ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY

# A PROGRAM FOR THE EXPLORATION OF HIGH TEMPERATURE AREAS IN ICELAND.


Sveinbjörn Björnsson

National Energy Authority,

Iceland


AUGUST 1970

# A Program for the Exploration of High Temperature Areas in Iceland.

Sveinbjörn Björnsson, National Energy Authority, Iceland.

## 1. Introduction.

The high temperature areas in Iceland are valuable resources of energy, but only a minor part of their potential has yet been harnessed. There are about seventeen areas of this type, located in the recent volcanic zone, where temperatures of 250 to 300°C exist within 2 km depth. It is estimated that the smaller areas could produce some hundreds of tons of steam per hour whereas the largest ones might reach several thousands of tons per hour. The price of the steam is still very uncertain, but it is likely that a unit price of $0.20/tn would cover the production costs in most of the areas.

In spite of these favourable characteristics, the utilization of the high temperature areas has mainly been limited to domestic heating and greenhouse farming. As a first step to industrial utilization a plant for the drying of diatomaceous earth with geothermal steam has been operated successfully for several years and is doubling its initial capacity. An experimental back pressure turbine generating 3MW of electric power has been in operation since 1969. Large scale generation of electricity with geothermal steam is, however, not likely to occur within the next decade, since abundant cheap hydropower, at a unit price of about 3 U.S.mills/kwh, is still available in the country, The main possibility of large scale utilization of geothermal steam appears to lie in chemical- or processing industries, producing or refining raw materials. Since there is only a tiny market for the products in the country they must be exported and the capital cost of the plants would in general be so high that foreign capital is needed for their construction.

In the last years interest in attracting foreign capital for utilizing the steam in high temperature areas has been rapidly growing. This has partly been due to the need of establishing new industries to reduce large variations in the country's economy, but there has also been a growing concern, that within the next twenty years electricity and steam generated with nuclear energy, may become so cheap and widely available that the geothermal energy in Iceland will not be competent in attracting industries to the country.

Feasibility studies have been made for piping superheated water to the capital area for industrial and domestic uses, but the most promising projects of larger scale industry seem to be the production of heavy water and a sea chemicals complex utilizing geothermal brine and steam for the production of sea chemicals, magnesium metal and chlorine gas. Thermal energy is a critical economic factor in these projects and it has been a major drawback in the feasibility studies, how little is known about the physical and chemical characteristics of the different thermal areas, their production capacity, reliability and the cost of the steam they could deliver. That knowledge cannot be obtained without a considerable effort of research, which may take 3-5 years in each area. Exploration has been initiated in several of these areas but the technically harnessable potential is still uncertain and even more so the economic potential.

## 2. A program of exploration.

In 1969 the National Energy Authority proposed a program for the exploration of eleven high temperature areas which are likely to be utilized in near future. Originally the program was proposed as a five-year-program but it is already obvious that its completion will take at least 8-10 years. Thus, cost estimates will soon become outdated, but the program is of great value in organizing the exploration work and deciding the sequence in which areas should be explored, estimating the research work and scientific manpower required and the exploratory drilling some years ahead. The exploration of each area is planned in three phases, regional survey, exploratory drilling and production drilling and testing. This approach is believed to be the most economical.

In the regional survey all relevant methods of geology, geochemistry and geophysics are applied to obtain a primary model of the hydrothermal system and to locate favourable production sites within the areas. After a production site is selected, exploratory drilling is carried out. The objective of the drilling is to verify and modify the primary model of the hydrothermal system. It will also furnish critical information for designing production wells and evaluating, whether the exploitation of the area will be technically possible and economically feasible. If the results of this phase are promising, production drilling and testing will be carried out in several steps to test the production capacity and the reliability of the thermal area.

The regional survey of an area is estimated to take 1-3 years, the exploratory drilling at each production site 1-2 years and the production drilling and testing 1-3 years, The last phase is by far the most expensive and would in general not be undertaken, unless it was justified by a definite project of utilization in the area. However, by completing the two former phases, the time for the investigation of an area after a feasible project of utilization has been conceived, is shortened by as much as 5 years.

Fig. 1 is a schematic geological map of Iceland, showing the high temperature areas as solid triangles all located in the active volcanic zone. An estimate of the natural heat loss and the excess heat stored in the reservoir of the major areas is indicated in Fig. 2. Although many of these areas possess a large potential, they are so inaccessible that it is very unlikely that they will be utilized in the next decades. In the research program, therefore, only eleven of the major areas have been selected for study. These are Reykjanes, Svartsengi, Krísuvík and Hengill on the Reykjanes Peninsula, Torfajökull in South Iceland, Kerlingarfjöll, Geysir and Hveravellir in Central Iceland and Námafjall, Krafla and Theistareykir in North Iceland.

An outline of the general approach will be given.

## 3. Regional Survey of high temperature areas.

During the regional survey the areas of interest are studied with all relevant available methods of geology, geochemistry and geophysics. No drilling is carried out in this phase but an attempt is made to outline a primary model of the hydrothermal system on the basis of this multidisciplinary approach and to locate possible production sites within the area. The methods generally applied are indicated in Fig. 3. The geology of the region is studied with main emphasis on petrology and stratigraphy, tectonic structure and hydrology, hydrothermal alteration, faults and the distribution of hot springs and fumaroles. Samples are taken from springs and fumaroles in the region for chemical analysis and studies of deuterium and tritium content in order to obtain information on the hydrology of the hydrothermal system, circulation of the thermal fluid and to estimate temperatures to be found in the reservoir. The crustal structure is furthermore studied with refraction seismology and gravity surveys. Tectonic activity is monitored by locating microearthquakes occurring within the area. An aeromagnetic survey flown at low altitude, combined with a detailed ground survey of magnetic lows, is used to locate faults, and areas where alteration has destroyed the magnetism of the rock.

Temperature conditions in the region are studied with direct current resistivity measurements and surface manifestations of thermal activity are mapped with aerial surveys of infrared radiation and shallow temperature surveys in soil. These observations along with flow measurements of hot springs and fumaroles are combined to obtain an estimate of the natural heat loss of the area and the excess heat stored in the reservoir.

This first phase of investigation produces a geological map of the area. It gives also the main features of the hydrothermal system, indications of the composition, temperature and circulation of the thermal fluid, an estimate of the excess heat stored in the reservoir and the natural heat loss from the system. These results are combined into a primary model of the hydrothermal system and on the basis of the model, suggestions for production sites and exploratory drilling are made. Thus the regional survey is a natural forerunner of drilling and, in general, necessary to ensure that successful exploratory drilling can be carried out.

## 4. Exploratory drilling.

When a favourable production site has been selected on the basis of the primary model of the high temperature area, the validity of conclusions drawn from surface observations and indirect geophysical or geochemical methods must be tested with exploratory drilling. An outline of the investigations undertaken during this phase is given in Fig. 4. Drilling rate and the loss of the circulation fluid are recorded carefully, drilling chips continuously sampled and cores taken occasionally at the request of supervising geologists. This material is used for petrological and stratigraphical studies and investigations of permeability and alteration. Temperature and pressure logging are carried out after most intervals in drilling, aquifers located and samples taken for chemical analysis.

The aim of this phase of exploratory drilling is threefold. Firstly it should furnish data to check and revise the primary model of the hydrothermal system. Secondly, it must show whether the production site in question is technically exploitable. Although the primary investigations have shown that the area is hot and the stored excess heat considerable, the permeability may prove to be so small that the heat is not recoverable at a reasonable cost. The site may also prove to be unreliable because of probable invasion of colder aquifers when the hot reservoir is heavily drained for a long time. Thirdly, this phase should give necessary information for the location and design of production wells. Of importance are data on stratigraphy and drilling characteristics of the formation, distribution of temperature, alteration, permeability and the location of aquifers. On this basis proposals for drilling sites, depth and the casing program of wells are worked out.

## 5. Production drilling and testing.

If the results of the second phase are favourable, the production site technically exploitable and the production capacity and reliability are regarded to be within the demands of the projected utilization, production drilling and testing of the area is initiated.

If the production needed is close to the estimated production capacity of the area, the wells are drilled in steps and the flow and enthalpy tested for several months before further steps are undertaken. This time is also used to test well head equipment and to study corrosion and scaling. A complete test of all wells blowing simultaneously for a minimum period of six months will in general be carried out before the site may be regarded ready for utilization and construction work can be initiated.

## 6. Cost and manpower.

Estimated exploration costs for a typical high temperature area involving regional survey of 50 $km^2$ and exploratory drilling at one production site, are shown in Table 1. The relatively low amount devoted to geochemistry in the regional survey is due to the fact that in most high temperature areas in Iceland only the steam phase of the primary thermal fluid is found at the surface. Chemical analyses of the secondary thermal water found in hot springs are therefore not of much interest. In general the last three items of the regional survey will not be carried out unless the other methods have strongly indicated that the area is of great promise. The number of exploratory wells that is needed may vary greatly from site to site but an average of 3 exploratory wells, 1000 m deep and 2 experimental production wells, 1800 m deep is regarded a likely estimate. To ensure reliable production, the production wells must in general be protected by a liner, perforated at aquifers.

In the program by NEA the completion of the regional survey of eleven areas and the exploratory drilling at ten production sites is proposed. The regional survey of some of these eleven areas has been slowly progressing during the last decades, mainly due to work in geology and geochemistry. To complete the survey of all the areas 60 man-months of geologists, 10 man-months of geochemists and 180 man-months of geophysicists are required. The total cost for completing the regional survey is estimated 800,000 dollars. (July 1970). The requirements for the phase of exploratory drilling are more uncertain, since the number of wells that has to be drilled at a production site may vary greatly according to the nature of the hydrothermal system. In the program it was proposed to drill a total of 36 exploratory wells reaching 1000 m depth with a diameter of 3 1/2" and 21 experimental production wells reaching a depth of 1800 m with a diameter of 8 3/4". For the investigation of these wells 41 man-months of geologists, 50 man-months of geochemists and 33 man-months of geophysicists are required. The average cost of an exploratory well is at present (July 1970) estimated $ 22,700 but that of an experimental production well protected with a perforated 7 5/8" liner to the bottom, $ 113,000. The investigation of the wells by geo-scientists is expected to average $ 27,000 for 3 exploratory wells and 2 experimental production wells at each production site. Thus the total cost of the proposed phase of exploratory drilling adds up to 3.5 million dollars and the total cost of the program to 4.3 million dollars.

Table 1

Estimated Exploration Costs for a Typical High Temperature Area.

| 1. Regional Survey (50 $km^2$) | Cost $ | $ |
|---|---|---|
| Geology and petrology | 10,000 | |
| Geochemistry | 4,000 | |
| Infrared survey [1)] | 1,000 | |
| Resistivity survey | 15,000 | |
| Magnetic survey | 4,000 | |
| Refraction seismology | 11,000 | |
| Geodaetic and gravity survey | 10,000 | |
| Microearthquakes and ground noise | 10,000 | |
| | 65,000 | 65,000 |

1) Only ground work and interpretation. Cost of infrared aerial mapping not included.

| 2. Exploratory Drilling (one production site). | $ | $ |
|---|---|---|
| 3 exploratory wells (Depth 1000 m, diameter 3 1/2". Casing 250 m, 5" cemented) | 68,000 | |
| 2 experimental production wells (Depth 1800 m, diameter 8 3/4". Casing 300 m, 9 5/8" cemented. Liner, 1500 m, 7 5/8" partly perforated) | 226,000 | |
| Investigation of wells | | |
| Geology | 9,000 | |
| Geochemistry | 11,000 | |
| Geophysics | 7,000 | |
| | 321,000 | 321,000 |
| Total for 1 and 2 | | 386,000 |

Legend for figures

Fig. 1. Schematic geological map of Iceland. The high temperature areas along the active volcanic zone are indicated by solid triangles.

Fig. 2. Estimate of the natural heat loss and the excess heat stored in the reservoir of the major high temperature areas in Iceland.

Fig. 3. Schematic diagram of the general approach and the primary results of a regional survey.

Fig. 4. Schematic diagram of the investigations and the results obtained by exploratory drilling.

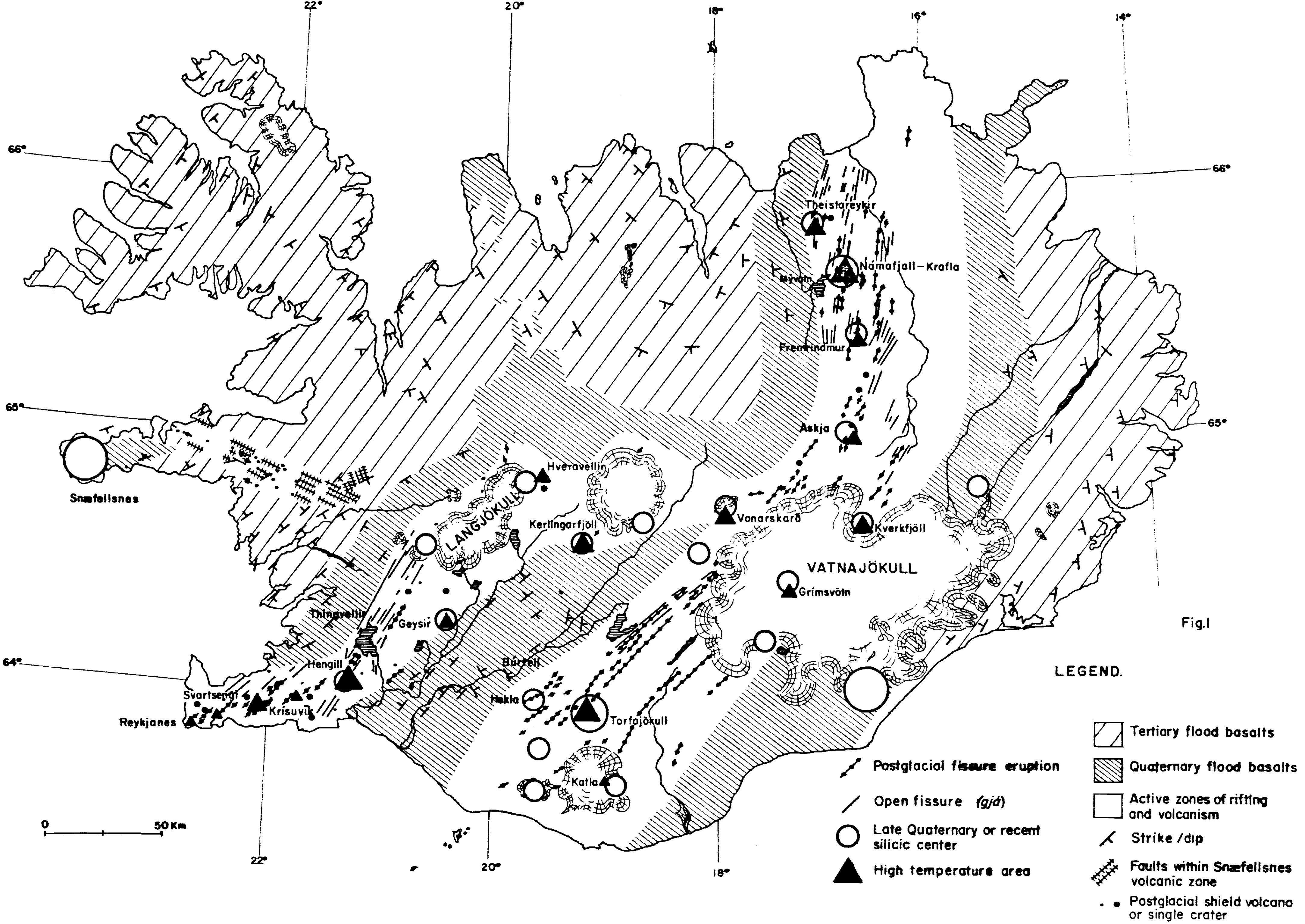
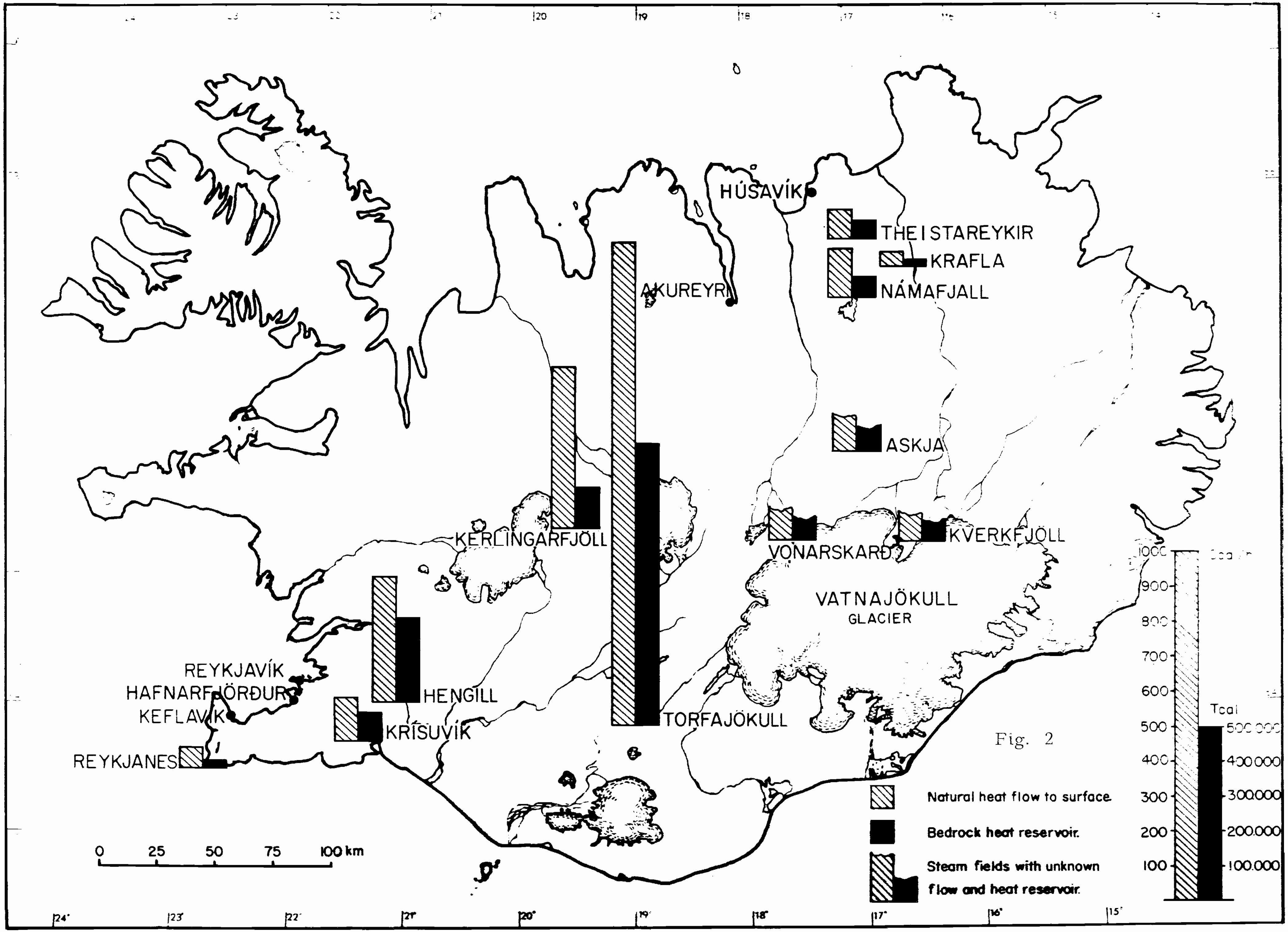

22°
20°
18°
16°
14°
66°
65°
64°
Snæfellsnes
LANGJÖKULL
Hveravellir
Kerlingarfjöll
Geysir
Thingvellir
Hengill
Svartsengi
Krisuvik
Reykjanes
Búrfell
Hekla
Torfajökull
Katla
Vonarskarð
VATNAJÖKULL
Grímsvötn
Kverkfjöll
Askja
Fremrinámur
Mývatn
Námafjall–Krafla
Theistareykir
0
50 Km
LEGEND.
Tertiary flood basalts
Quaternary flood basalts
Active zones of rifting and volcanism
Strike / dip
Faults within Snæfellsnes volcanic zone
Postglacial shield volcano or single crater
Postglacial fissure eruption
Open fissure (gjá)
Late Quaternary or recent silicic center
High temperature area

Fig.I


HÚSAVÍK
THEISTAREYKIR
KRAFLA
NÁMAFJALL
AKUREYRI
ASKJA
KERLINGARFJÖLL
VONARSKARD
KVERKFJÖLL
VATNAJÖKULL
GLACIER
REYKJAVÍK
HAFNARFJÖRÐUR
KEFLAVÍK
REYKJANES
HENGILL
KRÍSUVÍK
TORFAJÖKULL
0 25 50 75 100 km
Natural heat flow to surface.
Bedrock heat reservoir.
Steam fields with unknown flow and heat reservoir.
Tcal
500.000
400.000
300.000
200.000
100.000
1000
900
800
700
600
500
400
300
200
100
24° 23° 22° 21° 20° 19° 18° 17° 16° 15°
Fig. 2

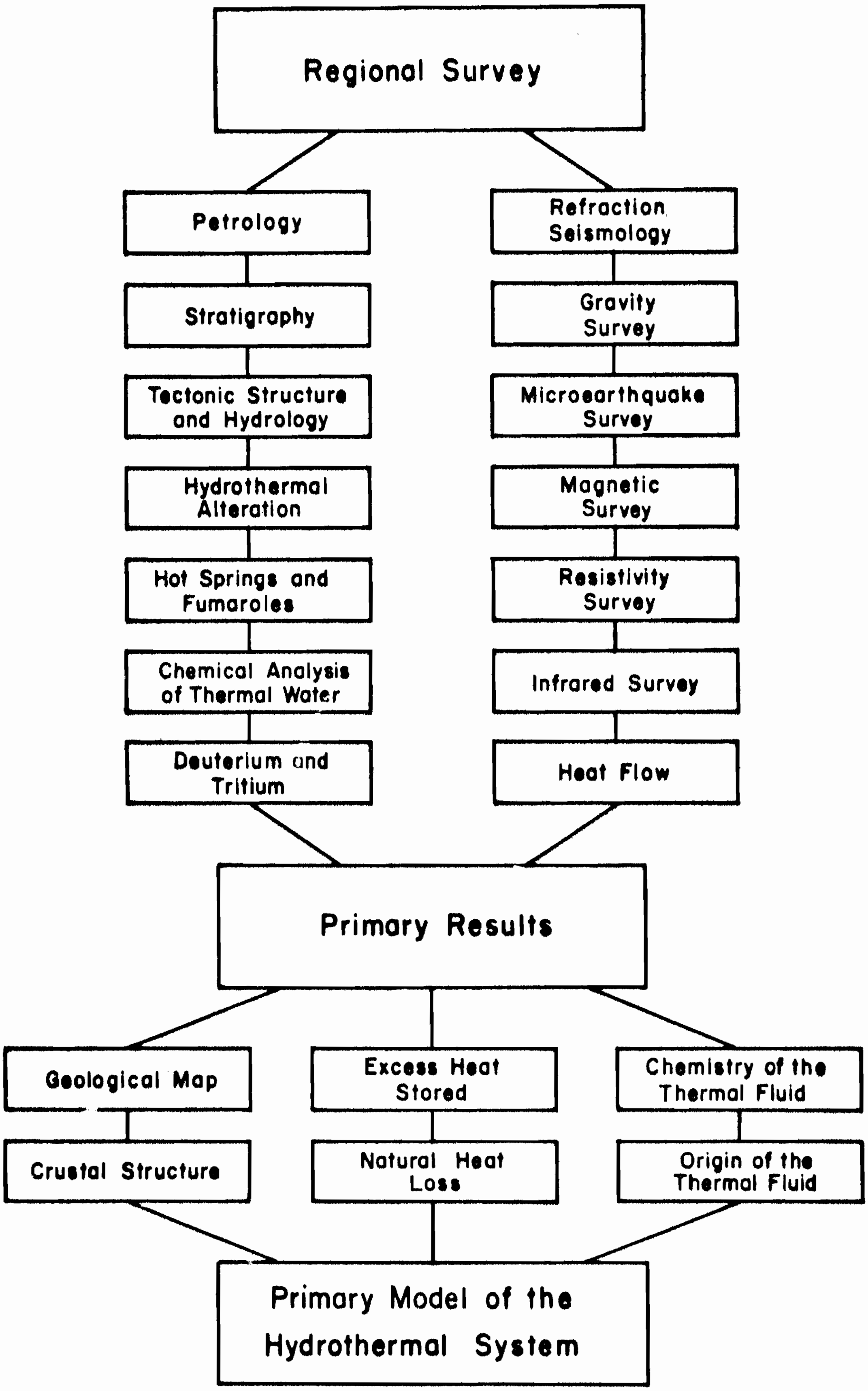

Regional Survey
Petrology
Stratigraphy
Tectonic Structure and Hydrology
Hydrothermal Alteration
Hot Springs and Fumaroles
Chemical Analysis of Thermal Water
Deuterium and Tritium
Refraction Seismology
Gravity Survey
Microearthquake Survey
Magnetic Survey
Resistivity Survey
Infrared Survey
Heat Flow
Primary Results
Geological Map
Crustal Structure
Excess Heat Stored
Natural Heat Loss
Chemistry of the Thermal Fluid
Origin of the Thermal Fluid
Primary Model of the Hydrothermal System

Fig. 3

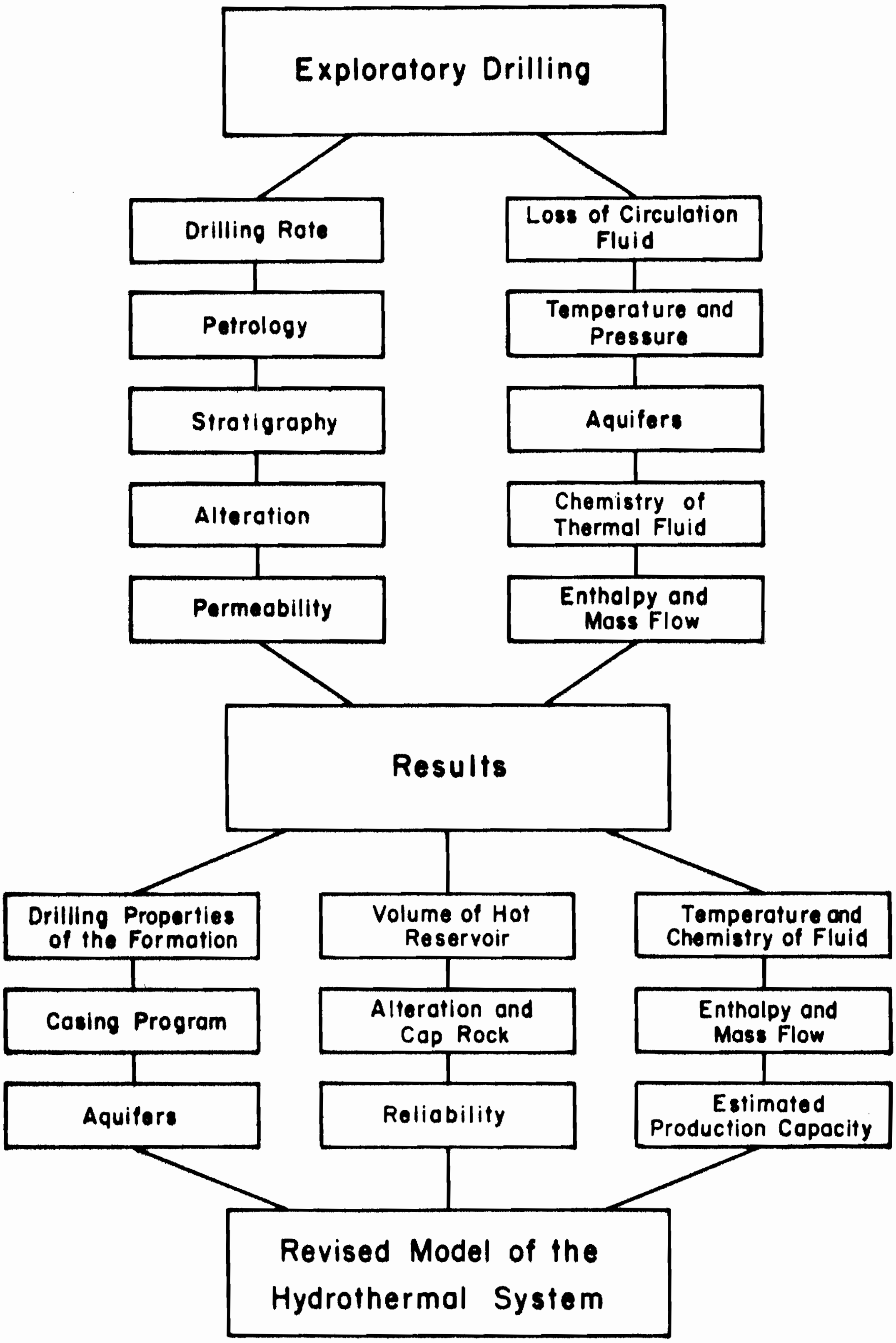

Exploratory Drilling
Drilling Rate
Petrology
Stratigraphy
Alteration
Permeability
Loss of Circulation Fluid
Temperature and Pressure
Aquifers
Chemistry of Thermal Fluid
Enthalpy and Mass Flow
Results
Drilling Properties of the Formation
Casing Program
Aquifers
Volume of Hot Reservoir
Alteration and Cap Rock
Reliability
Temperature and Chemistry of Fluid
Enthalpy and Mass Flow
Estimated Production Capacity
Revised Model of the Hydrothermal System

Fig. 4