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LITHOLOGY AND STRUCTURE OF GEOTHERMAL RESERVOIR ROCKS IN ICELAND

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ABSTRACT

The two main factors controlling the distribution of low temperature hydrothermal activity in Iceland are i) the regional heat flow, and ii) the lithology and structure of the strata. The island is built almost entirely of volcanic rocks, but variations in a) environmental conditions at the eruptive site, and b) the chemical composition of the volcanics, cause significant variations in factor ii) above.

During the upper Tertiary the eruptives were mostly thick, compact, subaerial flood basalt lavas with minor clastic beds; hence the overall porosity of the pile is very low. Central volcanoes with thin basalt lavas, intermediate and acid lavas, breccias and tuffs interdigitate with the flood basalts and cause localised (20 km diameter) accumulations of relatively porous rocks, which may serve as reservoir rocks for hydrothermal systems.

Since 3 M.y. ago there are indications of over twenty glaciations in Iceland. The continuous volcanic activity during the Quaternary is reflected in successions of subaerial lavas intercalated, at intervals corresponding to glaciations, with morainic horizons and thick, elongated piles of subglacial volcanics, which form structural irregularities in the strata. Since the porosity of subglacial volcanics is approximately twice that of the lavas, the Quaternary provinces are characterized by regional accumulations of porous rocks which make ideal reservoirs for hydrothermal systems.

Intrusive activity, faulting and tilting produces secondary permeability which greatly affects the flow of thermal water so as to make it more easily harnessed.

INTRODUCTION

Iceland lies astride the Mid-Atlantic Ridge and has been the site of volcanic eruptions continually from the upper Tertiary to the present day (Thorarinsson, 1965). The heat flow decreases and the volcanics age more or less symmetrically away from the active volcanic zone in Iceland (Palmason and Saemundsson, 1974), as can be expected at a constructive plate margin. The geothermal gradient is very high in Iceland compared to most parts of the world. It ranges from about 40°C/km in the oldest Tertiary rocks to about 160°C/km in early Quaternary rocks adjacent to the active volcanic zone (Palmason, 1973, 1974). In view of the high geothermal gradient it is no wonder that hydrothermal activity is widespread in Iceland (Bodvarsson, 1961; Arnorsson et al, 1969; Arnorsson, 1974).

It appears that the distribution and intensity of hydrothermal activity in Iceland is mainly controlled by i) the regional heat flow, and ii) the lithology and structure of the essentially volcanic strata. The scope of the present paper is to look at the latter factor. It will be argued that the lithology is critically dependant on both the chemical composition of the eruptives and the environmental conditions during eruption. It will be pointed out that the structure of the strata is further controlled by the volcanic and tectonic development both while the potential reservoir rocks are within the active volcanic zone, and after drifting out of the zone due to plate movements.

THE POROSITY OF ROCKS IN ICELAND

Nearly all rocks in Iceland are of volcanic origin, ranging in age from about 20 M.y. to present (Palmason and Saemundsson, 1974). Sediments, which make up less than 10% of the Tertiary strata (Walker, 1959; Einarsson, 1963), are derived from the volcanics through the action of wind and water. These agents have been greatly aided by glaciers since the beginning of the Quaternary giving rise to an increased sediment proportion in the strata.

Subaerial volcanics

Subaerial volcanic products (Macdonald, 1972) can in general be divided into two categories: lavas which flow from the crater, and airborne volcanic tephra (pyroclastics). The character and relative volume proportions of these two categories in the individual volcanic eruption is greatly dependant on the chemical composition of the magma. Basaltic eruptions are characterised by the preponderance of lavas, but the volume proportion of airborne material generally increases with increased acidity of the magma.

Basaltic lavas can normally be divided into a scoriaceous and often rubbly top and bottom and an inner massive central part. The scoria is compressed when the lavas are buried under younger strata. The aggregate thickness of the vesicular top and bottom subsequent to compression is commonly (in the authors experience) of the order of 1 m, largely irrespective of the total thickness of the lava flow. The thickness of the massive central part depends both on the chemical composition (i.e. viscosity) and the topography in which the lava flows.

Olivine tholeiite* lavas sometimes form lava shields characterised by numerous thin flow units (Walker, 1971), which are highly vesicular right through. Simple olivine tholeiite flows are, however, also common in Iceland, but they tend to be thinner than the olivine free tholeiite flows; Walker (1959) obtained an average thickness of 7 m for 170 flows of the former type but an average of 10 m for 250 flows of the latter type. Olivine tholeiite lavas are normally rich in vesicles, and vertical pipe vesicles are (in Icelandic rocks) practically confined to this type (Walker, 1959).

Olivine free tholeiites more commonly occur as simple flows. They are usually not markedly vesicular, but such vesicles as do occur are often large (Walker, 1959). Plagioclase porphyritic tholeiites tend to be similar if not more massive in character than the tholeiites. Intermediate and acid lavas tend to be much thicker than their basic contemporaries, the rhyolites sometimes reaching 60 m or more (Walker, 1959).

* Icelandic rocks are predominantly of a tholeiitic composition and petrologically similar to the now classical Thingmuli series (Carmichael, 1964, 1967). The discussion on porosity will be confined to rocks of the tholeiitic series.

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Table 1 shows the average porosity* of basaltic lava types typical for the tholeiite series. Most of the samples were originally collected for chemical analyses (Fridleifsson, 1973), and are therefore from the densest parts of the individual lava flows. There is not a significant difference between the porosity of the three types of simple flows, but the olivine tholeiite flow units are three or four times more porous than the others.

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TABLE 1

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The porosity of the central part of a lava depends more on its thickness than the chemical composition of the lava. The center of a thick flow may cool and solidify slowly enough to allow most of the gas to escape, and the resulting rock is dense.

The porosity of compacted pyroclastics and vesicular tops of lavas is highly variable, but values between 20 and 30% have been measured in several samples.

* Porosity measurements were made both on whole rock samples and on samples crushed to $\leq$1 mm grain size. Only the values for crushed samples are quoted in the paper. The volume of the samples was measured by immersion in distilled water under vacuum, and the rock density with a pycnometer. The method is described by Palsson (1972).

Subaquatic volcanics

Subaquatic volcanics include pillow lavas, pillow breccias and tuffs (e.g. Jones, 1970). The size and vesicularity of pillows depends both on the chemical composition of the magma and the depth of the water into which it is erupted. Icelandic hyaloclastites are typically formed in water shallower (commonly much shallower) than 1 km. Due to the shallow depth the lithic rock may be highly vesicular (e.g. Moore, 1965), and the pillow breccia and tuff fraction is commonly very large. Tuffaceous hyaloclastites are much more easily eroded than lavas. Reworked but short transported hyaloclastites are therefore a common feature.

No systematic study has been made of the porosity of the various facies of subaquatic volcanics in Iceland. But to illustrate how the porosity compares with that of lavas Fig. 1 shows the percentage distribution of porosity in late Quaternary to recent lavas, pillow lavas, tillites and reworked hyaloclastites from the Tungnaa area in southern central Iceland (data from Palsson, 1972). The pillows tend to be the densest parts of a hyaloclastite sequence. Fig. 1 indicates that the porosity of a hyaloclastite sequence is at least twice that of a subaerial lava sequence.

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Fig. 1

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Rock alteration

The effects of progressive alteration (Walker, 1960) on the porosity of the different rock types will not be discussed here due to lack of data. From the little available data it can, however, be stated, that the relative porosity of lavas and hyaloclastites does not change significantly. The permeability of all the rock types will, on the other hand, decrease markedly with alteration.

THE POROSITY OF TERTIARY STRATA

The Tertiary strata in Iceland are mostly composed of plateau-basalt lavas, but interdigitated with these are local accumulations of basic, intermediate and acid lavas and tuffs erupted from silicic central volcanoes. In a study of a Tertiary area of 500 - 600 km^2 in Reydarfjordur, eastern Iceland, Walker (1959) estimated in a pile of some 4.5 km thickness the following proportion of rock types in the strata: olivine (tholeiite) basalts 23%, tholeiite basalts 48%, plagioclase porphyritic basalts 12%, andesites 3%, rhyolites 8% and detrital beds 6%. The proportion of intermediate and acid types relative to the basalts in the strata diminishes rapidly with distance from a central volcano.

Flood basalts

Apart from the detrital beds (sedimentary and pyroclastic rocks), the only layers with a high primary porosity in the flood basalt pile are the vesicular tops and bases of lava flows, which form probably about 10% of any particular flood basalt sequence. If, however, the olivine tholeiites are in the form of compound lavas (flow units) the aggregate thickness of the flows can be looked on as having a porosity similar to the vesicular tops and bases of normal flows. The shield forming olivine tholeiites may therefore form significant water reservoirs on a regional scale within the strata. The volume of the largest postglacial lava shield known in Iceland is estimated 17 km^3 (Kjartansson, 1967) but several are known with a volume exceeding 1 km^3. Assuming a porosity of 5% for the massive central part and 25% for the vesicular tops of flood basalts and 15% for flow units, a lava shield of 10 km^3 would contain 1.5 km^3 pore volume as opposed to 0.7 km^3 pore volume of a normal flood basalt sequence.

The detrital beds in the Tertiary strata are mainly in the form of thin (normally less than 1 m) partings of windblown dust and pyroclastics (which locally may reach tens of meters) between successive lava flows, but waterlaid sediments (laminated silt, sandstone and conglomerate) are much less common (Einarsson, 1963). Prominent sedimentary horizons have, however, been found on regional scale in rocks of Pliocene age in the Borgarfjordur area, W. Iceland (Johannesson and Saemundsson, 1975), where they are found to comprise nearly 20% of a 2.7 km thick succession. The sediments are of fluvial and lacustrine origin and do not occur randomly, but tend to group at certain levels in the pile where they may reach up to 50% of the rock. The average porosity of the sediments is probably over 20%, and these sediments may be of importance both as reservoir rocks for water and as aquifers.

Central volcanoes

About 40 central volcanoes have now been identified within the Tertiary regions in Iceland (Saemundsson, 1975) and nearly half of these have been mapped in detail. The Breiddalur volcano in eastern Iceland (Walker, 1963) can be taken as typical of these. It has a volume of about 400 km^3 of basic, intermediate and acid lavas and pyroclastic rocks, with a maximum thickness of 1500 to 1800 m. At times the volcano stood up as a cone above the flood basalt plains, but flood basalts were all the time being erupted; they were interdigitated with the products of the volcano and later completely buried it. Walker divided the volcano into two main groups, the core and the flanks (Fig. 2). The core is marked by a profusion of acid lavas, pyroclastic rocks and minor intrusions; in it the rocks are drastically altered and show variable and sometimes abnormally high dips indicative of cauldron-subsidence. The flanks of the volcano are made up predominantly of unusually thin tholeiite lavas which sometimes have a rubbly top of aa type, and at other times of pahoehoe type. Vesicles are abundant, particularly near the top of a flow, and a distinctive feature is their frequent large size; vesicles 30 cm or more across are common (Walker. 1963). The small thickness of the lavas is attributed to eruption on the sloping flanks of the volcanic cone.

Walker found the average thickness of 242 tholeiite lavas from the flanks of the volcano to be 4 m, and in sharp contrast with the average thickness of 14 m obtained for 266 tholeiite flows in the flood basalt succession.

In order to demonstrate that extinct central volcanoes may be potential reservoir rocks in the Tertiary strata we can make a simple calculation. First we assume that the entire volcano (400 km^3) consists of tholeiite lavas with an average thickness of 4 m and that the aggregate thickness of vesicular top and base of each lava is 1 m. Secondly we assume that the vesicular part of each lava has a porosity of 25%, but the massive central part of each flow a porosity of 5%. Then we find that out of the 400 km^3 volcano 40 km^3 is pore volume in contrast to a pore volume of 26 km^3 for the same rock volume consisting of 14 m thick tholeiite flows with 1 m thick vesicular parts. The pore volume in the flank tholeiites would thus be about 50% higher than that in the flood-basalt tholeiites.

The intermediate and acid lavas are commonly glassy or felsitic and have a relatively low primary porosity except some of the more acid types. which are fissile. The intermediate and acid lavas have a higher viscosity, they tend to be thicker and normally flow much shorter distances than the basic lavas (Walker, 1959, 1973).

It is felt that the main contribution of the intermediate and acid lavas to the overall porosity of a potential reservoir rock (buried central volcano) is that they create irregularities in the strata. The contacts between the acid lavas and the basic lavas that submerge them may be potential aquifers.

The volume of pyroclastic tuffs and breccias is variable from one central volcano to another, and hyaloclastites have been formed in caldera lakes in some of the volcanoes. Pyroclastics, more notably the acid ones, are sometimes dispersed hundreds of km away from the volcano by the wind and form a tephra layer that thins and widens away from the volcano (Thorarinsson, 1967). The porosity of the pyroclastics when compressed is usually over 20%. Of particular interest, even though rare*, are the voluminous welded tuffs (ignimbrites), which are usually highly and in some places extremely vesicular. The original extent of one of these Tertiary tuffs is estimated to have been over 400 km^2 of which 260 km^2 are welded and with an average thickness of about 8 m (Walker, 1962). The pyroclastics, in particular the coarse grained basic ones and the ignimbrites, may be of considerable importance both as reservoir rocks and as aquifers.

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* Walker (1962) estimates that welded tuffs make up only 1/3 per cent of the total Tertiary volcanic pile in eastern Iceland.

THE POROSITY OF QUATERNARY STRATA

During the Tertiary the volcanism in Iceland was mostly subaerial and the volcanic products therefore subaerial lavas and much subordinate airborne tuffs. Some 3 M.y. ago the climate changed and since then to the present day there have been over twenty glaciations with intermittent warmer periods. During the glaciations most of the island has been covered by thick sheets of ice. Subglacial volcanics tend to pile up around the eruptive orifice, and thus produce a much greater relief in the topography than do subaerial lavas. Erosion also becomes much more rapid, and less controlled by tectonic features, after the onset of glaciations.

After a glaciation, hyaloclastite ridges and hills with steep slopes (equivalents to the fissure and shield volcanoes of the plateau basalts) are the dominant feature of the topography. In subsequent volcanic eruptions lava flows bank up against the hyaloclastites or flow down their slopes depending on the eruptive site. The lavas may fill the valleys between the hyaloclastites and eventually bury them (Fig. 3). Some of the lavas may be very thin due to flowing down steep slopes, but others may reach great thickness due to ponding in topographic depressions.

Due to the rugged topography after a glaciation, valleys, a short distance apart, may be physically isolated from one another. Thus, an absence of volcanism in one valley may allow the development of aprons of sediments spreading out over the lava plains at the feet of the easily eroded hyaloclastite mountains, while simultaneously, active volcanism in an adjacent valley may give rise to a pile of lavas with no sedimentary intercalations. The overall effect of this is a "cedar-tree" structure with a bulky "stem" formed of mainly primary hyaloclastites with thin (tens of cm to tens of m), wedge shaped "branches" of resedimented hyaloclastite, intercalated in the lavas submerging the "stem". The number of the "branches" depends on the rate of erosion of the stem and the rate of eruption of lavas submerging the "stem" (Fridleifsson, 1973).

Due to the high porosity of the hyaloclastites (20 - 30%) good reservoirs on a regional scale are common in the Quaternary strata. The largest reservoirs (several hundred km^3) can be expected in the vicinity of the central volcanoes due to their high volcanic production rate. Large reservoirs may be interconnected by "channels" formed of hyaloclastite ridges buried in the strata. The numerous hyaloclastite intercalations between successive subaerial lava flows increase the number of contacts of lavas and hyaloclastites (primary or reworked) many times the number of glaciations. Such contacts are probably the most common aquifers in the low temperature areas in Quaternary volcanics in Iceland (Tomasson et al, 1975).

STRUCTURE OF THE RESERVOIR ROCKS

We can divide potential reservoir rocks in the Tertiary and Quaternary provinces into four groups:

TERTIARY

Group I: Relatively thin, stratiform horizons of high porosity rocks such as pyroclastics, ignimbrites, sedimentary horizons, and olivine tholeiite compound lava shields.

Group II: Local accumulations in the vicinity of central volcanoes of relatively high porosity lavas, agglomerates, tuffs, hyaloclastites (in caldera lakes), and contacts of structurally irregular extrusives.

QUATERNARY

Group III: Stratiform horizons same as in Group I plus primary and reworked high porosity hyaloclastites intercalated between subaerial lavas of variable thickness. The individual hyaloclastite horizons reach greatest thickness over the eruptive sites.

Group IV: Local accumulations in the vicinity of central volcanoes of mostly primary high porosity hyaloclastites and subaerial eruptives similar to those of Group II.

Group III is probably often more porous than Group II on a regional scale.

High porosity does not necessarily mean high permeability. High porosity material can often be impermeable. But we think that secondary permeability is more easily produced in rocks of a high primary porosity, which tend to break up very irregularly, than in rocks of a low primary porosity which break up in more clear cut lines. Intrusive activity, faulting, and tilting is thought to play an important role in producing secondary permeability, and in directing the flow of water from reservoirs at depth towards the surface.

Near vertical dykes (mostly 0.5 to 5 m thick) are by far the most common intrusions in the Icelandic strata. Walker (1960) demonstrated the progressive increase of dyke density with depth in the lava pile in eastern Iceland and showed (Walker, 1963) that narrow dyke swarms (where dykes make up 10 to 20% of the country) are commonly associated with the central volcanoes. Natural thermal springs are commonly linearly distributed along dykes (Bodvarsson, 1961), especially in the Tertiary provinces, and the dykes and/or faults associated with them thus act as permeable channels from porous horizons at depth to the surface. Dyke swarms can, however, also act as impermeable barriers that divide thermal systems, as is suggested for the Reykjavik thermal area (Tomasson et al, 1975).

Minor intrusions, such as irregular sheets and sills, are abundant in the immediate vicinity of the central volcanoes, but rare in the plateau basalts. Centrally inclined sheet swarms have been found in the majority of the central volcanoes investigated to date in Iceland. Intrusions larger than 1 km^2 in surface exposures are very rare in Iceland and all known examples are associated with central volcanic complexes. The majority of basaltic intrusions falling into this category are intruded into soft and "structureless" host rocks such as tuffaceous hyaloclastites, sediments, vent and caldera agglomerates, hydrothermally propylitized lavas (which behave structurally similarly to tuffaceous hyaloclastites) and "hot" and still partly liquid acid intrusive material (Fridleifsson, 1973). All types but the last in this list are relatively high porosity rocks. The emplacement of the intrusions will probably commonly produce secondary permeability in the porous host rocks.

The depth to seismic layer 3 (V_p= 6.5 km/s) is mostly in the range 2 to 5 km in Iceland (Palmason, 1971),but all the sites where layer 3 has been recorded at depths less than 2 km are associated with central volcanoes. This layer, which probably consists mostly of very low porosity, impermeable intrusions, is thought to form a base to water circulation in the crust.

While the shallow level intrusions are cooling most of the heat will be dissipated to the surface through the relatively porous volcanic products of the central volcano. The intrusions will act as heat sources to high temperature areas. Fossil high temperature geothermal areas are seen in dissected central volcanoes both in Tertiary (Walker, 1960) and Quaternary (Fridleifsson, 1973) strata.

After the intrusions have cooled down, they will mostly act as impermeable plugs in the strata, which by that time has drifted out of the active volcanic zone.

If we look on the surface of layer 3 as a flat impermeable base to water circulation, we can envisage the roots of the central volcanoes as "hills" on the base. Such impermeable "hills" will disturb the flow of water along horizontal, permeable layers in the upper crust. The water may "flow in rapids" around the obstruction, or it may flow upwards along faults and dykes cutting the relatively porous rocks on the flanks of the central volcano, but outside the densest intrusive core of the volcano.

Normal faults (with throws seldom exceeding 200 m) are common both in the Tertiary and Quaternary strata, but are more numerous in the latter, probably due to the lower tensile strength of strata composed of hyaloclastites and lavas as opposed to lavas. The faults may act as the dykes in forming paths for the flow of water to the surface. Of special interest as producers of secondary permeability are faults significantly younger than the strata they cut, such as transform faults or normal faults formed in a stress system different to that dominating while the strata built up.

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TABLE 1

Average porosity of the central part of basaltic lavas of the tholeiitic series

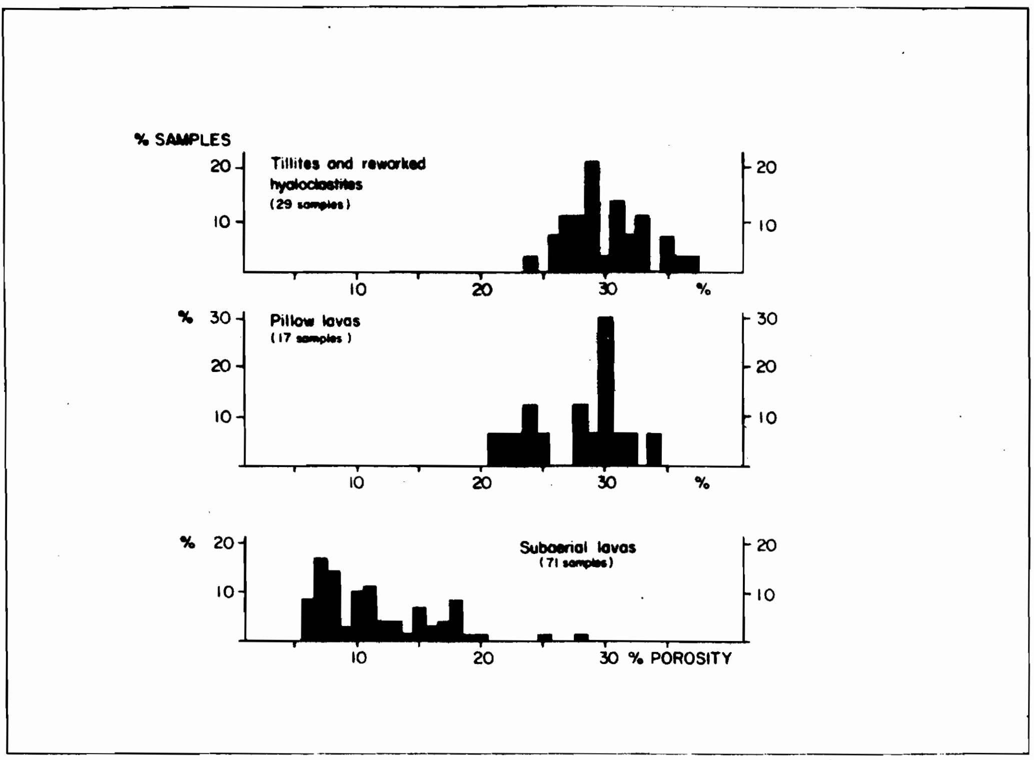
Lava type	No. of samples	Average porosity	Standard deviation
Tholeiite	8	0.048	0.026
Porphyritic tholeiite	6	0.039	0.020
Olivine tholeiite (simple)	3	0.033	0.012
Olivine tholeiite (flow units)	7	0.134	0.056

FIGURE CAPTIONS

Fig. 1. The percentage distribution of porosity (crushed samples) in subaerial lavas, subaquatic pillow lavas, tillites and reworked hyaloclastites from the Tungnaa area (data from Palsson, 1972). The porosity measurements were made on core samples from drillholes.

Fig. 2. Diagrammatic section showing how the relatively high porosity products of the Breiddalur central volcano (stippled) are enveloped by low porosity flood-basalt lavas (shaded). Low porosity intrusions (black) are most abundant in the core region of the volcano. The section (slightly modified from Walker, 1963) is approximately 35 km long, and the vertical scale is approximately two times the horizontal.

Fig. 3. A section through the Esja Quaternary volcanic sequence, SW-Iceland (Fridleifsson, 1973). High porosity subglacial hyaloclastites (primary and reworked) representing seven glaciations can be seen separated by relatively low porosity subaerial lavas. Note how lavas have banked against hyaloclastite units 12, 15 and 18 (unit numbers of Esja stratigraphic column). The greater thickness of the hyaloclastites in the western (left) part of the section is due to the higher volcanic production rate of a central volcano (units 10 and 12) as opposed to plateau basalt volcanism (units 15 and 18). Numerous wedge shaped "branches" (too thin for the section) of reworked hyaloclastites are interdigitated with the lavas closest to the main hyaloclastite bodies.


% SAMPLES
20
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Tillites and reworked hyaloclastites
(29 samples)
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10
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Pillow lavas
(17 samples)
30
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10
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Subaerial lavas
(71 samples)
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20
30 % POROSITY

Fig. 1

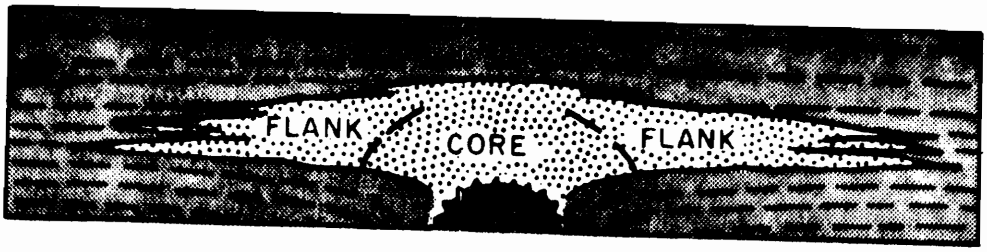
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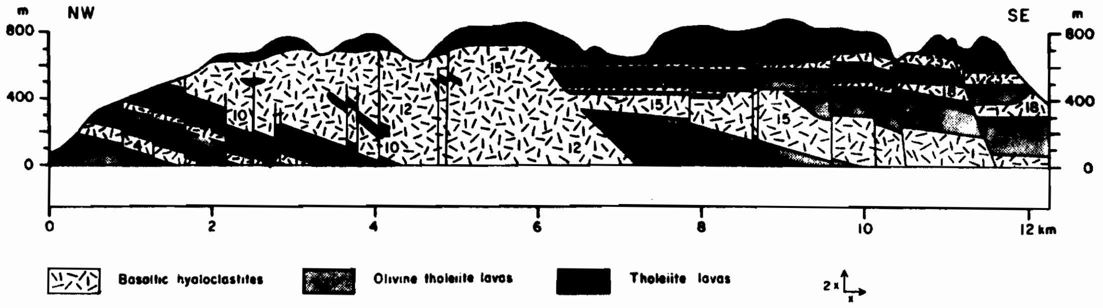
Fig. 2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Basaltic hyaloclastites
Olivine tholeiite lavas
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Fig. 3