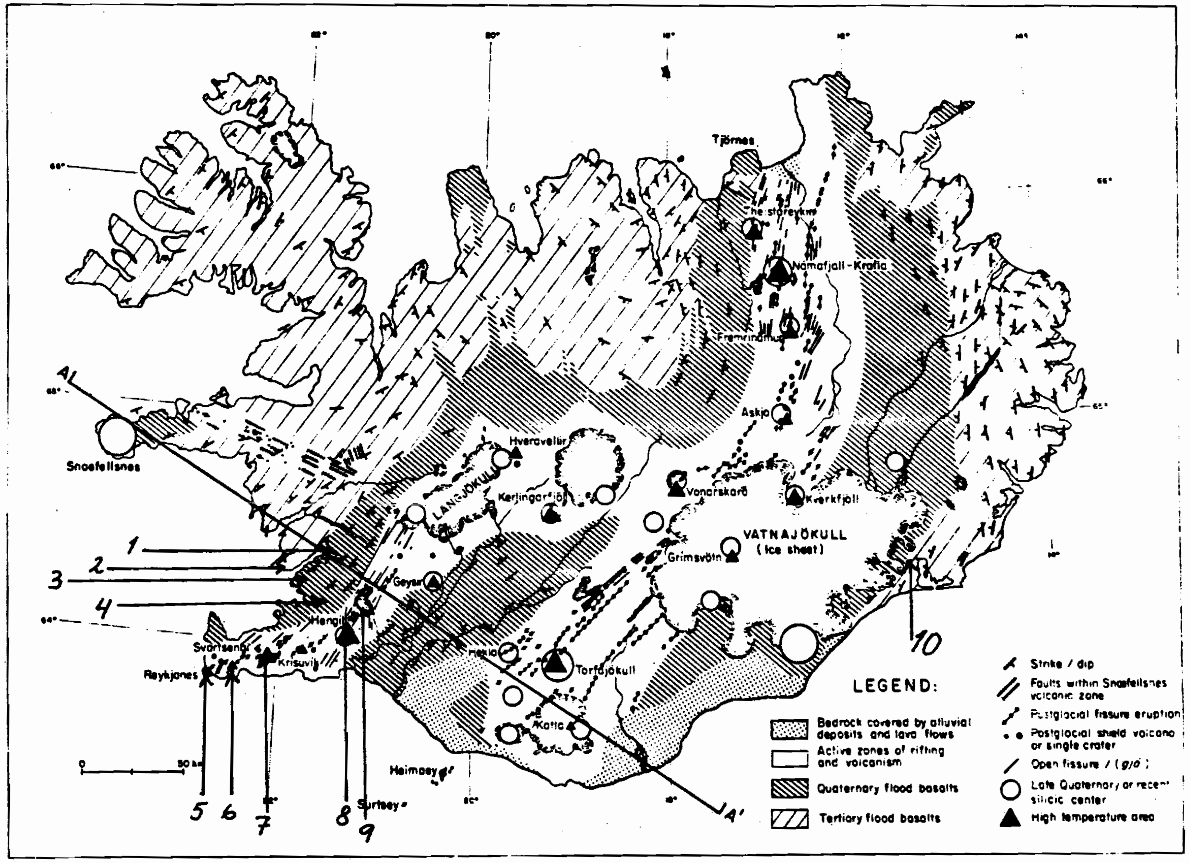

Fig. 2. Geological map of Iceland. Numbers show the location of potential drill sites mentioned in the report.
1 Hvalfjordur, 2 Akranes, 3 Kjalarnes, 4 Stardalur, 5 Reykjanes, 6 Svartsengi, 7 Krísuvík, 8 Hengill, 9 Stapavík, 10 Hornafjordur.
Section A-A' shows the location of the profiles in Fig. 3.

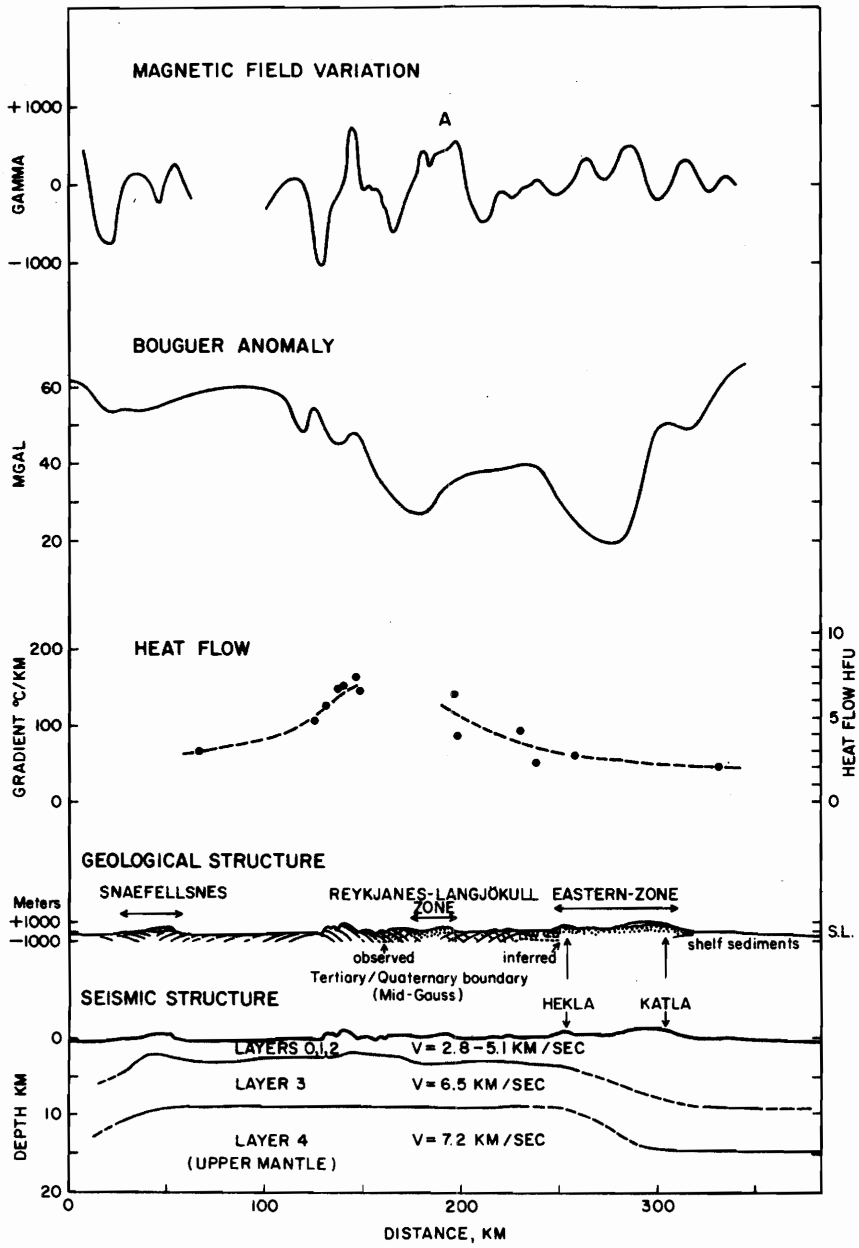

Fig. 3. Profiles along line A-A[1] in Fig. 2 showing magnetic field variation, Bouguer anomaly, heat flow, geological structure and seismic structure.