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APPLIED VOLCANOLOGY IN GEOTHERMAL EXPLORATION IN ICELAND

INGVAR BIRGIR FRIDLEIFSSON

Paper presented at the IASPEI/IAVCEI Assembly, Durham, England, Aug. 1977.

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Abstract

In an active spreading area like Iceland, where the regional geothermal gradient is in the range 50-150 °C/km (2-7 HFU), it is normally not a problem to find high enough temperature with deep drilling, but the difficulties arise with finding permeable layers at depth within the strata.

The island is built almost entirely of volcanic rocks, but a) the environmental conditions at the eruptive site, b) the chemical composition of the volcanics, and c) the erosional and sedimentary processes affecting individual stratigraphic units, give rise to great variations in the primary porosity of the strata locally. The high porosity rocks are thought to serve as geothermal flow channels and reservoirs, but the permeability is commonly enhanced and upflow zones controlled by faults, dykes and other igneous intrusions.

No direct surface methods have been developed for measuring effective permeability at depth; this can only be done in expensive drillholes. But detailed volcanological and structural analyses on a regional scale, using a combination of geological and geophysical surveys are effectively used to select drill sites.

1. Introduction

The utilization of geothermal energy is very important for the national economy of Iceland. During the last three decades geothermal energy has been harnessed on an increasingly large scale, mainly in the form of space heating (BÖDVARSSON 1961, PÁLMASON and ZOEGA 1970, PÁLMASON et al. 1975). When the energy crisis came on at the beginning of this decade, Iceland like most other countries tried to increase the use of the countries natural energy sources, hydropower and geothermal energy, in order to cut down the use of fossil fuel which has to be imported to the country. This effort has been fairly successful, as can be seen in Fig. 1. The total net energy consumption has increased by about 23% from 1972 to 1976. This increase has been met entirely by hydropower and geothermal energy. Over this four year period the hydropower consumption has increased by 40%, and the geothermal energy consumption by 43%. Despite the increasing number of cars and fishing vessels the oil consumption has stayed constant. Between 60 and 70% of buildings in Iceland are now centrally heated by thermal water. By using geothermal energy the nation is saving close to 2 metric tons of fossil fuel per inhabitant per year.

In geothermal research many scientific disciplines are involved. In Iceland various geological, geophysical, and geochemical methods are applied in order to locate and develop new geothermal fields (e.g. ARNÓRSSON et al. 1975, PÁLMASON 1975, STEFÁNSSON and ARNÓRSSON 1975, TÓMASSON et al. 1975). The present paper deals mainly with the application of one of these disciplines, volcanological research, in geothermal exploration in Iceland. A review will be made of the structural control of the flow pattern of the thermal water and examples will be presented of how volcanostratigraphic mapping, petrochemical, and lithological research can be put to use, and thus the term applied volcanology promoted.

2. Distribution of geothermal activity in Iceland

Iceland lies astride the Mid-Atlantic Ridge, and like other segments of an active ocean ridge Iceland is characterized by very high heat flow. The regional heat flow varies from about 2 HFU furthest away from the active volcanic zones crossing the country to about 7 HFU in some regions at the margins of the longest lived volcanic zone. The geothermal gradient as measured in over 100m deep drillholes outside known geothermal fields and outside zones of active volcanism, ranges from 37 $^{o}C/km$ to 165 $^{o}C/km$ (PÁLMASON 1973). With such a high thermal gradient it is normally not a problem to obtain high enough temperatures with deep drilling, but difficulties often arise in finding high permeability layers at depth within the strata.

Active volcanoes and high temperature areas (BÖDVARSSON 1961) are confined to the active zones of rifting and volcanism that run through the country (Fig. 2). The high temperature areas are thought to draw heat from both the very high regional heat flow in the volcanic zones and from local accumulations of igneous intrusions cooling at a shallow depth in the crust. The low temperature areas are, on the other hand, in Quaternary and Tertiary volcanics, and are thought to withdraw heat from the regional heat flow. This paper will mainly deal with geothermal exploration in the low temperature areas.

Fig. 2 shows the distribution of natural hot springs in Iceland. A comparison of the deuterium content of the thermal water and the local precipitation in the individual areas has shown (ÁRNASON 1976) that the thermal water is of meteoric origin. In most cases it is precipitation which has fallen in the highlands. There the water manages to percolate deep into the bedrock and then, driven by the hydrostatic gradient, flows laterally for distances of tens and up to 150km before it appears on the surface along dykes or faults on the lowlands. As previously mentioned the water is believed to take up heat from the regional heat flow during its flow through the strata, This model was originally proposed by EINARSSON (1942), but later verified by ÁRNASON'S isotope studies.

Fig. 3 shows ÁRNASON'S flow pattern for the thermal water, with arrows joining the individual hot spring areas with possible recharge localities (ÁRNASON 1976), superimposed on a geological map of Iceland. The arrows were drawn independently of the geological map. On basis of a comparison of the flow directions with hydrostatic pressure isolines of the country ÁRNASON concluded that the hot water appeared to "flow equally in every direction away from the highlands, without regard to the direction of the fissures in the surface rock". A close comparison of the geological map and the flow pattern arrows shows, however, a remarkably good correlation between the flow directions and the geological strike. This suggests that the water may flow along the same high porosity layers in the strata and/or dykes and faults along the strike all the way from the highlands to the lowlands. A detailed comparison of the flow pattern with unpublished data on dyke swarms in some Tertiary provinces indicates that there the dykes are more important as controlling factors for the regional flow than the stratiform horizons (SAEMUNDSSON, personal communication).

Further indication of the preferential flow of the water along stratiform horizons and/or dyke swarms (which generally have a direction deviating 0^{o}-30^{o} from the strike) is seen in the distribution of hot springs with regard to erosional features. Although hot springs are very widely distributed in Iceland (Fig. 2) there are certain areas, particularly in the eastern part of the country, that are almost devoid of thermal activity. A comparison of the distribution of hot springs and geological strike with the direction of major erosional features, such as fjords and valleys, shows that all the major thermal areas of the country are characterized by the erosional directions being approximately parallel to the strike. This implies that water can flow undisturbed along the same permeable horizons from the recharge areas in the mountains to the outflow areas in the lowlands. The regions that are devoid of hot springs, such as the eastern fjords, are on the other hand characterized by the erosional directions being nearly perpendicular to the strike directions. This can be interpreted in the way, that water that seeps into the bedrock in the mountains in these areas cannot flow for but a few kilometers along strike, as the permeable horizons and the dyke swarms are intersected by erosional features (valleys and fjords) at relatively short intervals. As the flow distance is so short and the hydrostatic gradient much disturbed, the water does not get the same opportunity to withdraw heat from the regional heat flow as water that flows undisturbed for tens of kilometers. Indeed the few hot spring localities in eastern Iceland are in areas where the erosional directions are nearly parallel to the strike of the bedrock (Fig. 2).

3. Geothermal flow channels and reservoir rocks

The crustal thickness of Iceland varies from 8 to 15km, and the crustal structure is known in a considerable detail from geological and seismic surveys (e.g. PÁLMASON and SAEMUNDSSON, 1974). The crust is formed almost entirely of igneous rocks. The uppermost 2 to 3km are composed of subaerial lavas and much subordinate airborne tuffs in the Tertiary provinces, but of subaerial lavas intercalated with morainic horizons and thick piles of hyaloclastites in the Quaternary provinces, which flank the active volcanic zones (Fig. 2). Each eruptive unit is fed by a dyke, and consequently the dyke intensity increases with depth in the crust. Below 3 to 4km the crust probably consists mostly of very low porosity impermeable intrusions (e.g. FRIDLEIFSSON, 1977). This layer (the oceanic layer, V_p= 6.5 km/s) may form the base to water circulation in the crust (BÖDVARSSON, 1961).

The Tertiary strata in Iceland are mostly composed of thick, compact low porosity flood basalt lavas, with only minor clastic beds. But interdigitated with the flood basalts are basaltic lava shields built of thin flow units (compound lavas), as well as localized silicic central volcanoes constituting thick piles of thin basaltic lavas, thick intermediate and acid lavas and pyroclastics. On basis of the structure and the relative primary porosity of the various rock types FRIDLEIFSSON (1975) proposed that potential geothermal reservoir rocks in the Tertiary strata could be divided into two groups (Table 1). The flow channels or aquifers forming the plumbing system from the recharge areas in the highlands to the hot spring areas in the lowlands are probably the thin, high porosity stratiform horizons of Group 1 (Table 1) as well as dykes and permeable faults (BODVARSSON 1961). The geothermal reservoirs, which are fed by the stratiform aquifers and which supply the water to the major hot springs, however belong probably to both Group 1 and Group 2.

Since 3 m.y. ago (SAEMUNDSSON 1974) there have been over twenty glaciations with intermittent warmer periods in the Iceland region. The continuous volcanic activity during this period is reflected in strata characterized by successions of subaerial lavas intercalated,at intervals corresponding to glaciations, with morainic horizons and thick (tens to hundreds of meters) and commonly elongated piles of subglacial volcanics. FRIDLEIFSSON (1975) divided the potential geothermal reservoir rocks of the Quaternary strata into two groups (Table 1). The flow channels from the recharge areas to the lowlands are thought to belong mainly to Group 3 (Table 1) as well as dykes and faults, but the reservoirs of the main hydrothermal systems are thought to belong to both Group 3 and Group 4.

The division between geothermal aquifers and geothermal reservoirs must clearly be a matter of debate, and a clear definition of the terms will not be attempted here. Low temperature thermal areas, where the free flow from wells can be multiplied several times by lowering the water table some tens of meters by pumping can, however, be regarded as supplied by reservoirs. The thermal areas, where the free flow from wells can only be doubled or so by pumping and a similar drawdown can similarly be regarded as being fed by individual, narrow aquifers. Both types of thermal areas are presently harnessed in Iceland.

4. Geological mapping

It is evident from the assumed nature of the flow channels and the geothermal reservoir rocks that detailed geological mapping on a regional scale is of a primary importance in the geothermal exploration. The volcanics are divided into mappable units on basis of lithology and paleomagnetic polarity directions. The average thickness and general characteristics of lava flows in individual units as well as the thickness variation and grain size distribution of volcanoclastics and sediments are studied. Dykes and faults are traced and the displacement on the latter measured when possible. After an area has been mapped in detail the potential aquifer horizons and reservoir rocks can be identified and subsequently tested by drilling.

A simplified cross section of Quaternary volcanic strata in SW-Iceland is shown in Fig. 4 to demonstrate this. The rocks are divided into two groups; lavas with relatively low primary porosity and hyaloclastites (including pillow lavas and pillow breccias) of a much higher primary porosity. In this particular area the regional geothermal gradient is 165 °C/km as measured in a 240m deep drillhole which had no aquifers. The country rock can therefore be assumed to be at a temperature of 100 °C or higher below a depth of 800m or so, if there is no hydrothermal convection in the strata. It is clear that an exploration well would be sited where the high porosity rocks are found below the 100 °C isotherm in the diagram. The primary aim of the exploration well would be to test whether there was active hydrothermal convection in the strata. Prior to the exact siting of the well, detailed geological and geophysical analyses would be made of the potential drilling area in order to locate and trace structural irregularities such as dykes and faults that might have enhanced the permeability of the strata locally.

In case the thickness of the high porosity volcanics can be expected to diminish downdip or when surface exposures are poor, attempts are made to trace the high porosity rocks by geophysical methods to a depth great enough so that the water in the pores is hot enough for commercial use. This is demonstrated in Fig. 5.

It should be stressed here that the model shown in Fig. 4 is greatly simplified, as high primary porosity of a rock does not necessarily mean high permeability. In a subglacially erupted hyaloclastite sequence for instance field analyses indicate that the pillow lava portion is relatively highly permeable, whereas the tuffaceous part is commonly impermeable. Direct laboratory measurements have not been carried out on the correlation between the primary porosity and the effective porosity of the various types of volcanics in the various stages of compaction and alteration. This is a very important field of study to pursue.

Experience from deep drilling has shown that aquifers in volcanic strata are most likely to occur at the contacts of lithological units, such as interbeds in a lava sequence, contacts of hyaloclastites and lavas,and contacts of dykes or other intrusives with the host rock. Table 2 (from TÓMASSON et al. 1975) shows the occurrence of aquifers as recorded by circulation loss during drilling in 29 wells (800-2045m deep) in the Reykir thermal area in SW-Iceland. The volume percentage of hyaloclastites (including pillow lavas and pillow breccias) ranges from 30 to 60% in these wells, the rest being mostly lavas It is apparent from Table 2 that aquifers are by far more likely to occur at contacts than in lavas alone or hyaloclastites alone.

This should be taken into account in well siting. For example in Quaternary volcanic strata large hyaloclastite mountains are sometimes literally buried in subsequent subaerial lavas that bank up against the hyaloclastite slopes. During intervals between lava eruptions aprons of sediments spread out over the lava plains at the base of the easily eroded hyaloclastite mountains. The overall effect of this is a "cedar-tree" structure with a bulky "stem" formed of mainly primary hyaloclastites (including pillow lavas and pillow breccias) with thin (tens of cm to tens of m), wedge shaped "branches" of resedimented hyaloclastite, intercalated in the lavas submerging the "stem" (FRIDLEIFSSON 1975). In order to drill through as many contacts between lithological units as possible it is clearly advisable to site a well at the margin of the bulky high porosity hyaloclastite body rather than into its center.

Detailed mapping of dykes and faults is very important, as these cause structural irregularities in the strata and commonly create significant secondary permeability. Natural hot springs in Iceland are most commonly located along dykes and faults, and especially in the Tertiary strata the main upflow zones are generally controlled by such structures. In Quaternary strata characterized by good reservoir properties and horizontal aquifers such as in the Reykjavik thermal area, dyke swarms appear, however, to act as impermeable barriers that separate harnessable thermal systems (TÓMASSON et al. 1975). Similarly in the Quaternary strata in the Reykir thermal area in SW-Iceland the deep wells drilled into the structural irregularities that controlled the main natural hot springs in that area yield significantly less than wells drilled some hundreds of meters away from the natural hot spring area (TÓMASSON, personal communication). Step faults in that area are thought to create vertical impermeable boundaries (THORSTEINSSON 1975).

5. Primary porosity of volcanics - petrochemical and lithological control

5.1 Subaerial lavas

The primary porosity of the central parts of simple lava flows does not vary significantly between the three main types of basalts of the tholeiitic suite (CARMICHAEL 1964), olivine tholeiites, porphyritic tholeiites, and tholeiites (Table 3). In comparing the porosity of the relatively thick simple olivine tholeiite flows with the thin olivine tholeiite flow units of compound lavas, FRIDLEIFSSON (1975) found that the primary porosity of the central part of a lava depends more on its thickness than its chemical composition. The average thickness of the various lava types is, however, related both to their chemical composition and the mode of the eruption (e.g. WALKER 1959, 1963, 1972).

By simple calculations assuming that the vesicular top and base of each basaltic lava has a porosity of 25% but the massive central part of each flow a porosity of 5% FRIDLEIFSSON (1975) showed that a suite of thin flank tholeiites, typical for the central volcanoes of Iceland, had about 50% higher primary pore volume than a suite of flood-basalt tholeiites. Similarly he showed that lava shields (olivine tholeiite compound lavas) could be expected to have about twice the primary pore volume of a normal flood-basalt sequence in Iceland.

5.2 Subaquatic volcanics

The term hyaloclastite is commonly used in the Icelandic geological literature in a collective sense for all subaquatic volcanic products. The subglacially erupted hyaloclastites in Iceland are generally formed in water shallower (commonly much shallower) than 1km. Due to the shallow depth the pillows may be highly vesicular (e.g. MOORE 1965), and the pillow breccia and tuff fraction is commonly very large. On basis of a comparison of the porosity (Fig.6) of fresh core samples of subaerial lavas and pillow lavas, both of olivine tholeiite composition, as well as reworked hyaloclastites and tillites, FRIDLEIFSSON (1975) concluded that the porosity of a typical subglacial hyaloclastite sequence appeared to be at least twice that of a subaerial lava sequence.

Experience from drilling indicates that pillow lavas generally speaking have higher effective permeability than other major rock types in Icelandic geothermal areas. During a glaciation,fissure eruptions (which are the most common volcanic type in Iceland) can produce series of parallel hyaloclastite ridges 1-5km broad, a few hundred meters thick, but up to tens of kilometers long. In subsequent subaerial eruptions lava flows may bank up against the ridges and eventually bury them. The core axis of the ridges is formed of pillow lavas, but this is coated on the sides and above by a thick layer of pillow breccias, and further out by tuffaceous hyaloclastite. The permeability of the core can be expected to be high, but the outermost glassy hyaloclastite layer can be expected to have very low permeability and thus serve as an aquiclude. TÓMASSON et al. (1975) suggested that such hyaloclastite ridges served as flow channels for the water from the central highlands to the thermal areas of Reykir and Reykjavik in SW-Iceland.

The primary porosity of a pillow lava sequence is of two types. Firstly there is the interspace between individual pillows, which is large because of the geometric shape of the pillows. Secondly there is the pore space of the pillow bodies themselves. Both factors are affected by the chemical composition of the pillows. Fig. 7 shows the variation of the average size of pillows with a change in the chemical composition (FRIDLEIFSSON et al., in preparation). Considering secondary mineralization processes it is likely that a close packed pillow sequence will be less effectively sealed by mineralization the larger the diameter of the pillow is. This is because of the inverse relation between the average diameter of the pillows and the surface area of the rock that is in contact with the water. Hence a sequence of large pillows can be expected to have higher effective porosity than a sequence of small pillows. Systematic porosity measurements of pillows of different compositions are in progress, but field inspection and preliminary laboratory results indicate that there is a very marked drop in porosity from Mg-rich olivine tholeiites to FeTi-rich quartz normative tholeiites. This effect is complementary with the decrease in the average diameter of pillows from olivine tholeiites to tholeiites. One implication of this is that effective porosity can be expected to be higher in the olivine tholeiite pillow sequences in the volcanic zone outside central volcanoes than in central volcanic sequences, which are very often dominated by quartz normative tholeiites.

6. Summary

The thermal water of low temperature areas in Iceland falls as precipitation in the highlands, percolates deep into the bedrock and (driven by the hydrostatic gradient) flows laterally for tens of kilometers through the volcanic strata before it appears along dykes and faults on the lowlands. Impermeable intrusions (the oceanic layer, V_p=6.5 km/s) probably form a base to the water circulation at a depth of 3-4km. The thermal water withdraws heat from the regional heat flow which is very high (2-7 HFU) due to Iceland's location astride a spreading ridge.

The correlation between the flow pattern of the thermal water (as deduced from deuterium studies) and geological structures indicates that the water flows preferentially along high porosity stratiform horizons and dyke swarms. This indication is further supported by a comparison of the distribution of natural hot springs, the geological strike, and the direction of major erosional features (valleys and fjords). The major low temperature thermal areas are characterized by the erosional directions being approximately parallel to the strike and/or the dyke swarms, thus allowing an undisturbed flow along the same permeable horizons or dyke swarms from the recharge areas to the hot spring areas. Areas where the erosional directions are approximately perpendicular to the strike and the direction of dyke swarms, are characteristically devoid of hot springs.

The flow channels forming the plumbing system from the recharge areas in the highlands to the hot spring areas in the lowlands are thought to vary from the Tertiary to the Quaternary provinces. In the subaerially erupted Tertiary volcanics the flow channels are thought to be mainly thin high porosity stratiform horizons and dykes. In the Quaternary strata, which is characterized by successions of subaerial lavas intercalated with thick piles of subglacially erupted hyaloclastites and detrital beds, potential flow channels are much more abundant. There the most effective flow channels are thought to be the pillow lava cores of hyaloclastite ridges, which come in addition to the high porosity stratiform horizons and dykes.

In Tertiary strata the main upflow zones of geothermal water are generally controlled by dykes and faults. In Quaternary strata characterized by good reservoir properties and horizontal aquifers, dyke swarms appear, however, to act as impermeable barriers that separate thermal systems.

Examples are given in the paper of the application of some geological, volcanological, and petrochemical methods in geothermal prospecting in a volcanic terrain. These include some methods for evaluating the relative primary porosity distribution of volcanic strata formed in different environmental conditions and with varying magmatic compositions.

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Table 1

Potential geothermal reservoir rocks in Iceland (from FRIDLEIFSSON 1975)

TERTIARY	GROUP 1	Stratiform horizons of pyroclastics, ignimbrites, sediments, and olivine tholeiite compound lava shields.
	GROUP 2	Local accumulations in central volcanoes of high porosity lavas, pyroclastics, agglomerates, and hyaloclastites* (in caldera lakes).
QUATERNARY	GROUP 3	Same as GROUP 1 plus primary and reworked subglacial hyaloclastites.* Hyaloclastite* horizons reach maximum thickness over the eruptive sites.
	GROUP 4	Local accumulations in central volcanoes of hyaloclastites* and subaerial eruptives same as in GROUP 2.

* The term hyaloclastite is here used in a collective sense for all subaquatic volcanic products, thus comprising pillow lavas, pillow breccias and tuffs.

Table 2

Occurrence of aquifers in the different rock types of 29 drill holes (from TÓMASSON et al. 1975)

Rock type	Aquifers ≤ 2 l/s	>2-20 l/s	>20 l/s	Total number
Lavas	44	27	2	73
Hyaloclastites*	29	12	4	45
Dolerites		1	1	2
Lavas + hyaloclastites*	53	38	20	111
Lavas + dolerites	13	1	3	17
Hyaloclastites*+ dolerites	5	2	1	8

* The term hyaloclastite is here used in a collective sense for all subaquatic volcanic products, thus comprising pillow lavas, pillow breccias, and tuffs. Included in this group are also reworked hyaloclastites and detrital beds.

Table 3

Average porosity of the central part of basaltic lavas of the tholeiitic series (from FRIDLEIFSSON 1975)

Lava type	No. of samples	Average porosity	Standard deviation
Tholeiite	8	0.048	0.026
Porphyritic tholeiite	6	0.039	0.020
Olivine tholeiite (simple)	3	0.033	0.012
Olivine tholeiite (flow units)	7	0.134	0.056

FIGURE CAPTIONS

Figure 1 A comparison of the net energy consumption of Iceland in 1972 and 1976.

Figure 2 Geological map of Iceland (compiled by SAEMUNDSSON 1973) showing the distribution of natural geothermal activity (compiled by JÓNSSON 1967) and the direction of major erosional features (valleys and fjords). The volcanic strata dip towards but age away from the active volcanic zones. High temperature areas (with temperatures above 200 °C in the uppermost 1 km) are confined to the active zones of rifting and volcanism. The low temperature activity is most intense in areas where the major erosional directions are approximately parallel with the geological strike.

Figure 3 The general flow pattern of thermal groundwater systems in Iceland according to deuterium measurements (ÁRNASON 1976) superimposed on the geological map of Iceland (compiled by SAEMUNDSSON 1973). The arrows join the thermal areas in the lowlands with possible recharge areas in the highlands. The arrows were modified such that they are almost perpendicular to the isolines of average topographic heights based on rectangular areas of 520 km^2 (ÁRNASON 1976). The arrows were drawn independently of the geological map. Note how closely the flow direction arrows generally fall with the geological strike.

<u>Figure 4</u> Schematic cross section of Quaternary volcanic strata in SW-Iceland. The lavas are of a relatively low porosity compared with the subglacially erupted hyaloclastites, which include large proportions of pillow lavas and pillow breccias. The 100 °C isoline is drawn on basis of a 240m well (with a linear thermal gradient) in the left hand side of the picture. An exploration well to test for hydrothermal convection would be sited in the right hand side of the diagram, where the high porosity rocks are at a depth great enough so that the water in pores and fractures is hot enough for commercial use. In fact the thermal areas of Reykir and Reykjavik (TÓMASSON et al. 1975) would project on the right hand side of this section. The thermal areas are characterized by hydrothermal convection, and the best wells (1-2 km deep) yield over 70 l/s of 80-90 °C water by pumping with a drawdown of 30m or less (THORSTEINSSON 1975).

Figure 5 A combined geological (above sea level) and electrical resistivity (below sea level) section of Quaternary strata in SW-Iceland, demonstrating how prominent high porosity bodies (in this case sub-glacially erupted hyaloclastites) can be traced to depths of more than 1 km by resistivity soundings (from TÓMASSON et al. 1975).

Figure 6 The percentage distribution of porosity (core samples from drill holes crushed to $\leqq$ 1mm grain size) of fresh subaerial lavas, subaquatic pillow lavas, tillites, and reworked hyaloclastites (from FRIDLEIFSSON 1975). The volcanics are of olivine tholeiite composition.

Figure 7 Variation diagram of the diameter (average of the vertical and horizontal axes) of subglacially erupted pillows versus the $\% K_2O$ composition of the pillows (FRIDLEIFSSON et al, in preparation). The standard deviation is shown by bars. The composition of the rocks and the number of measurements at each locality is the following; olivine tholeiite L(100), M(256), S(100), St(49); tholeiite T(140); basaltic andesite Sf(66); andesite H(40), Lo(67). The rock classification is according to CARMICHAEL (1964).

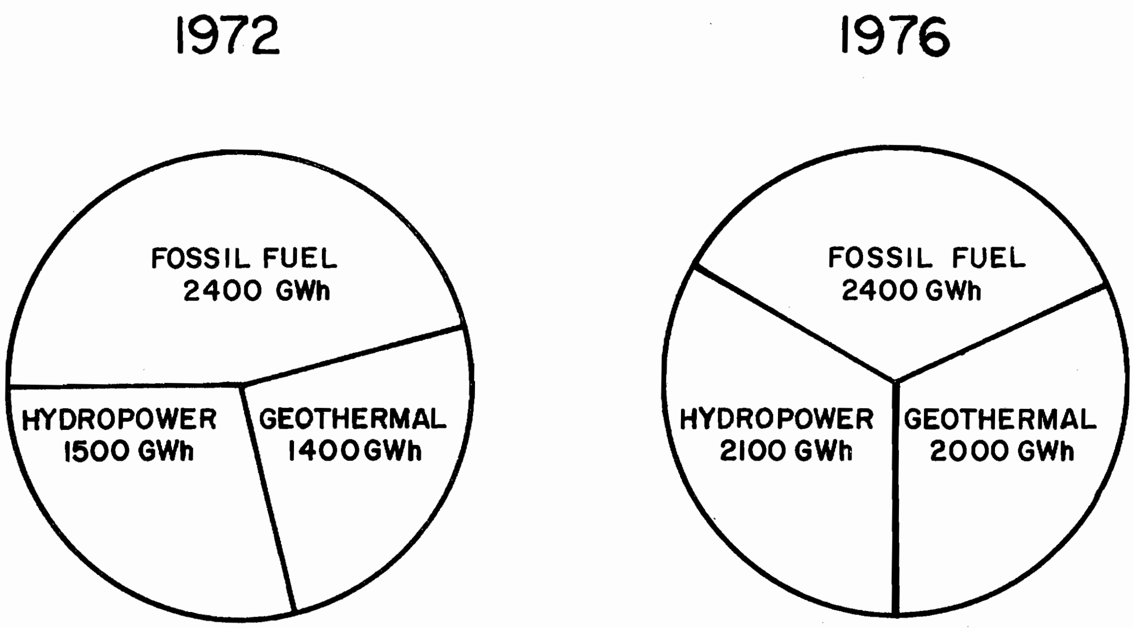
1972
1976
FOSSIL FUEL
2400 GWh
HYDROPOWER
1500 GWh
GEOTHERMAL
1400 GWh
FOSSIL FUEL
2400 GWh
HYDROPOWER
2100 GWh
GEOTHERMAL
2000 GWh

Figure 1

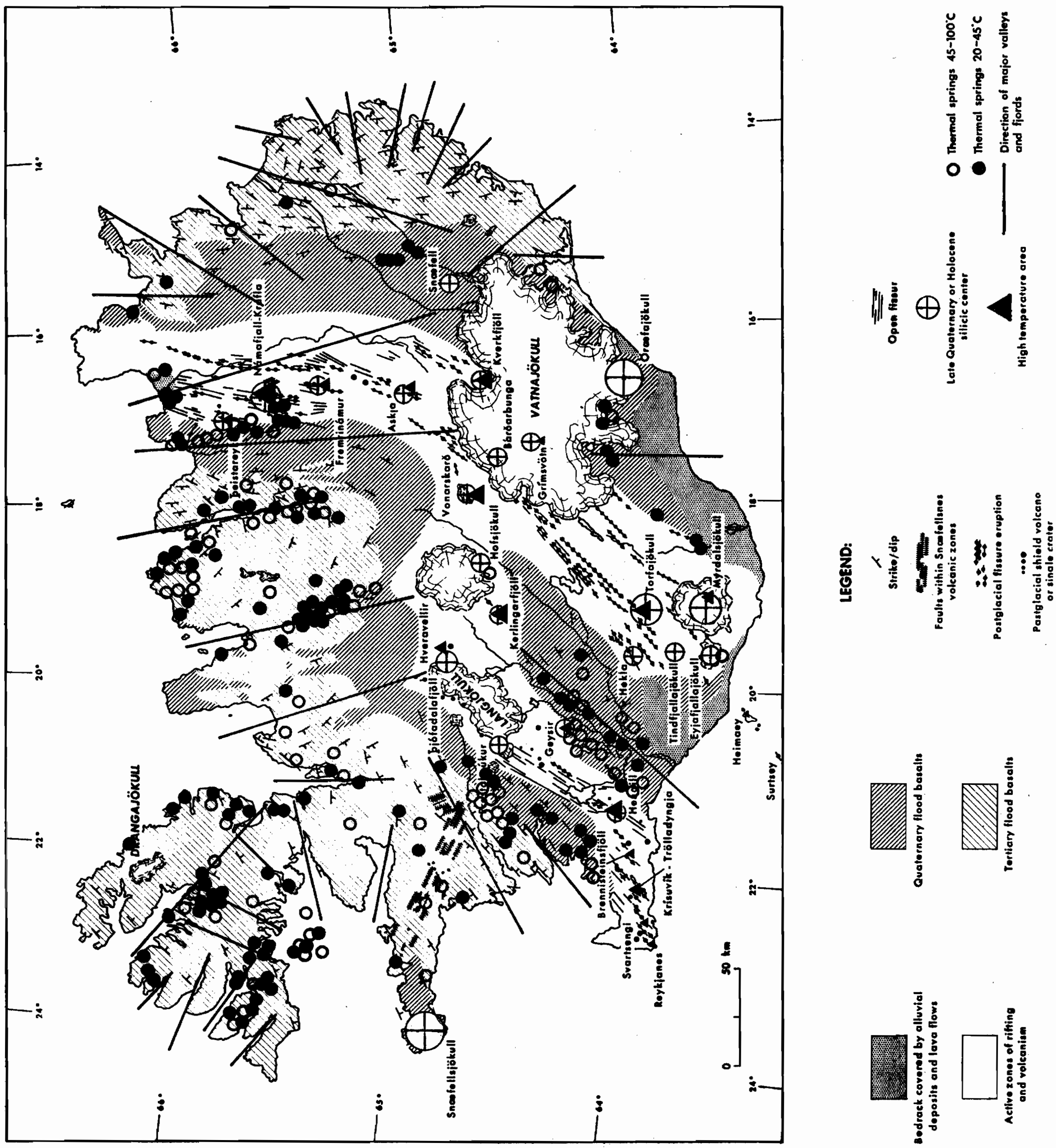
DRANGAJÖKULL
Snæfellsjökull
Reykjanes
Svartsengi
Krísuvík - Trölladyngja
Brennisteinsfjöll
Hengill
Geysir
Hekla
Tindfjallajökull
Eyjafjallajökull
Heimaey
Surtsey
Mýrdalsjökull
Torfajökull
Kerlingarfjöll
Hofsjökull
Hveravellir
LANGJÖKULL
Vonarskarð
Grímsvötn
Bárðarbunga
VATNAJÖKULL
Kverkfjöll
Askja
Fremrinámur
Þeistareykir
Námafjall-Krafla
Snæfell
Öræfajökull
0
50 km
LEGEND:
Bedrock covered by alluvial deposits and lava flows
Active zones of rifting and volcanism
Quaternary flood basalts
Tertiary flood basalts
Strike/dip
Faults within Snæfellsnes volcanic zones
Postglacial fissure eruption
Postglacial shield volcano or single crater
Open fissure
Late Quaternary or Holocene silicic center
High temperature area
Thermal springs 45-100°C
Thermal springs 20-45°C
Direction of major valleys and fjords

Figure 2

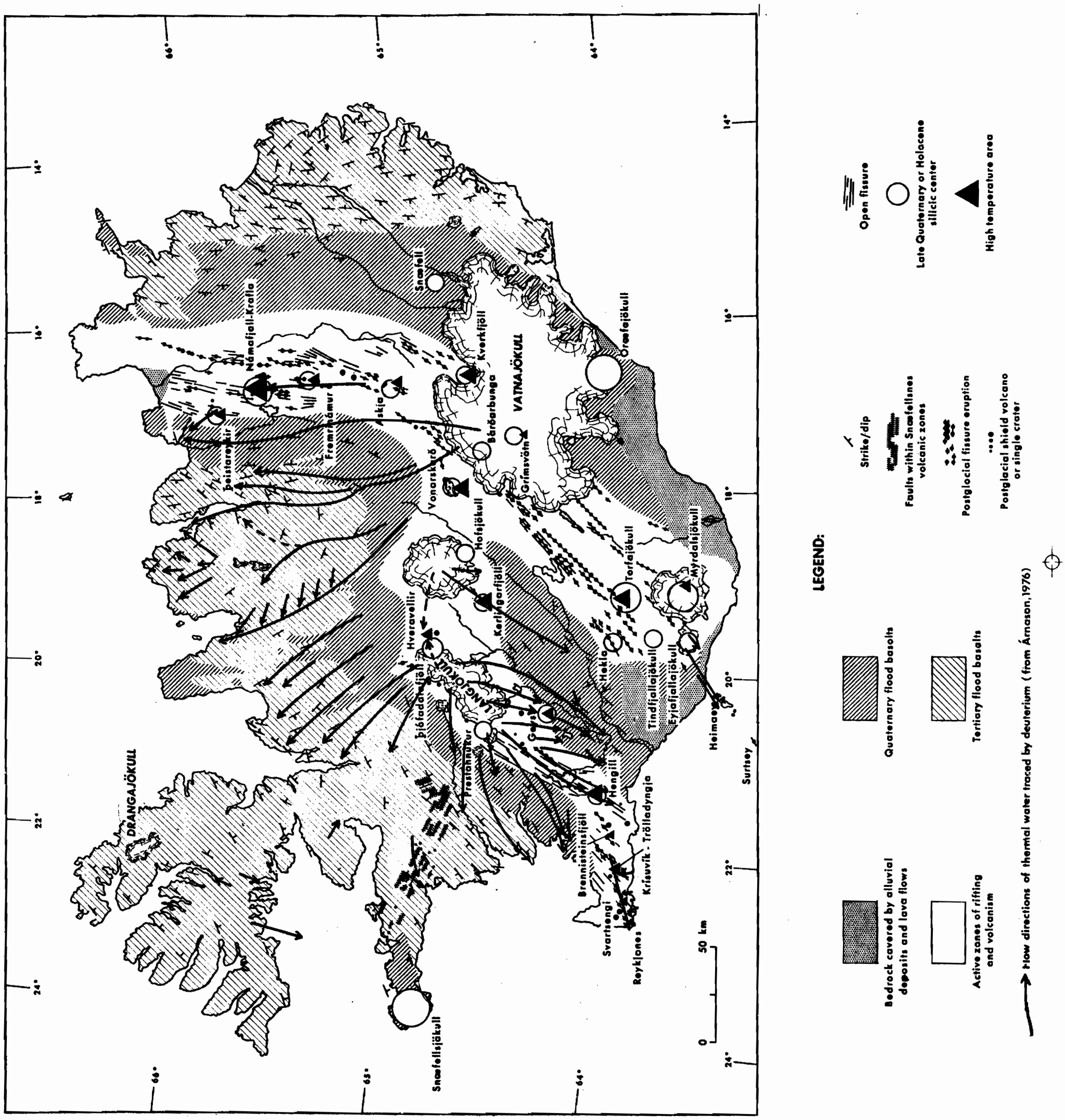
DRANGAJÖKULL
Snæfellsjökull
Reykjanes
Svartsengi
Krísuvík - Trölladyngja
Brennisteinsfjöll
Hengill
Surtsey
Heimaey
Geysir
Prestahnúkur
Þjófadalafjöll
Hveravellir
LANGJÖKULL
Kerlingarfjöll
Hofsjökull
Hekla
Tindfjallajökull
Eyjafjallajökull
Torfajökull
Mýrdalsjökull
Vonarskarð
Grímsvötn
Bárðarbunga
VATNAJÖKULL
Kverkfjöll
Öræfajökull
Snæfell
Askja
Fremrinámur
Námafjall-Krafla
Þeistareykir
0
50 km
LEGEND:
Bedrock covered by alluvial deposits and lava flows
Active zones of rifting and volcanism
Quaternary flood basalts
Tertiary flood basalts
Strike/dip
Faults within Snæfellsnes volcanic zones
Postglacial fissure eruption
Postglacial shield volcano or single crater
Open fissure
Late Quaternary or Holocene silicic center
High temperature area
Flow directions of thermal water traced by deuterium (from Árnason,1976)

Figure 3

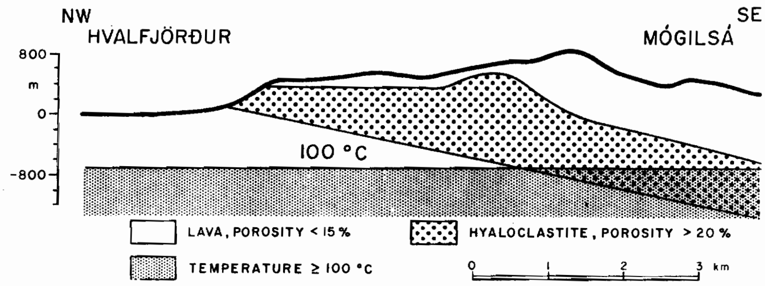
NW
HVALFJÖRÐUR
SE
MÓGILSÁ
800
m
0
-800
100 °C
LAVA, POROSITY < 15 %
HYALOCLASTITE, POROSITY > 20 %
TEMPERATURE ≥ 100 °C
0
1
2
3 km

Figure 4

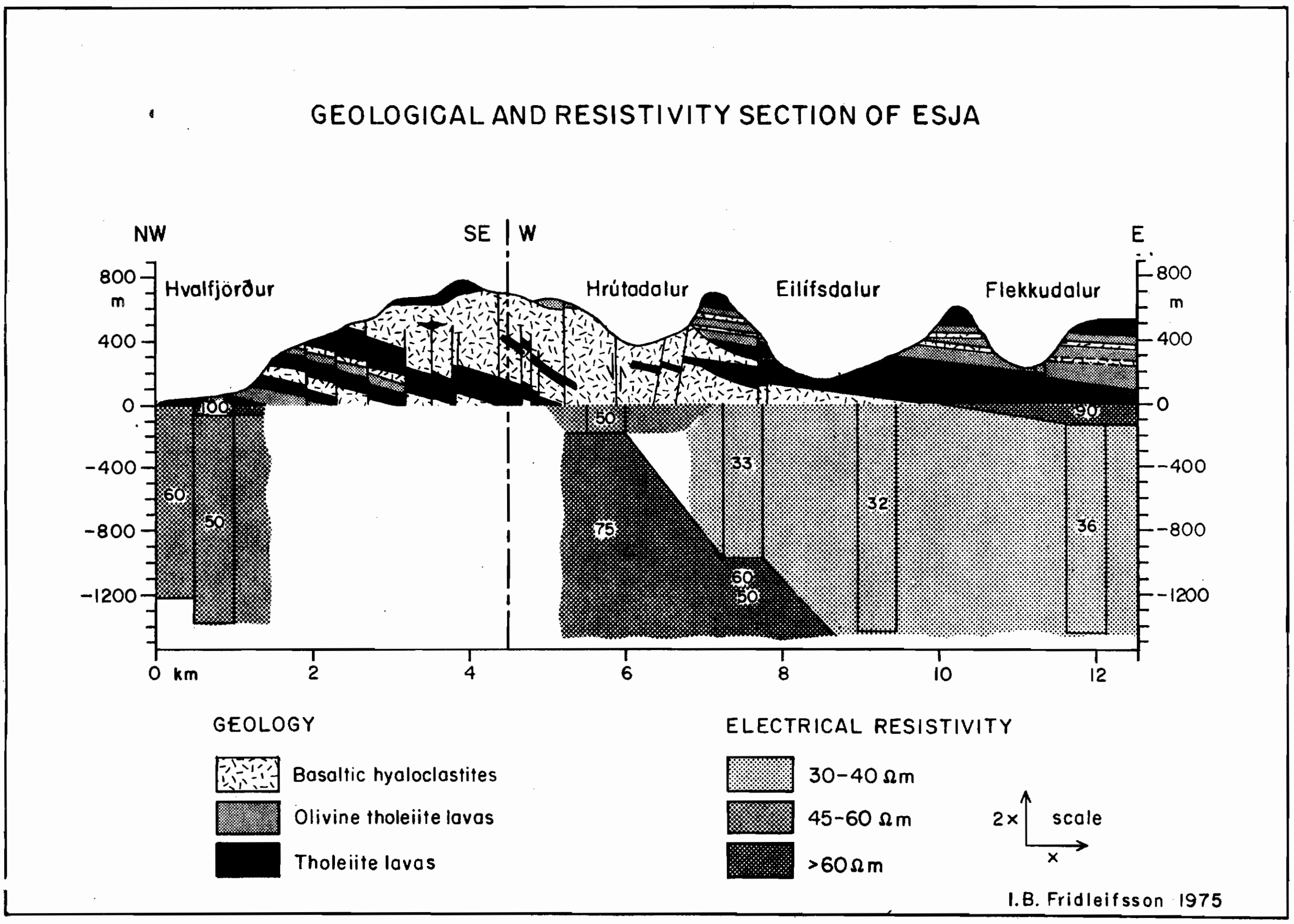
GEOLOGICAL AND RESISTIVITY SECTION OF ESJA
NW
SE
W
E
800
m
400
0
-400
-800
-1200
Hvalfjörður
Hrútadalur
Eilífsdalur
Flekkudalur
100
60
50
50
75
33
32
36
60
50
90
0 km
2
4
6
8
10
12
GEOLOGY
Basaltic hyaloclastites
Olivine tholeiite lavas
Tholeiite lavas
ELECTRICAL RESISTIVITY
30-40 Ωm
45-60 Ωm
>60 Ωm
2×
scale
x
I.B. Fridleifsson 1975

Figure 5

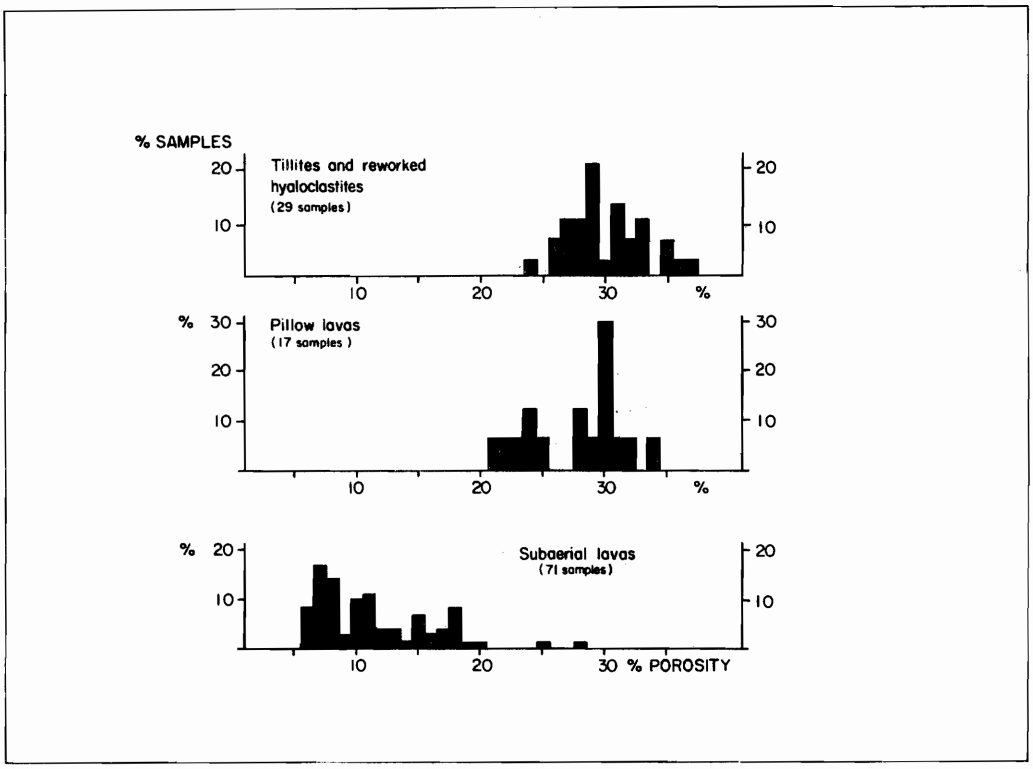
% SAMPLES
Tillites and reworked hyaloclastites
(29 samples)
Pillow lavas
(17 samples)
Subaerial lavas
(71 samples)
% POROSITY

Figure 6

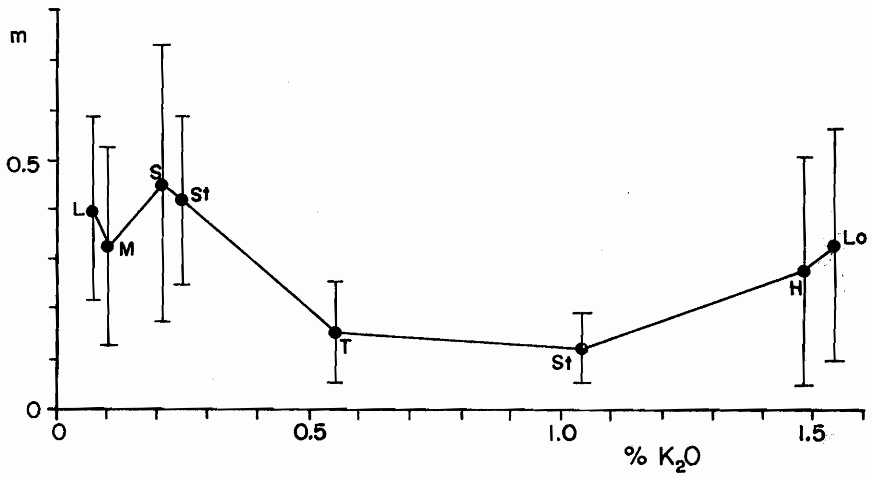

Figure 7