Petrophysical Properties of Icelandic Rocks

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Abstract

A systematic rock sampling has been carried out in the eroded equivalents of the presently active hydrothermal areas in Iceland in order to study the reservoir characteristics of geothermal systems. A total of about 500 rock samples form the database. The project is ongoing and in this paper we focus on two aspects of the data collection: Firstly, petrographic data is presented to show that hydrothermal alteration severely alters the primary porosity of the rock and furthermore show that the rock alteration in basaltic lavas is related to the primary porosity of the rock. It is suggested that the observed systematic difference between the porosity determined with gas expansion and petrographical analysis of thin sections is due to microporosity (<30 μm) which is below the detection limit in the thin section analysis. This difference is mostly within 5% for basaltic intrusions and for most lavas. At high alteration larger differences are observed for some of the lavas. Tuffaceous rocks and sediments show a much greater difference indicating higher proportion of microporosity. The pores are more than 85% filled at higher alteration than mixed layer clay zone. Rocks with primary porosities higher than about 14% seem to fill more readily than those with lower porosities, probably indicating better permeability of the former. Grain density is shown to decrease with increasing alteration, and it is plausible that grain density increases again as the rocks go through progressively higher temperature alteration where higher density alteration minerals are preferentially formed. The permeability of a young unaltered olivine tholeiite lava flow in Reykjavík shows unusual petrophysical properties: The highly porous margin of the flow has an order of magnitude lower permeability than the less porous inner part. The high permeability – low porosity samples are also characterised by low seismic velocity and high grain density. The preferred explanation of the permeability anomaly is that an extensive connected network of grain boundary microcracks is the feature that causes high permeability in the coarser and inner part of the flow. Another but apparently less likely explanation is that an isolating glass coating around the vesicles in the marginal part of the lava flow inhibits permeable connections between the pores.

Introduction

A project was initiated in 1992 by Orkustofnun and Orkuveita Reykjavíkur to enhance the knowledge base on reservoir parameters in Icelandic geothermal systems. A part of that project was to collect rock samples at the surface, which could be equivalent to rocks from the geothermal reservoirs. This sampling method was chosen due to the much higher cost of taking cores from drillholes in the presently active geothermal reservoirs. To date about 500 samples have been collected for this purpose. A large majority of these, about 400, were taken at surface from eroded sections of fossil hydrothermal systems as well as from outside such systems. Further 104 samples were taken specifically from a single unaltered lavaflow in Reykjavik of Pleistocene age to study in more detail variations in reservoir characteristics

within a single flow. This paper gives first a general picture of Icelandic geology and hydrothermal alteration followed by a description of the sampling and the methods of investigation. The effect of hydrothermal alteration on porosity is discussed as well as the change of grain density of holocrystalline basaltic rocks with increasing alteration. Lastly, the unusual petrophysical character of a single unaltered olivine tholeiite lava flow is described and discussed.

Geological framework

Iceland is formed within the rifting environment of the Mid-Atlantic ridge with the volcanic rift zone crossing the country from south-west to north-east (figure 1). New crust is formed within the rift zone driving the older crust further away where it becomes progressively more eroded. The oldest rocks in general lie furthest away from the rift zone and date back to 15-17 m.y. Icelandic rocks are of volcanic origin and are dominantly of basaltic composition with about 10% of more evolved compositions including andesites and rhyolites. Sedimentary rocks are scarce (<5%) and are dominantly erosional from the volcanic succession. Sub-aerial lavas dominate the Tertiary volcanic succession, while in Plio-Pleistocene age (< 3 m.y.) hyaloclastites (pillow basalt, breccias and tuffs), the products of sub-glacial eruptions, are found intercalating the interglacial lava sequences. Although the rock samples taken in this study apply to Icelandic rocks in general, the emphasis leans towards explaining the reservoir character of high-temperature systems. These systems are generally situated in the core of central volcanoes within the fissure swarms of the volcanic zones. The main rock units are basaltic lava series intervened by hyaloclastite formations. At deeper levels, intrusive rocks (mostly dykes and sills) become more common. While the age of the volcanic succession increases with depth, intrusions can be of any age younger than the volcanic formations they intrude. This fact complicates the time factor when relating to the intensity of hydrothermal alteration. One part of the reservoir studies is to relate permeability to the geological structures in the reservoir. It shows that permeability in the upper 600 m, as observed in the boreholes, is controlled largely by stratification boundaries, while faults and fractures along intrusive boundaries dominate in the lower part of the reservoir.

Hydrothermal alteration is a complex interaction of thermal fluids and rocks. In general it might be expected that increased permeability would lead to more hydrothermal alteration. Hydrothermal alteration involves, generally speaking, the replacement of the primary constituents of the volcanic rock by alteration minerals and the deposition of solids from the fluid into voids in the rock. The hydrothermal alteration is temperature dependent, and one would expect a general density increase of the alteration minerals with increased temperature of formation. Figure 2 shows the temperature dependent hydrothermal zonation established in Iceland, and the preferential breakdown of the primary constituents of the igneous rock. It shows that volcanic glass and olivine have been altered before entering the chlorite zone, while plagioclase and ore minerals (along with pyroxene) start altering at deeper levels. This inevitably means that a rock type with a high percentage glass, such as hyaloclastite, will be much more sensitive to alteration than a holocrystalline equivalent. Porosity of unaltered igneous rocks is quite variable as can be seen in figure 3, which is deduced from thin section analysis of the rockdata bank, and ranges from above 40% to zero. This includes pores larger than 30 µm, which is the lower limit of observation in a normal thin section analysis.

Sampling and analytical techniques

The method to obtain rock samples for reservoir study in the active geothermal reservoirs is to take cores during drilling. That method is, however, expensive, and another more economical one was adopted for this study. It involved surface sampling of variably eroded parts of the

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crust including fresh to highly altered rocks of fossil hydrothermal systems. It is assumed that no major changes have occurred in the samples since the time of maximum alteration stage. This is a reasonable assumption according to petrographic studies of the rocks. The sample areas are marked on figure 1 and sampling procedure have been described by Gudmundsson *et al.* (1995), Stefansson *et al.* (1997) and Sigurdsson *et al.* (2000). The samples were grouped according to their mode of emplacement, geochemistry and hydrothermal zonation, as indicated in table 1. A majority of the samples have been analysed petrographically through thin sections, and laboratory measurements have been carried out for gas permeability, porosity and grain density. Total porosity has been determined for about half of the samples. Liquid permeability, thermal conductivity, electrical resistivity and acoustical velocity have been determined for a small fraction of the samples. Pore size distribution has been determined with mercury injection for one sample (Sigurdsson *et al.* 2000). This paper focuses mainly on the evaluation of petrographic data and how the data correlate with changes in other parameters such as grain density, and measured porosity. The petrographic data includes an assessment of the primary rock character, nature of rock porosity before and after hydrothermal alteration and the extent of rock alteration. The statistics of these factors was mainly achieved by point counting (200 points) of these factors in the thin sections.

Results
Porosity
The porosity of unaltered Icelandic igneous rocks is quite variable. The schematic diagram in figure 3, is based on thin section analysis of the rock samples. This figure depicts this variation, which extends from 0 to above 40%. The pores are largely gas vesicles formed during the degassing of the magma and intergranular porosity in pyroclastic rocks, such as hyaloclastites and tuff based sediments. It must be noted, and further discussed below, that the lower size limit of pore diameter in petrographic analysis is assumed to be about 30 μm, which equals the thickness of the thin section. A discrepancy between porosity measured in thin section on one hand and that measured in laboratory is thus expected.

It is a well known fact that hydrothemal alteration is strongly dependant on rock permeability and on porosity to some extent. Deposition of solids from geothermal fluids into voids in the rock is due to the oversaturation in the fluid with respect to the depositing mineral. An oversaturation often occurs when fluid chemistry or temperature changes. The volume of mineral deposition is related to the volume of oversaturated fluid passing through the zone of deposition. Furthermore, a preferential increase in hydrothermal alteration is expected in zones of high permeability, due to the disequilibrium between the primary constituents of the igneous rocks and the geothermal fluid (e.g. Arnorsson and Andresdottir, 2000). This also implies that rocks with high-porosity but low permeability will result in relatively minor deposition, in spite of relatively large temperature changes. Figure 4 shows the relation of the primary rock porosity in basalt lavas and the rock alteration where a distinction is made between the 5 alteration zones. The graph shows a strong relation between porosity and alteration in the smectite zeolite zone. The same correlation exists but gets weaker towards higher alteration zones. One reason for the decreasing correlation might be that porosity decreases as the vesicles are gradually filled with deposition at mixed layer clay zone and higher alteration, resulting in diminished porosity/alteration relation.

Figure 5 shows the relation between alteration as observed petrographically and the difference in porosity determined in the laboratory. The thickness of a thin section is about 30 μm which puts a lower limit to the petrographic observation of an open pore. A difference between a laboratory measured porosity that measures all pores that gas can enter and the petrographically determined one can be caused by erroneous measurements or to a limiting

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factor of either method. The figure shows a systematic difference between the two methods and furthermore that this difference is in majority of cases within 0-5%. The samples are subdivided further according to their alteration zone identity. Although a broad alteration range within each zone is observed, the main bulk of the samples within each of them shift to the right with higher alteration zones. It is deemed likely that this systematic positive difference is due to porosity of less than 30 μm diameter, which cannot be detected petrographically. If that is true the distribution in the diagram indicates that microporosity is abundant in fresh rocks. It also shows that samples are gradually getting more dispersed over a larger field when surpassing about 85% alteration. This dispersion does not, however, appear to be connected to a particular alteration zone.

Figure 6 shows the same data as figure 5, except that the samples are further divided into basalt lavas, hyaloclastites and intrusions. Hyaloclastites show by far the greatest dispersion. The data points on the low alteration side and showing more than 10 % "micro-porosity" are hyaloclastic tuffs and tuff rich sediments, while those within the 5% limit are pillow basalt. The sampling is biased in hyaloclastites, as such samples are dominantly taken in an unaltered condition or from the chlorite-epidote group. However, both groups behave in a similar manner as they show generally higher than 10% porosity difference. Basalt lavas tend to be confined to the 5% limit at lower alteration but become gradually more dispersed at higher alteration (especially above 85% alteration). A closer look at the lavas reveals a slight preference of a larger porosity difference in samples taken at finer grained and more porous lava tops. The basalt intrusions, which are mostly holocrystalline, fine grained to doleritic minor intrusions, show generally a small porosity difference mostly confined to within 5%, irrespective of alteration. It thus seems likely that the "microporosity", expressed by the measured and petrographically determined porosity (figures 5 and 6), is related to the glass fraction in the rocks, where high glass content coincides with relatively high microporosity, while holocrystalline rocks show lower values.

It has been shown (e.g. Sigurdsson *et al.* 2000) that the capillary tube model fits best to the permeability-porosity relation of the rocks in the database. This model applies particularly well for such rocks as basaltic hyaloclastites and volcanic tuffaceous sediments but less so for the basaltic intrusions and some of the basaltic lavas. The apparent variation in microporsity shown in figures 5 and 6 may corroborate the applicability of this model.

Figure 7 shows the relation between primary porosity and the degree of filling of these pores in basaltic rocks, both determined by thin section analysis. An interesting relationship emerges which can be illustrated as follows. Deposition of alteration minerals sets in as soon as the rocks enter into the smectite-zeolite alteration zone, and continue to fill at higher alteration zones. The "rate of filling", however, appears to vary depending on the primary porosity of the rock, where hydrothermally altered rocks with porosity higher than about 14% have all been filled to above 85% of the pore volume. It is tempting to suggest that this differential rate of filling is related to permeability where rocks containing >14% petrographically determined porosity have higher permeability than those below. An interesting correlation can be made with other data in the same sample collection where Sigurdsson *et al.* (2000) concluded that there was a weak dependency of permeability on porosity at values less than about 20% porosity, while good correlation exists at higher porosity. The porosity determined from thin section analysis, as discussed earlier and shown in figure 7, lies about 5% lower than the one determined from laboratory measurements. If that is taken into account both studies show a similar porosity and permeability relationship.

Figure 8 shows a relation between alteration of basaltic lavas and minor intrusions on one hand and effective grain density on the other. The figure shows a general decrease of grain density with increasing alteration. The density of holocrystalline basalt from relatively

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primitive olivine tholeiite to quartz normative tholeiites extends from about 3.1 to just below 2.9 g/cm^3. Basaltic glass, however, has a considerably lower grain density in, the range of about 2.6-2.8 g/cm^3. Glass-rich rock samples would for that reason significantly increase the spread of density values, and were omitted from the figure. The figure therefore shows the effective grain density evolution from holocrystalline fresh basaltic rocks to totally altered ones. The dispersion of grain density values is relatively low at less than 40% alteration but increases somewhat at higher alteration. The best fit line through the samples has a confidence coefficient of about R^2=0.5, and indicates that a complete alteration of basaltic holocrystalline rocks would lower the grain density by about 0.2 g/cm^3. This density decrease is explained in terms of the replacement of the high-density primary minerals of the basalt with lower density alteration minerals. Although the confidence of the best fit lines through data points of samples belonging to the smectite-zeolite, chlorite-epidote and epidote-amphibole zones respectively are much less they interestingly imply a gradual increase in density with these corresponding zones, suggesting that the density of the alteration mineral assemblages are gradually getting higher towards the higher temperature alteration zones.

Öskjuhlíð compound lava flow
A total of 104 rock samples were taken from a slightly eroded 2-3 x 10^5 year old compound olivine tholeiite lava flow at Öskjuhlid in Reykjavik. The lava is about 6 m thick where the sampling was done. A sketch of the lava is shown in figure 9. The macroscopic porosity appears to consist of 4 main types: About a 0.5 m thick top zone of the lava has visually very high porosity with the diameter of the pores generally less than 1 cm. Below is about 1- 1½ m thick zone with larger and more dispersed vesicles usually flattened out horizontally parallel to the flow structure. Below that zone lies the 4 m thick interior of the lava with dominantly small inter-granular porosity and less <1 cm vesicles. Distinct pipe vesicles are observed to extend from near the bottom towards the top of the coarser part of the lava. These vesicle types may be explained in terms of decreasing viscosity of the lava during cooling. While the main body of the lava is well above solidus and has the highest fluidity, gas exsolves and produces individual vesicles which migrate rapidly towards the top of the lava where a cooling crust is forming due to the rapid cooling against air. There the gas either escapes from the lava through surface fractures or is captured in the downward migrating cooling crust of the lava. These vesicles are often glass rimmed. The lava gradually continues to cool and degas and fluidity decreases as a consequence. Gas exsolution near the base of the lava continues and pipe vesicles are formed, transporting the gas effectively towards the upper part of the lava. At this time, the fluidity of the lava in the upper part is becoming reduced to the extent, that gas derived from the pipe vesicles can no longer extend to the surface and gets trapped in the upper part of the flow. The small intercrystalline pores in the coarser part of the lava probably represent the last degassing in the lava. These pores are usually found in between plagioclase crystals, suggesting that the degassing represented by these took place prior to the pyroxene crystallisation, and were trapped by the plagioclase crystal mush. The sample locations are marked on figure 9 and it is suspected that samples may be lacking in the zone of the large vesicles.

The cores have been studied comprehensively including petrography, chemistry, porosity, permeability, thermal conductivity, grain density and sonic P-wave velocity (Fridleifsson and Vilmundardottir 1998, Gudlaugsson 2000).

The petrographic study of 40 thin sections from the lava flows involved a point counting mineral and glass portions, two pore types and minor opaline silica deposition. The central part of the lava has a relatively coarse grained sub-ophitic texture, while the upper more scoriaceous part of the flow is finer grained and partly chilled to glass, especially around the

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vesicles. A striking feature is a clear distinction between the type of pore space, where "normal" spherical gas-vesicles, 1-15 mm across, and an order of magnitude smaller inter-crystalline pores. The latter seem to be connected like pores in a sponge, while the larger pores seem to be more isolated and sealed by a glassy rim. These pores show a bimodal distribution where the spherical ones are concentrated in the upper finer grained part, while the inter-crystalline pores dominate in the coarser grained inner part of the lava. An interesting aspect is the common occurrence of glass-rim around the spherical pores, which either is due to a cooling effect of the gas on the surrounding magma or that the magma nearest to the pore is undergoing degassing with the resulting increase in the melting point which then in turn leads to a rapid solidification and glass formation if the magma is at that time near to solidus.

Eight samples were further impregnated with a fluorescent resin in order to detect possible microcracks. Two types of microcracks were identified; microcracks within crystal grains and grain boundaries and fractures cutting through the crystalline matrix possibly caused by thermal contraction or tectonic movements. These porosity types are underrepresented in the thin sections due to their small size.

Permeability, gas porosity, effective grain density and sonic velocity of the samples have been measured in the laboratory. The results of these measurements show a clear division of the samples into two main groups as shown in table 2. The Öskjuhlíð samples show a very unusual relationship, where the high porosity samples generally show distinctly lower permeability than the low porosity ones (Figure 10). This is contrary to the general relation in Icelandic reservoir rocks where permeability increases generally concomitantly with increasing porosity. A part of the thin section analysis was to assess the proportion of intercrystalline and sub-spherical gas pores, and these are shown in figure 11. It shows that the intercrystalline pores dominate in the central part of the flow (group B), while they play a more insignificant role compared to the gaspores in the upper part (group A). An interesting relation shown in figure 10 is the apparent constant permeability in group A across a wide range of porosity, and furthermore it is interesting to note how sharp the transition is between the two groups. The most spectacular separation of the two groups is, however, observed in sonic velocity values where group A gives values of 3500-5000 m/s, while the group B values concentrate between 2000-3000 m/s. This is shown in figure 12 where sonic velocity is plotted against gas porosity. Indeed the sonic velocity seems to be the only property which cleanly separates the two groups while the separation of all the other variables seem to diffuse into both of the groups. Sonic P-wave velocity is partly dependent on the rigidity of the rock matrix. The presence of grain-boundary microcracks can dramatically lower the sonic velocity. Microcracks have, as discussed above, been identified in fluorescent impregnated thin sections, but their differential abundance in the two groups is yet to be assessed. Figure 13 shows the relation between grain density and sonic velocity where group B shows higher effective grain density and lower sonic velocity values. The lower grain density of group B may be the result of higher glass content in group A, and furthermore sealed glassrimmed gaspores will render erroneous and consistently lower grain density values.

The explanation of these somewhat paradoxial results is still speculative and boils down to two main venues. The first one explains the division in terms of a well developed network of micro-fractures in the coarse grained matrix, caused by mineral grain boundaries or inter-mineral fractures, but less in the finer grained and glassier part of group A. The increased density of micro-fractures would lead to lowering of sonic velocity, and possibly to higher permeability as they would create the porethroat connecting the intercrystalline vesicles. The other possible explanation is that the two kinds of porosity structures lead to different porosity and permeability behaviour, where the normal gas vesicles are surrounded and isolated by a

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glass-rich and low-permeability layer, while the inter-crystalline pores are interconnected like wormholes resulting in higher permeability values. The slightly lower effective grain density in group A would either infer higher portion glass in that group or that the measured gas porosity ignored tightly sealed vesicles and thus created an under-estimation of grain density calculation.

Conclusions

The main conclusions of this study of about 500 rock samples of variable rock types and alteration in Iceland can be summarised as follows:

- The primary porosity indicated from petrographic analysis of Icelandic igneous rocks ranges from zero to over 40%. Hydrothermal alteration tends to reduce the porosity by depositing alteration minerals in the voids of the rock. A systematic difference found between porosity assessed by petrographic analysis and gas porosity measured in laboratory is interpreted as microporosity below petrograhic detection. This difference is noticeably higher for tuffaceous rocks and upper parts of lava flows, than for basaltic intrusions and denser part of lava flows.
- Grain density of basaltic rocks decreases by about 0.2 g/cm^3 during its gradual alteration. There is also an indication that the density of the alteration mineral assemblage increases as rocks enter into higher temperature alteration zones.
- The rate of mineral deposition into rock voids during alteration appears to be considerably higher in rocks with higher porosity than about 14%. Most voids seem to be more than 85% filled when the rock has entered into the mixed layer clay zone.
- A comprehensive study of a young unaltered olivine tholeiite compound lava flow at Öskjuhlíð shows an unusual inverse relationship between porosity and permeability. The higher permeability found in the lower porosity part of the lava flow is tentatively explained in terms of higher abundance of microcracks.

Acknowledgement

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Table 1. Classification of samples with respect to rock types and alteration stage.

| Rock type | Alteration stage | | | | | | |
	Unaltered	Smectite /zeolite	Mixed layer clay	Chlorite	Chlorite /epidote	Epidote /amphibole	Total
Basalt							
Lavas	122	44	22	2	42	36	268
Hyaloclastites	30	21	8	3	6	1	69
Intrusions		24	12		30	36	108
Andesites		5			2	2	9
Acid rocks		25			11	12	48
Sediments	2	3			1	1	7
Total	154	122	42	11	92	88	509

Table 2. Division of Öskjuhlíð samples into supergroups.

Supergroup	A	B
Permeability (mD)	<1	>1
Sonic velocity (m/s)	>3000	<3000
Grain density (g/cm^3)	<3.0595	>3.0595
Porosity (%)	>13.5	<13.5
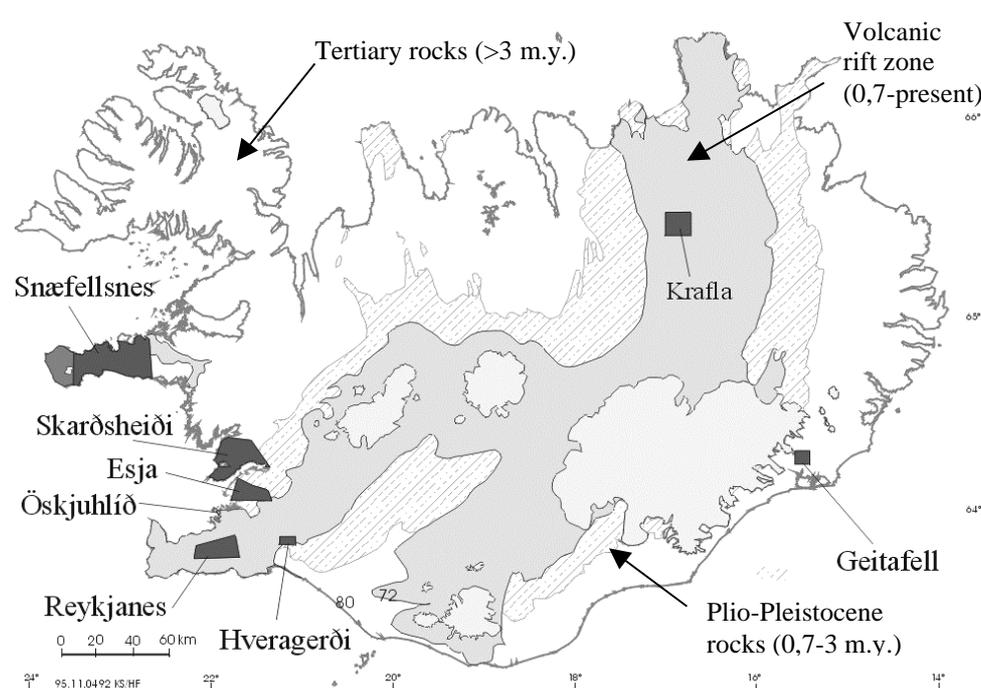
Figure 1. A simplified geological map of Iceland and location of sampling areas.

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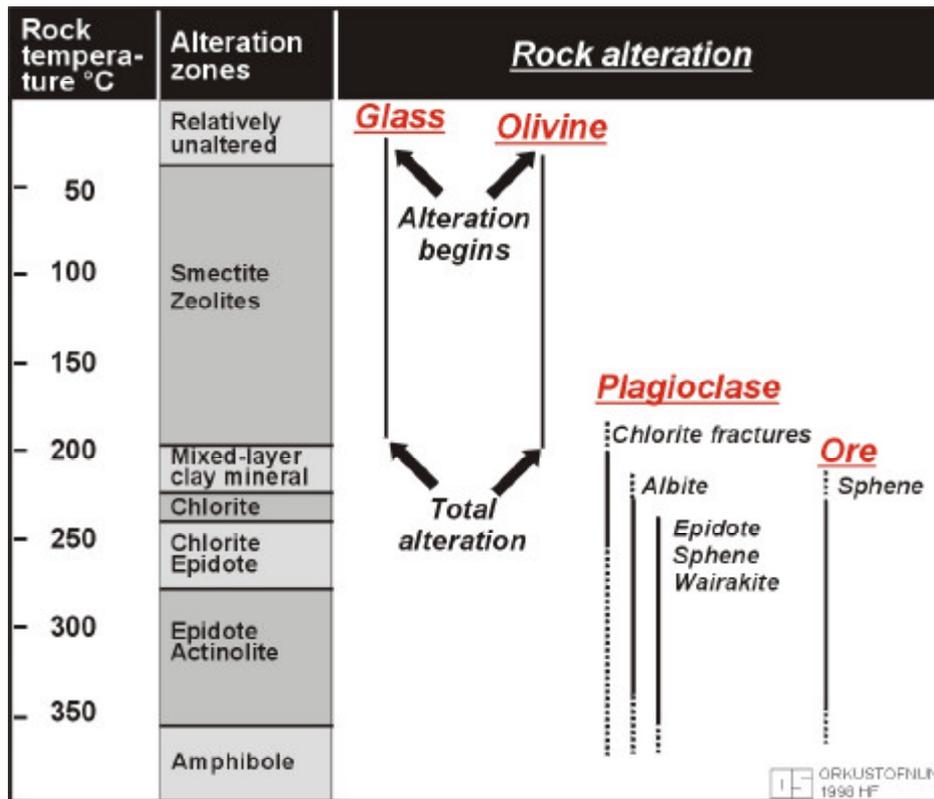
Figure 2. Temperature dependent hydrothermal alteration zones in Icelandic high-temperature systems.
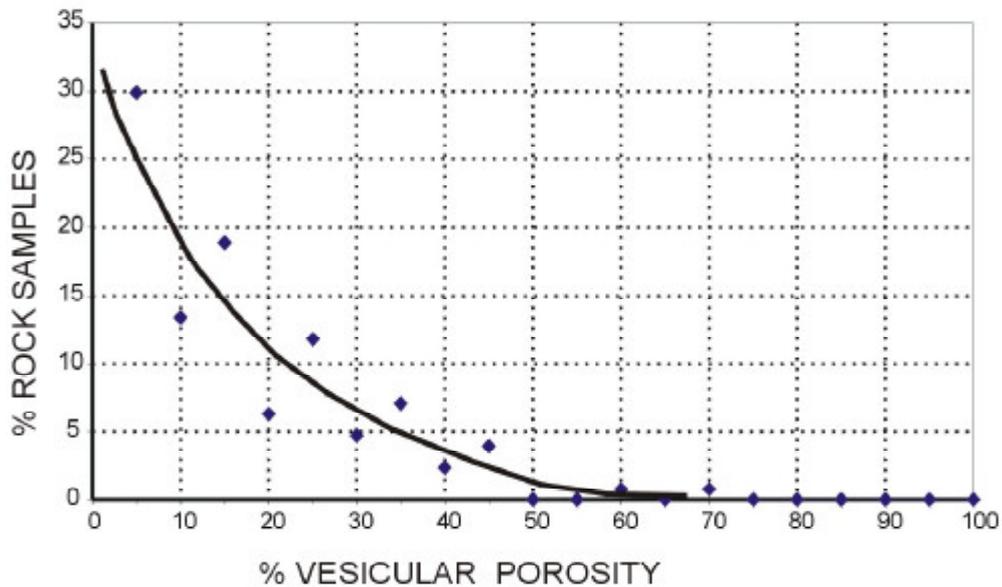

Figure 3. Primary vesicular porosity of basaltic rocks, based on the petrographic analysis of the rock samples.
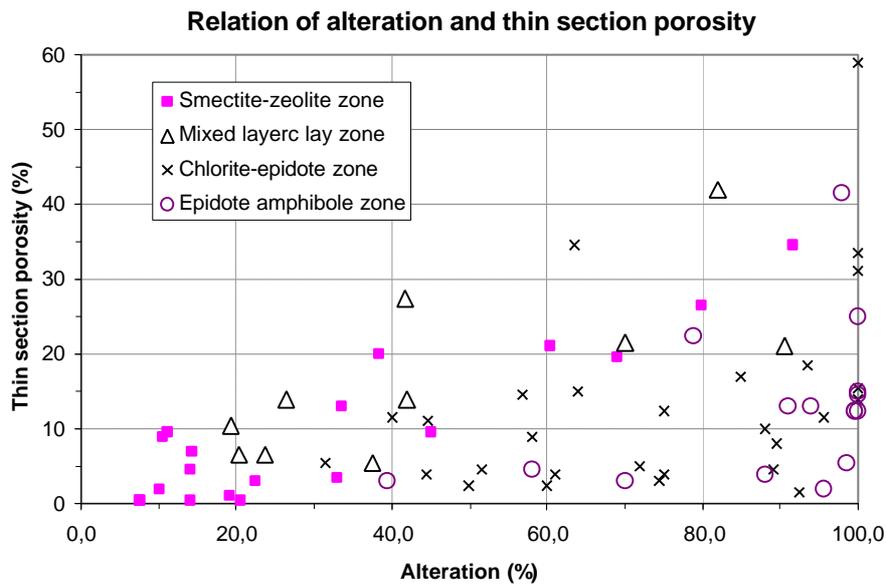
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Relation of alteration and thin section porosity

Figure 4. Relation between rock alteration and primary porosity determined by petrographic thin section analysis.
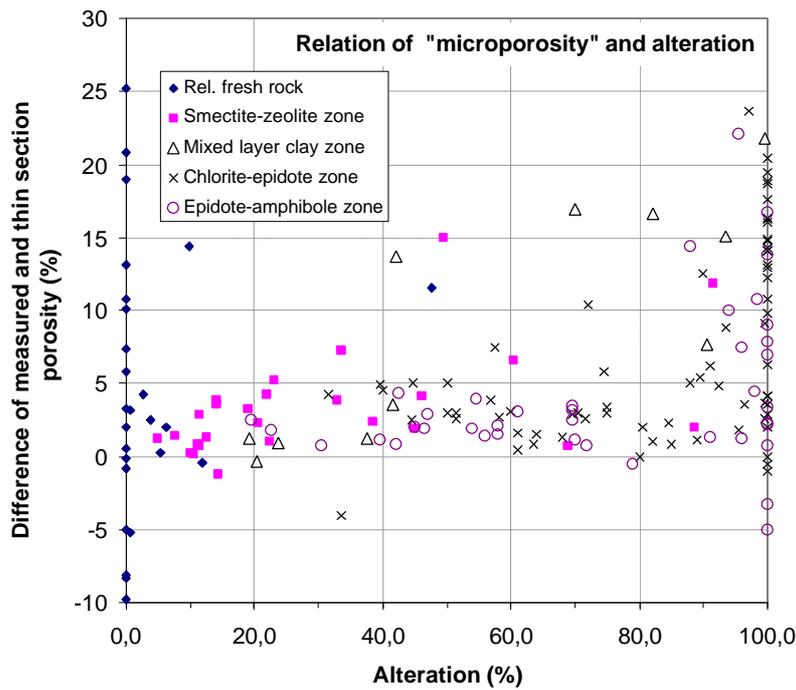
Figure 5. Difference in porosity determined on one hand by gas exansion (in the laboratory) and by thin section analysis on the other hand, plotted against rock alteration. Individual samples grouped according to alteration zone.

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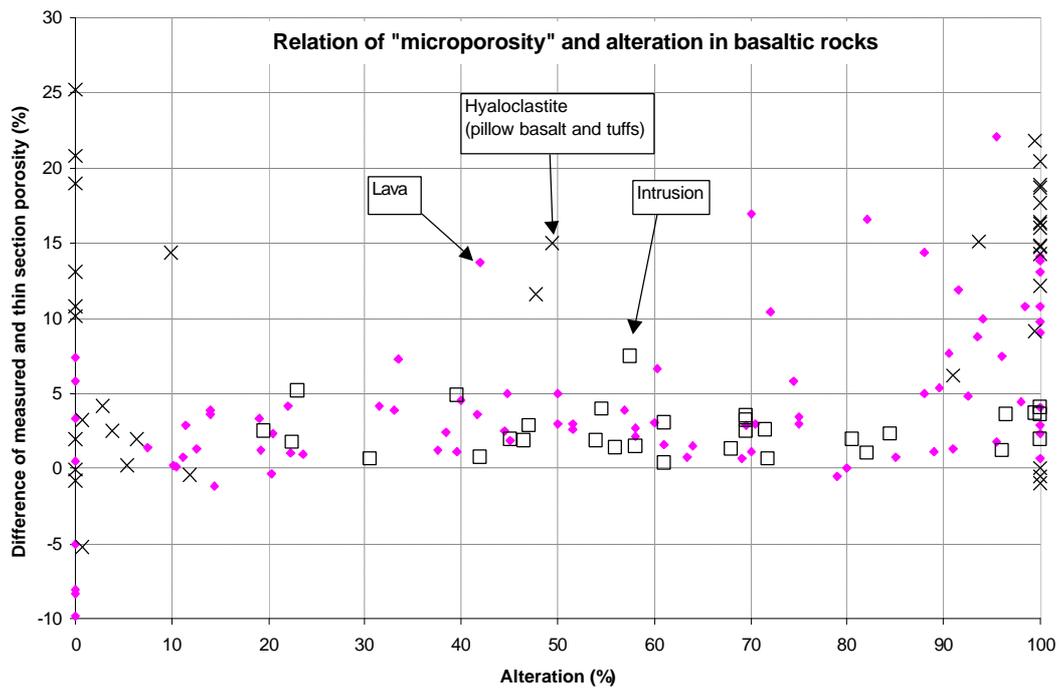
Figure 6. Difference in porosity determined on one hand by gas expansion and by thin section analysis on the other hand plotted against alteration. Samples are grouped according to their type of formation.
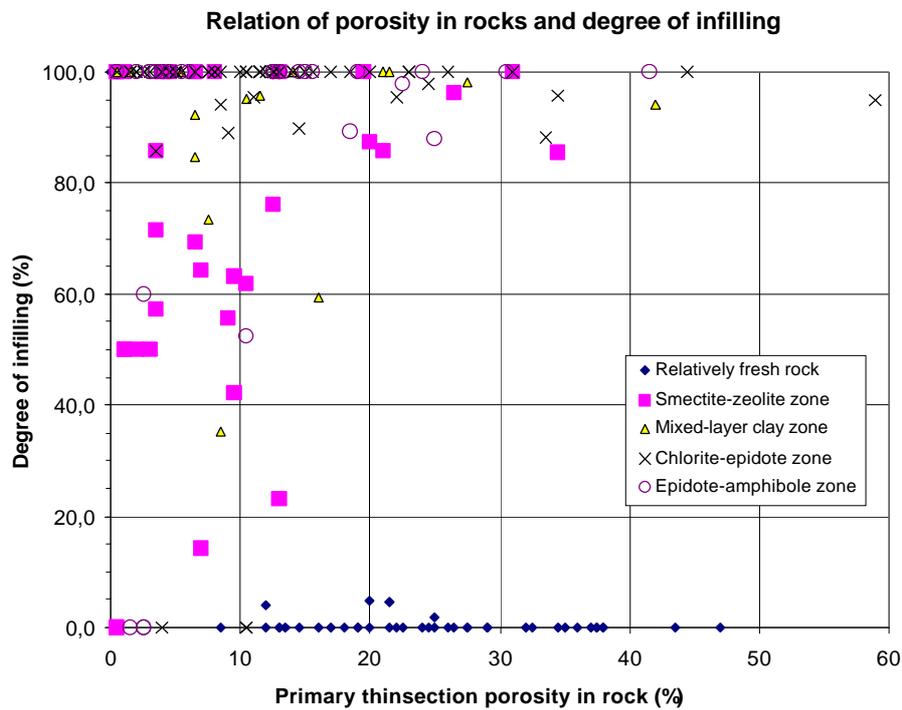

Figure 7. The relation between degree of infilling and the primary porosity of the rock. Samples are grouped according to their alteration zone.
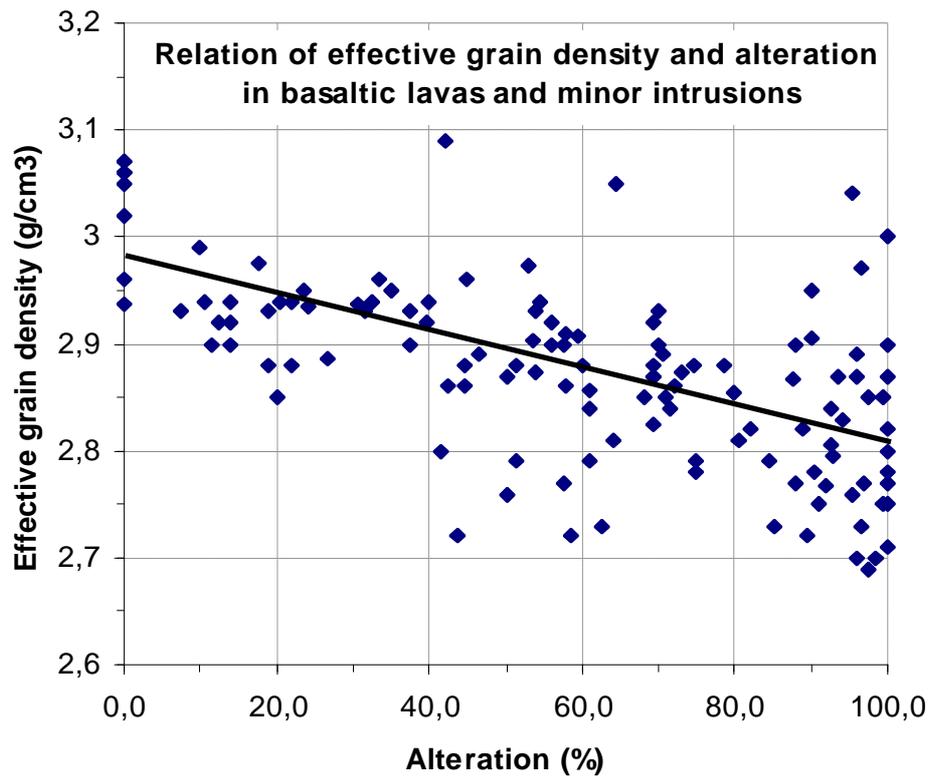
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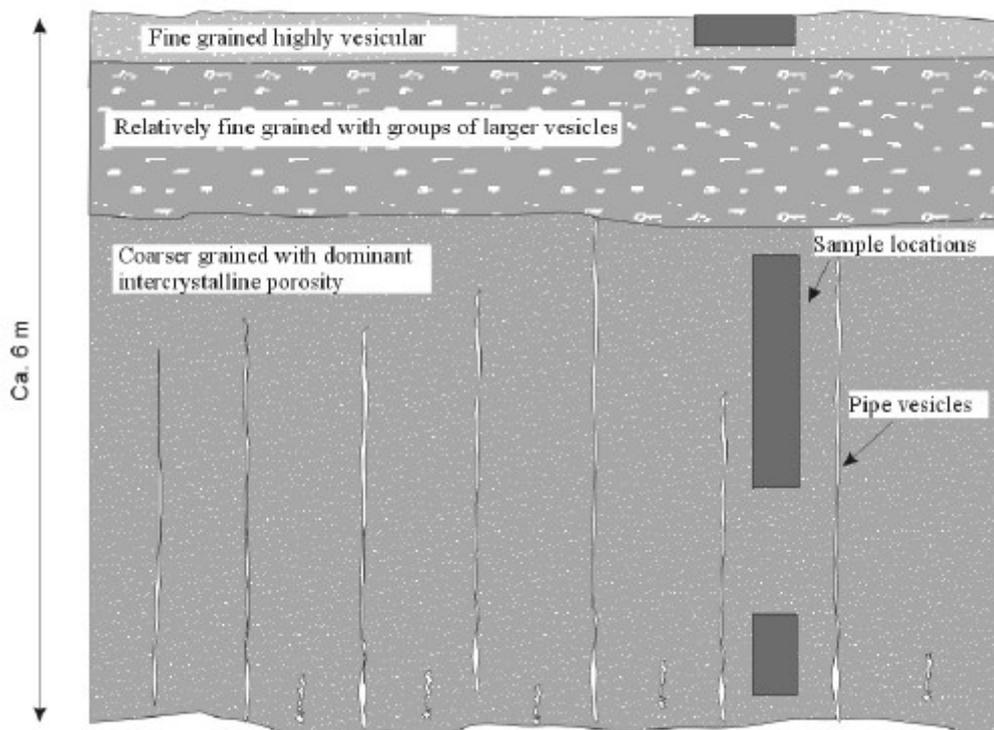Figure 8. The relationship between effective grain density and alteration in basaltic lavas and minor intrusions.

Figure 9. A sketch of the Öskjuhlid lava flow highlighting the different vesicular structures.
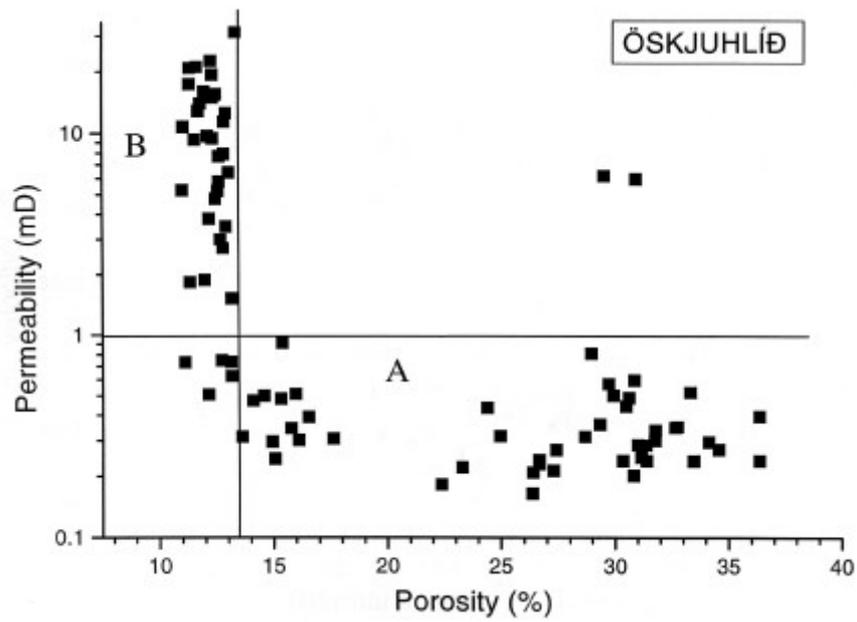
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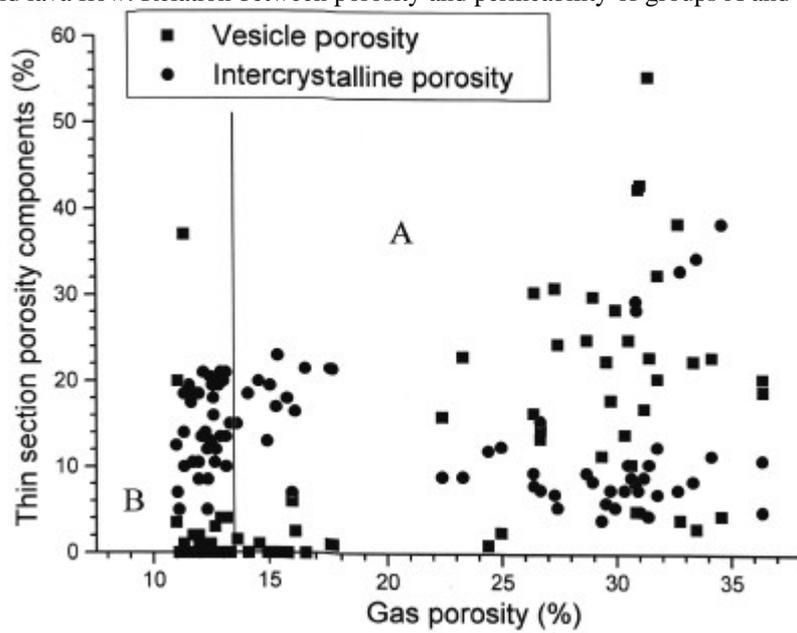Figure 10. Öskjuhlid lava flow. Relation between porosity and permeability of groups A and B.

Figure 11. Öskjuhlid lava flow. Relation between measured gas porosity and thin section porosity components.
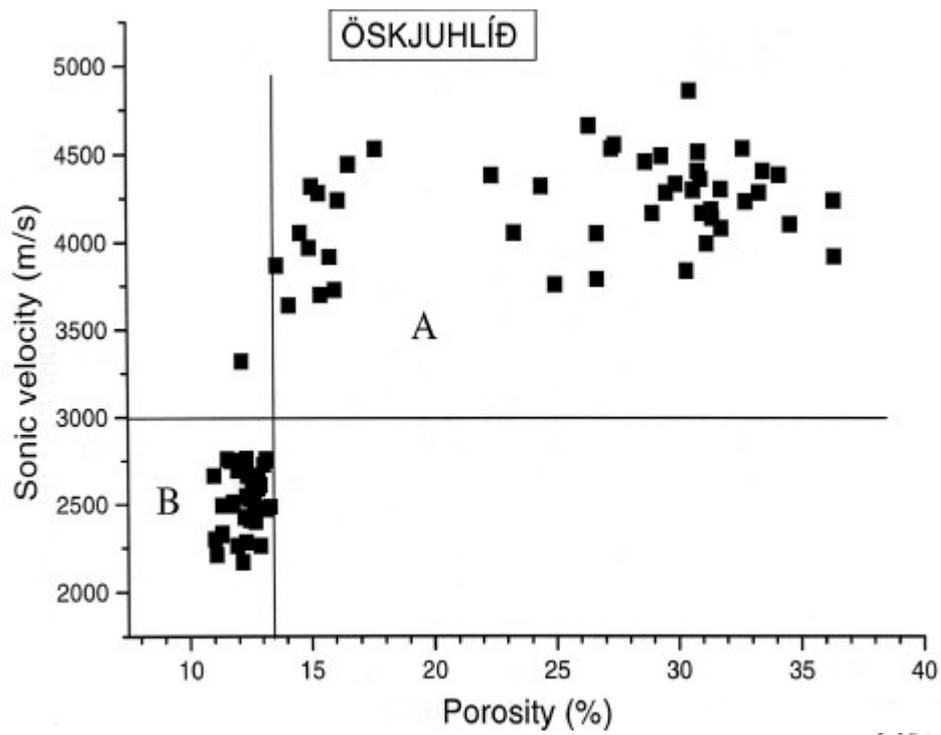
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Figure 12. Öskjuhlid lava flow. Relation between sonic velocity and porosity.
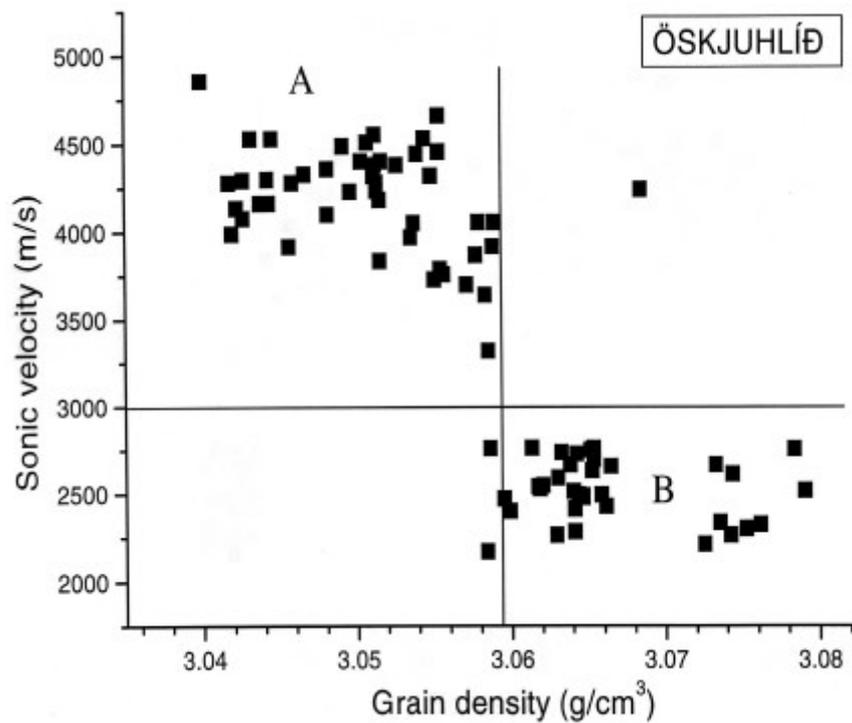

Figure 13. Öskjuhlíd lava flow. The relation between grain density and sonic velocity.

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