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DATABASE ON IGNEOUS ROCK PROPERTIES IN ICELANDIC GEOTHERMAL SYSTEMS. STATUS AND UNEXPECTED RESULTS.

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ABSTRACT

A rock database has been established at Orkustofnun, Iceland, representing formations in active low- and high-enthalpy geothermal systems in the country. More than 500 rock samples have been collected spanning basaltic to rhyolitic composition and including lavas, hyaloclastites, intrusions, and a few sedimentary rocks of volcanic origin. The hydrothermal alteration of the samples varies from literally fresh rocks to true greenschist facies rocks. Petrological and mineralogical studies as well as chemical analysis are completed on more than half of those samples. The majority of the samples has been measured with respect to gas permeability, porosity, and grain density. A portion of the samples has undergone more specialized measurements such as acoustic velocity, thermal conductivity, resistivity and mercury injection.

The results show among other things very little difference between effective and total porosities. Liquid permeability is considerably lower than gas permeability, but relationship based on physical parameters can be shown to exist between those properties. Matrix permeability is shown to predominately relate to capillary tube model behavior with weak dependency on porosity. There are indications for significant reduction in permeability for a small degree of alteration, while the opposite is indicated for higher degree of alteration. The physical parameters show little dependency on confining pressure.

1. INTRODUCTION

Many of the leading energy producer companies in Iceland in co-operation with Orkustofnun decided in 1992 to increase the emphasis on researches leading to construction of geothermal power plants. One project rising from that decision aimed at improving the knowledge of the parameters required as input to numerical simulators, which are extensively used for modeling geothermal systems. Part of that project included the collection of data on the physical properties of the rocks hosting the geothermal resources.

In practice few cores have been taken during drilling into geothermal reservoirs in Iceland over the years, the main reason being the relatively high cost of the coring operation. To obtain representative rock samples in a reasonable amount of time and at minimal cost it was decided to collect samples mostly at surface from eroded sections of fossil geothermal systems as well as from younger lavas. In 1993 more than 400 samples had been collected and in the following years about 100 samples have been added to the collection. The composition of the rock samples spans from being basaltic to rhyolitic and includes lavas, hyaloclastites, intrusions, and a few sedimentary rocks of volcanic origin. The hydrothermal alteration of the samples varies from literally fresh rocks to true greenschist facies rocks.

The rock samples are of igneous origin and their composition and degree of hydrothermal alteration cover most rock types and alteration found in active low and high enthalpy geothermal systems in Iceland. Results from measurements and researches on these samples form a database on the petrophysical properties of the host rocks of Icelandic geothermal systems. The objective is to compare the laboratory measurements on the samples with results obtained from geophysical logs and the best fit parameters obtained from mathematical modeling of geothermal systems. In that way the petrophysical results are expected to be transferable onto presently active geothermal systems. By the end of 1998, petrological, and mineralogical studies on more than half of these samples were completed as well as chemical analysis. Similarly, the majority of the samples had been measured with respect to gas permeability, porosity, and grain density and a portion of them had undergone more specialized measurements.

This paper presents the main results concerning the rock types and hydrothermal alteration found within Icelandic geothermal systems. Some unexpected results are highlighted.

2. ROCK SAMPLING

The most appropriate way to obtain samples of reservoir rocks is to take core samples during drilling of a well. This is, however, a rather expensive sampling method, and few cores are currently available from Icelandic geothermal wells. In order to obtain a reasonable number of samples at a reasonable cost and statistically representative; it was decided to make surface sampling of rocks compatible to those found in active geothermal systems. One way of meeting this objective was to carry out systematic sampling from eroded sections of the Icelandic upper crust. In this geological environment, the rocks from fossil low and high enthalpy geothermal systems can be sampled easily and systematically. It is assumed that the petrophysical character of the rock samples has not changed significantly from the time of geothermal alteration at depth to its present fossil state at surface.

Iceland is located on the Mid-Atlantic ridge with high frequency of volcanic activity. The volcanic and tectonic activity is mostly confined to the neovolcanic zone that crosses the island from southwest to northeast and is the continuation of the ridge on land. Due to the spreading of the ridge, active high enthalpy systems drift out from the volcanic zone, cool down and eventually die out. The geological formations are relatively young (< 17My) and mostly of basaltic type.

Figure 1 shows the main sampling sites. In the field, each sample is composed of at least four core plugs drilled out from a given spot (~10 cm^3). A short description was made of each sampling location and the sample grouped, based on visual analysis, into rock type and alteration zoning (Gudmundsson et al, 1995). Their grouping was later revised slightly as results from thin sections and chemical analysis became available (Franzson et al, 1997). Table 1 summarizes the distribution of the samples into rock types and alteration state. Of the samples collected only about 40 were taken during drilling operations.

3. INVESTIGATION

Thin sections were made for all samples and the rock type and degree of hydrothermal alteration were determined petrographically with greater accuracy than was possible in the field. Point counting in thin sections was used to determine the degree of alteration of the original rock and volume of secondary minerals. The thin section study distinguishes between gas vesicles and intercrystaline pores, primary and secondary minerals, and reprecipitation of minerals in pores or fractures. This petrology and mineralogy study is supported by chemical analysis of about half the samples. Its objective is to quantify the effect of chemical transport and hydrothermal alteration on other physical parameters such as porosity and permeability.

The majority of the samples has gone through basic measurements for gas permeability, porosity and grain density. Total porosity was measured for nearly half the samples and liquid permeability has been measured in about 60 samples. Portion of the samples has undergone more specialized measurements such as thermal conductivity (80), resistivity (100), acoustic velocity (110), and mercury injection (1). The objective is to establish predictive relationships between the core measurements and easily obtainable geophysical logs in boreholes.

4. RESULTS

Porosity determined from thin section point counting showed generally about 5% lower porosity than that measured by He-gas expansion. This difference can become much higher in young and unaltered formations (Franzson et al, 1997). This difference becomes slightly greater the higher the alteration state and more pronounced at a higher alteration stage than 85%. The explanation for the large difference in the unaltered rock samples could be that most of those samples are olivine-tholeiite basalt, where micropores or intercrystaline porosity are more common than in more evolved rock types. It is also implied that micropores may increase in number with increasing alteration, especially in highly altered samples. Normal thickness of a thin section is about 30 microns (μm) and therefore it is difficult to detect pore space smaller than that. The study further indicates that grain density is decreased with increasing degree of alteration (Figure 2). Less conclusive yet are results for permeability, where small degree of alteration (smectite/zeolite) appears to reduce permeability, possibly by clogging pore throats. However, at a higher degree of alteration (>60%) higher permeabilities are observed again. This could be caused by formation of secondary permeabilities resulting from breakdown of minerals and chemical transport within and out of the rocks.

Porosity in the igneous samples has been found to be as high as 49%. The porosity distribution is relatively even, but with a larger part of the samples falling below 20% porosity. The small difference between effective and total porosities is noticeable (Sigurdsson and Stefansson, 1994). For samples with total porosity higher than 20%, the relative difference between effective and total porosity is typically less than 2%, where the relative difference is the absolute difference between total (ϕ_t) and effective (ϕ_e) porosities divided by the total porosity ($[\phi_t - \phi_e]/\phi_t$). The relative difference increases as the total porosity becomes smaller, but is usually less than 6% for total porosity in the range 6-20% (Figure 3). For small total porosity values, the relative difference can be significant. However, the absolute difference between effective and total porosities in Icelandic rocks is generally small or 1-2% (Figure 4), and appears to be independent of the porosity (Stefansson et al, 1997). Since the effective porosity represents the volume in the rock which is open to flow, it can be concluded for Icelandic reservoirs rocks that nearly all pores are connected.

Average grain density for the main rock types in Icelandic geothermal systems can be determined with relatively good accuracy. Firstly, the effective and total grain density has been measured for a large number of samples and secondly, the measured effective grain density for other samples can be converted to total density on the basis of the small difference observed between effective and total porosity. In general the results indicate that grain densities decrease from crystallized basaltic rocks (2.9 g/cm^3) to glassy basaltic hyaloclastites and then on to acid rocks (2.7 g/cm^3). However, further subdivision of the main rock types can show a similar span in grain density as that observed between the main rock types.

Permeability is generally considered to be a physical property of the rock. By that definition, the use of different fluids to measure permeability should yield results within the error limits of the method used. In theory this is the case but in practice the outcome of the measurements can turn out to be quite different depending on the fluid used. There are many possible reasons for this and one commonly mentioned states that brine may react with the minerals in the samples thereby reducing, clogging or narrowing the flow paths through the rock samples. On the other hand the driving force of the gas can cause alteration in the flow path through the rock sample and thereby affect the results. This phenomenon is not widely discussed in the literature, although it is likely to be quite common.

Permeability has been measured with gas in nearly all the igneous Icelandic samples and with brine for more than one tenth of them. The results show that the liquid permeability is consistently lower than the gas permeability (Figure 5). On average the measured liquid permeability is about three times lower than the corresponding gas permeability. The observed difference in flow resistance between the two fluids is here considered to be controlled by other factors than mentioned earlier. It is thought that the difference is partly related to the measurement technique. The gas measurement is done on dry samples, while the brine measurement is done on saturated samples. While the sample is dry all pores and flow paths are open for flow. When saturated a connate liquid film adheres to the rock and in combination with capillary forces reduces and blocks portions of the flow paths for liquid flow. Similar difference in permeability measurements using gas and brine has been observed for sedimentary rocks from the North Sea (Juhasz, 1986). Furthermore, it appears that an empirical relationship developed to convert gas permeability values to brine permeability values for sedimentary rocks applies to the Icelandic igneous rock samples too (Sigurdsson, 1998a).

A relationship to convert gas permeability values to brine permeability values was introduced by Swanson (1981). It is based on correlations between permeabilities and mercury capillary pressure measurements on samples from carbonates and sandstone formations. Equating the correlations through the common correlating parameter (ratio of mercury saturation to capillary pressure) and applying a clay-bound water correction Juhasz (1986) arrived at an improved conversion formula. The effect of immobilization of a part of the brine is inherent in the correlation. This relationship appears to be just as applicable to the igneous rock samples as to the sedimentary rock samples. Figure 5 shows two correlation lines for that relationship, one where the ratio of available pore space for brine flow is equal to the effective pore space of the sample. The other line where the available pore space for brine flow is less than the effective porosity of the sample.

A search for a predictive model for permeability in Icelandic igneous rocks has shown that the majority of the samples predominately relate to a capillary tube model (Figure 6). A general equation describing a capillary tube model is given as;

$$k = D^2 * \phi / [32 (L_e/L)^2]$$

where k is permeability (mD), D is pore throat diameter, ϕ is porosity and the length ratio (L_e/L) describes the tortuosity. The permeability and the effective porosity have been measured for the samples so their ratios give values for the unknowns in the above equation, which are plotted in Figure 6. Further work attempting to relate the measured parameters to permeability has indicated, that dependency on porosity appears to be weak for samples with porosities less than 20% (Sigurdsson, 1998b). This is demonstrated in Figure 7 that shows an optimal transform of the porosity data, which can be used in a nonparametric regression algorithm (Xue et al., 1997). This means that the pore throats or the flow paths connecting pores control the flow of fluids through the rocks, but not the bulk volume of the pores. A thin-section study on relatively fresh olivine-tholeiite basalt from a batch of the samples revealed that the larger gas vesicles were often nearly blocked or isolated by glass at the vesicles rim while smaller intercrystaline pores were open (Fridleifsson and Vilmundardottir, 1998). Results of measurements made on a few samples under varying confining pressure further support the capillary tube flow model behavior as the different parameters measured showed little dependence on confining pressure (Johnson and Boitnott, 1998). Samples belonging to the rock types basaltic hyaloclastites, andesites, acid rocks and volcanic sediments (Table 1) all correlate to the capillary tube model, while some samples of basaltic lavas and basaltic intrusions deviate from that model. Looking closer at the rock types that deviated from the capillary tube model, it was found that the lava samples belonged to the alteration stages smectite/zeolites and chlorite/epidote. As mentioned earlier, the results of the thin section studies indicated a reduction in permeability for a low degree of alteration (smectite/zeolite) and it has been implied that clogging of pore throats causes the reduction. Therefore, the flow paths in these samples might be more dispersed. The intrusion samples were from the chlorite/epidote and epidote/amphibole alteration stages.

Based on a capillary tube model and assuming a fixed value of 1.73 for the tortuosity factor a controlling tube diameter has been calculated, using the above equation, which is assumed to represent the pore throat diameter of the highest frequency in the sample. Results of measurements on a few samples have indicated that the pore throat diameters are grouped on a narrow width band for a given sample. The calculated tube diameters are in the range 0.03-80 μm (Figure 8), while measurements on a few samples have given diameters in the range of 0.05-100 μm. The majority of the calculated diameters for the samples is less than 0.7 μm or shorter than the wavelength of visible light (0.4-0.7 μm).

A portion of the samples (35 of 85), especially taken from a homogeneous fresh olivine-tholeiite lava shield for thermal conductivity study, had very low sonic P-wave velocity or in the range 2200-2700 m/s. The expected sonic P-wave velocity for basaltic samples with grain densities higher than 3000 kg/m^3 should be in the range of 4000-4600 m/s as was the case with the remainder of these samples. The samples with the low acoustic velocity had generally a lower porosity than the rest of the samples and a higher permeability (Figures 9 and 10). This correlation is somewhat paradoxical, but higher acoustic velocity could be expected for smaller porosity while lower velocity could be expected for a higher permeability. Fractures are not observed in thin sections from this fresh lava, but the acoustic measurements were only carried out at a low confining pressure. Until these samples have been measured at higher confining pressures one cannot rule out the existence of microfractures along crystalline surfaces in these samples.

5. DISCUSSIONS AND CONCLUSIONS

Transmissivity and hence productivity of geothermal reservoirs is generally dominated by fractures. However, the bulk of their fluid storage is within the matrix rock and the rock parameters control the productivity decline and longevity of the reservoirs. It is therefore of importance to have knowledge about the physical properties of the matrix rocks that compose the geothermal systems. A first step in that effort has been described in this paper, where a database is accumulating for the rock types in Icelandic geothermal systems.

The rock types in Icelandic geothermal systems are of igneous origin and mostly basaltic. Investigations on reservoir parameters for igneous rocks have not been as extensive as corresponding studies on sedimentary rocks that compose oil and gas reservoirs. Results from studies on rocks in this database show that similarities can be found between the igneous and sedimentary rocks. The physical behavior and response to a given agitation can be similar for both igneous and sedimentary rocks. Results obtained and relationships developed may therefore have a broader application.

First results for the igneous rocks in the database indicate that hyaloclastites are the preferred reservoir matrix for Icelandic geothermal systems. The hyaloclastites have generally higher porosities and permeabilities than basaltic lavas and intrusions.

A small difference of only 1-2% is observed between effective and total porosities for the majority of the rock samples.

Empirical relationship developed for sedimentary rocks can also be used to transfer measured gas permeability for igneous rocks to equivalent liquid permeability.

Most of the samples in the database match the capillary tube type of predictive model for permeability. The results also indicate that the pore throats diameters for the larger portions of the samples are less than the wavelength of visible light (0.4-0.7 μm).

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

Rock Type	**Alteration Stage**						
	Unaltered	Smectite/ zeolites	Mixed layer clay	Chlorite	Chlorite/ epidote	Epidote/ amphibole	Total
Basaltic							
Lavas	122	44	22	2	42	36	268
Hyaloclastites	30	21	8	3	6	1	69
Intrusions		24	12	6	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

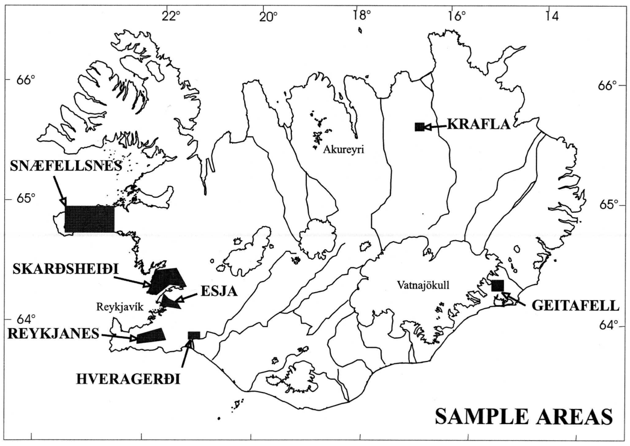

Figure 1. Location of sampling sites in Iceland.

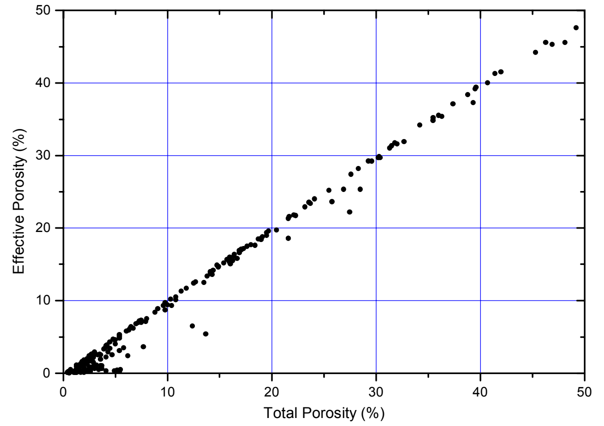

Figure 4. The correlation between total and effective porosity.

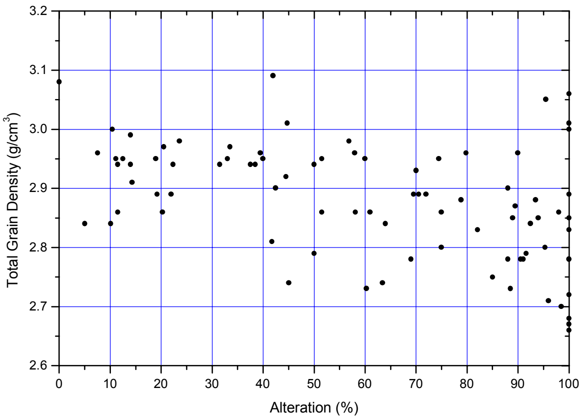

Figure 2. Change of grain density with alteration.

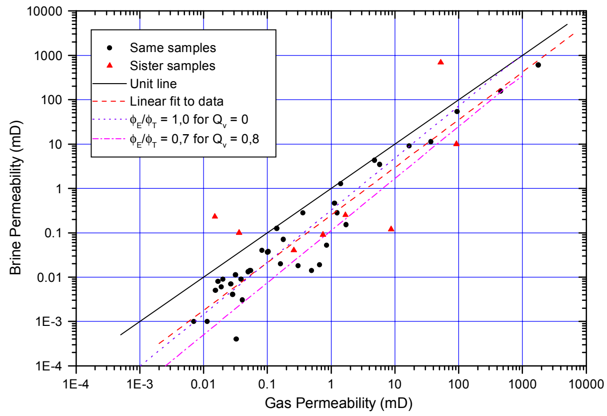

Figure 5. Relationships between gas and brine permeabilities.

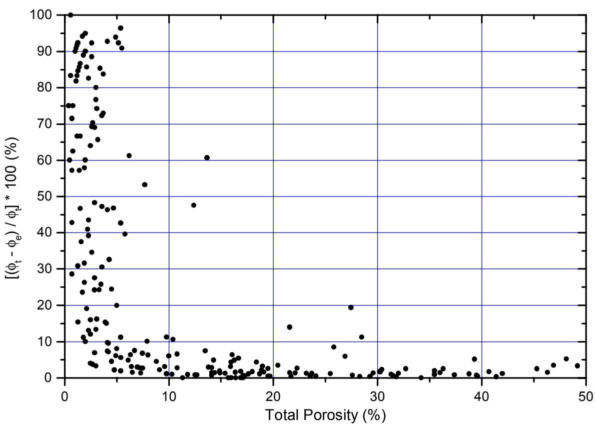

Figure 3. Relative difference between total and effective porosity.

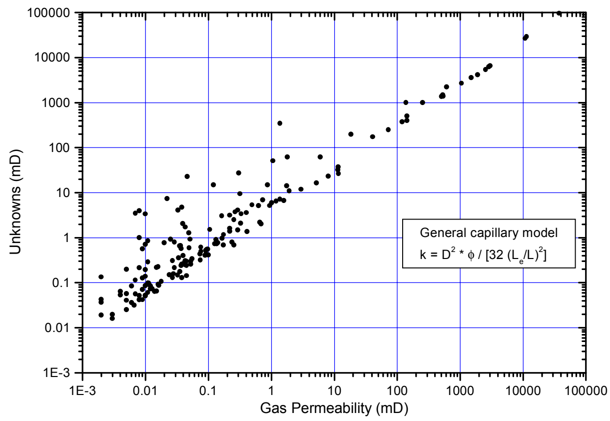

Figure 6. Indication of permeability-porosity relation for capillary tube model.

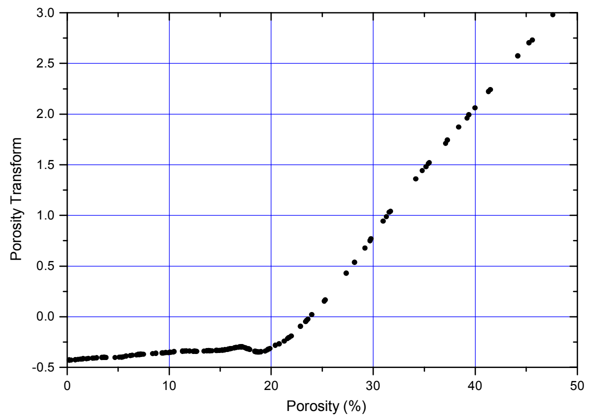

Figure 7. Ordered optimal transform of the porosity data for the alternating conditional expectation algorithm (see Xue et al., 1997).

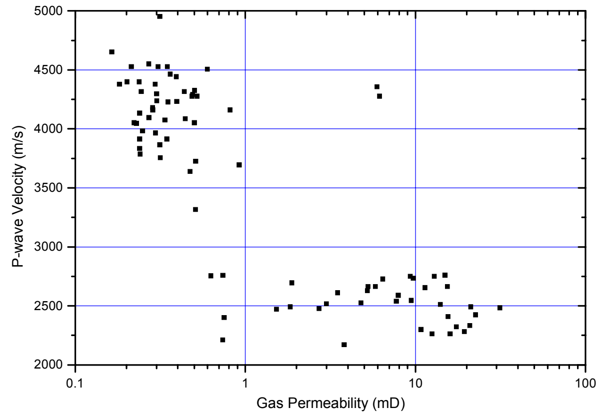

Figure 10. Samples from fresh olivine-tholeiite lava shield showing unexpectedly low P-wave velocity at normal permeability values.

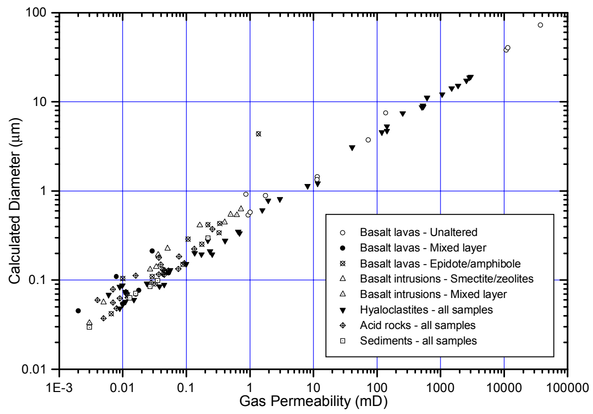

Figure 8. Calculated pore throat diameters for all the samples that strongly relate to the capillary tube flow model.

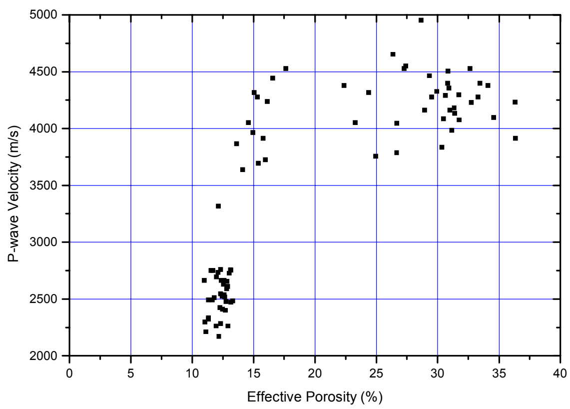

Figure 9. Samples from fresh olivine-tholeiite lava shield showing unexpectedly low P-wave velocity.