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Temperature-Dependence of Seismic Properties in Geothermal Core Samples at In-Situ Reservoir Conditions

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ABSTRACT

The goal of the present work is to predict the effect of saturating pore fluid on seismic properties using a rock-physics model in two Icelandic core samples (hyaloclastite and basalt) saturated with a low-saline fluid.

To achieve this goal, the fluid substitution analysis of seismic properties (velocity and attenuation) as a function of temperature under simulated reservoir conditions using the Gassmann equation has been employed. To include the temperature effect in the Gassmann equation, assumptions have been made: 1) the grain/mineral and dry bulk moduli (initially in the absence of microfractures) are independent of temperature; 2) the temperature dependence follows solely from the thermophysical characteristics of the saturating fluid through the fluid bulk modulus and fluid density. Therewith, a temperature-dependent fluid substitution modeling using the Gassmann relationship has been realized.

Laboratory measurement results show that P- wave velocities decrease with increasing temperature. This trend in seismic velocity with temperatures is related to the thermophysical characteristics of the fluid. The Q factor behaves almost in the same way with temperature as the seismic velocity, except in the lower temperature range.

The results shown here indicate that both velocity and attenuation may be diagnostic for the temperature conditions of a reservoir. The Gassmann equation applies reasonably well for the sample material investigated in the present study and can help explain the contribution of grain/mineral and fluid bulk modulus change with temperatures to the velocity and attenuation. The way how such approaches are implemented in the current study may give the modality for the prediction of a temperature dependence of seismic properties and demonstrates that the application of a fluid substitution modeling using the Gassmann relationship may be useful for the characterization and interpretation of geothermal reservoir systems.

1. INTRODUCTION

Seismic methods have been among the most important non-invasive techniques applied to explore and characterize geothermal reservoirs. Simiyu and Malin (2000) used microearthquake data in volcanically active areas to map the size, depth and fracture density of possible shallow geothermal resources. Vanorio et al. (2004) and Vanorio et al. (2006) studied the interpretation of seismic tomography results using a rock physics approach at the Campi Flegrei caldera and the Larderello-Travele geothermal field, respectively. Recently, DeMatteis et al. (2008) presented a high-resolution study of the three-dimensional compressional and shear wave velocity structures from microearthquake travel times for the Larderello-Travale geothermal field, Italy. Knowledge of the compressional wave velocity field alone was not sufficient to connect the velocity changes to fluid content and state. Therefore, they used the seismic properties deduced from a rock-physics modeling to improve the interpretation of the seismic tomography results. It is well known that numerous factors such as spatial variability in porosity, fracture density, salinity, saturation, tectonic stress, lithology, fluid-steam phase change, fluid pressures, and temperature can potentially produce and/or contribute to geophysical anomalies (e.g. Jones et al., 1980; Boitnott and Bonner, 1994). In geothermal reservoirs, a fluid-steam phase transition, as well as fluid pressure and temperature are crucial factors that potentially produce and/or contribute to seismic anomalies (as shown in the studies cited above). When interpreting such anomalies, realistic assumptions based on validated rock physics models are important.

Laboratory measurements of temperature dependent seismic velocities of rocks at high temperature reservoir conditions have been performed, for example, by Kern (1978); Kern et al. (2001); Punturo et al. (2005); and Scheu et al. (2006). However, these laboratory experiments have been mainly employed on dry samples and under deep mantle rock condition, i.e., very high pressures (up to 600 MPa in 50 MPa intervals) and very high temperatures (up to 1000 ◦C in 100 ◦C intervals). In contrast, many geothermal reservoirs, like Icelandic reservoirs being addressed in the present study, are characterized by temperatures up to 200-300 ◦C and pore pressure around 10 MPa with the pore water being in the liquid phase (Fl´ovenz et al., 2005). An analysis of core scale properties of rock sample at simulated reservoir conditions is useful to identify the role of temperature on the seismic velocity and attenuation (hereafter referred to as seismic properties). The goal of this work is to predict the effect of the saturating pore fluid on the seismic properties by applying a rock-physics model on two different Icelandic core samples (hyaloclastite and basalt) saturated with low-saline water. Such an analysis which predicts how the rock bulk modulus (accordingly 41 the seismic velocity) changes with a change of pore fluids is well known as a fluid substitution analysis (Gurevich et al., 2007, and references therein). Central to the fluid substitution problem are Gassmanns relations (Gassmann, 1951), with the companion result that the shear modulus is independent of the pore fluids.

In this work, the Gassmann equation is modified to account for the temperature dependence of pore fluid characteristics. Using this temperature dependent Gassmann relationship, an attempt is made to relate the influence of temperatures on seismic properties of pore fluids and those of fluid saturated rocks during the change of temperatures. Using the Gassmann relationship it is also possible to include the effect of partial saturation due to the creation of bubbles and their influences on effective seismic properties of rocks. The temperature dependence of seismic wave attenuation is shown for the hyaloclastite sample. Guided by the result of temperature-dependent seismic velocities of pore fluids and fluid saturated rocks, a possible explanation of the seismic attenuation of hyaloclastite is related to the thermophysical characteristics of the fluid (Jaya et al., 2009).

2. SAMPLES AND EXPERIMENTAL SETUP

2.1 Samples

The samples investigated in this work came from geothermal wells in Iceland. Both samples were selected from cores coming from the wells of the geothermal fields in Krafla (sample 58) and in Hengill (sample 3A). The well locations are shown in Figure 1(a). The samples 58 and 3A are part of 12 cores from different alteration zones of the Icelandic crust (Figure 1(b)). Table 1 gives an overview of the samples and their properties prior to the laboratory measurements. Water of very-low salinity was used as the saturating fluid (see Kristinsd´ottir et al. (2009) for more details).

2.2 Experimental Setup

As in Kristinsd´ottir et al. (2009), the experiments were conducted at the GFZ in a recently set up high pressure-high temperature flow-through apparatus. The apparatus consists of an internally heated oil-medium pressure vessel and a connected pore fluid system. The apparatus allows simultaneous and continuous measurements of permeability, electrical conductivity as well as P- and S-wave velocities. Ultrasonic measurements were performed with piezoelectric ceramics (Stelco, type P850 and PPK62, Curie temperature = 360 ◦C and 320 ◦76 C) for both compressional- (P) and shear- (S) waves, respectively. The ultrasonic excitation signal was a rectangular voltage single burst at 1.0 V and 400 kHz. In the present study only the recorded P-wave data will be evaluated. The temperature was measured with two PT-100 sensors, one close to the top and one close to the bottom of the specimen, respectively. We noticed a temperature gradient of approximately 1 - 2 ◦C along the sample, the top side being the hotter part. A detailed description of the apparatus and specific measurement procedures can be found in Milsch et al. (2008). As described in Kristinsd´ottir et al. (2009, this issue), the samples were vacuum saturated with their respective fluids prior to setting up the specimen assembly. This method also served for calculating the (connected) sample porosity listed in Table 1. For both specimens, the fluids were synthetically prepared. This was achieved by dissolving specific amounts of reagent grade NaCl, KCl, Na2SO4, and K2SO4 salts in distilled water. The sample specific concentrations chosen reflect the measured chemical fluid in situ composition and estimated fluid conductivity at the respective geothermal site (Kristinsd´ottir et al., 2009). During the experiments both confining and pore pressure were kept constant (Table 1). P-wave signals were recorded in parallel to the electrical conductivity measurements reported in Kristinsd´ottir et al. (2009). Measurements were made in 25◦C intervals in the temperature range between 50 and 250 ◦96 C. The temperature history is displayed in Figures 2(a) and 2(b) for sample 3A and 58, respectively.

3. P-WAVE VELOCITIES

3.1 Fluid Substitution Analysis

The effect of temperature due to the presence of a saturating fluid is closely related to the thermophysical characteristics of the corresponding fluid. Figure 3 shows some of the related fluid characteristics which help to interpret fluid substitution analysis results described as follows. In that figure one oserves that the density, viscosity and velocity of water change with increasing temperatures at a constant pore fluid pressure. The behaviour of those temperature dependencies varies depending on each thermophysical characteristics, i.e., most significant changes appear at the temperature range of 100-125 ◦C at which the curve trend change slightly (in the case of the water velocity and density) or abrupt (in the case of water viscosity at the temperature range below 100 ◦C). Gassmann equation has routinely been used for the fluid substitution analysis of seismic and sonic log data. Gassmann equation relates the saturated bulk modulus, K_{sat} and the dry one, K_{dry} , as follows,

$$K_{sat} = K_{dry} + \alpha^2 \frac{K_g}{\left(1 - \frac{K_{dry}}{K_g}\right) - \phi\left(1 - \frac{K_g}{K_f}\right)}; \qquad \mu_{sat} = \mu_{dry} \tag{1}$$

with $\alpha = 1 - K_{dry} / K_g$ is the Biot-Willis coefficient, ϕ is porosity, K_g and K_f are the bulk moduli of the solid grain material and fluid, respectively. Using Gassmann equation, an attempt is here given to introduce a temperature dependency in the fluid substitution modelling.

The temperature dependency of Gassmann equation is first assumed solely due to the effect of temperature on the fluid bulk modulus. That is, by introducing

$$K_f = \rho(T)\left[v(T)\right]^2, \tag{2}$$

into Eq. (1), where *T* is the temperature, ρ and *v* is the fluid density and velocity, respectively.

3.2 Sample 3A

Figure 4 shows the determined P-wave velocities of sample 3A. In Figure 4 (and in other following figures), C1, C2 and C3 indicate the first, second and third temperature cycles, respectively. One cycle consists of increasing and decreasing the temperature. It can be observed that the P-wave velocities generally have decreasing trend with increasing temperature. For sample 3A, the value of Kdry was extracted from the previous (pressure dependent) measurements on the same core (Franzson and Tulinius, 1999). Measurements were done under atmospheric fluid pressure and room temperature and the sample was saturated with water. Results from the core analysis and borehole geology of the offset well in the same geothermal field showed that the primary mineral grain composition of hyaloclastite tuff is volcanic glass (Furnes, 1974; Bakht, 2000, therein called sideromelane). Therefore, the work of Pan et al. (1998) which intensively investigated the elastic properties of sideromelane is used for obtaining Kg value. Note that Pan et al. (1998) measured the elastic properties of their samples under different confining pressures and at dry conditions. For this work, only results which were obtained close to the present confining pressure (175 bar) and corrected for pure glass situations are used in the current temperature-dependent Gassmann equation.

Figure 5 shows the result of the Gassmann fluid substitution on sample 3A. The solid line depicts the result of applying Equation (1) with Kf obtained from the temperature-dependent fluid density and velocity shown in Figure 3(a). This curve seems to fit the velocity-temperature relationship in the temperature range between 50 − 125 ◦175 C but not for higher temperatures.

3.3 Sample 58

Figure 6 shows P-wave velocities of sample 58. Here, C1 and C2 have the same meaning as those shown in Figure 4. Note, only two cycles of measurements are available for the present analysis. As has been previously depicted in Figure 2(b), for this sample the measurement was performed up to the maximum temperature 200 ◦181 C. In Figure 6 the decreasing trend of P-wave velocities for sample 58 is also evident. Figure 7 shows the result of using Equation (2) for sample 58 (basalt). Here, no previous measurement of the same sample was available. To obtain Kg and Kdry a typical core sample in the region (Iceland basalt) from other measurements has been used. Therefore, measurement results of vP and vS on dry samples of Icelandic basalts reported by Vinciguerra et al. (2005) are used for the values of Kdry. In addition, their result for mineral composition studies has been used to calculate the effective grain/mineral bulk modulus Kg needed for the application of the Gassmann equation. The solid line in Figure 7 shows the prediction of P-wave velocities using the Gassmann equation. We observe that predicted P-wave velocities fits reasonably well with the experiment data.We discuss the predicted P-wave velocities of both samples (3A and 58) in the following section by including other possible scenarios of the temperature dependence of fluid.

3.4 Discussion and Analysis

One notices that, the P-wave velocities of sample 58 show different behaviour to sample 3A. That is, the velocity difference at the maximum and minimum temperatures for sample 58 is smaller than for sample 3A which would roughly indicate that temperature changes have a smaller influence on the P wave velocity for basalt material (sample 58) than for hyaloclastite material (sample 3A). We will try to explain this behaviour by using the results obtained by applying the Gassmann relationship. The crucial assumption in the Gassmann equations (Equation 1) is that the fluid pressure is spatially constant in a representative volume throughout the sample. This requires that all pore space is interconnected. While the Gassmann equations are quite general and robust, they are based on several assumptions: (1) the rock is monomineralic or effectively homogeneous; (2) the pore space is very well connected; (3) the seismic frequency is low; and (4) the saturating pore fluid is homogeneous. Any deviation of seismic properties to those predicted by the Gassmann equa tion may indirectly indicate a heterogeneity of the rock samples: the presence of isolated pores and the polymineralic grain composition of the rock. The deviation of the Gassmann equation at higher temperature for sample 3A is most likely related to the heterogeneity of the microstructure, i.e., the presence of isolated pores and the mineral composition of the hyaloclastite. Such an effect of microstructural heterogeneity on physical properties of hyaloclastite has been shown by Frolova (2007). It may also indicate the creation of a patchy fluid saturation due to the presence of bubble at higher fluid temperatures. To address such a possibility, in the following, we performed the fluid substitution analysis using the Gassmann equation with bubble inclusions.

Figure 8 shows the result of Eq. (1) with the same parameter as before but now involving a portion of bubbles in order to elaborate the high temperature effect. The effective fluid bulk modulus with the presence of steam bubbles is computed by using $K_f^{-1} = S_g K_{gas}^{-1} + \left(1 - S_g\right) K_{water}^{-1}$ (Jaya et al., 2008). The Gassmann relationship assumes that the shear modulus is not affected by the presence of a fluid. Laboratory studies showed however, that pore fluids may have significant effects on the saturated rock shear modulus as a result from the chemo-mechanical weakening caused by the presence of pore fluid, in particularly under the presence of microfracturing due to the high pressure and temperature (Boitnott, 1995; Berryman, 2005). To address such a temperature dependence of the shear modulus due to the presence of pore fluid it is assumed that the saturated shear modulus is linearly dependent of the temperature. This assumption has been successfully applied to the Gassmann equation by Boitnott and Bonner (1994) for Geysers metagraywacke and metashale. In order to include this assumption, the Gassmann equation is modified by setting

$$\mu_{sat}(T) = \mu_{dry} + \nabla\mu T \tag{3}$$

where $\nabla\mu = \partial\mu / \partial T$ is the shear modulus derivative (gradient) with $\nabla\mu \approx 0.001$ GPa/°C (as obtained by Boitnott (1995)).

The dotted line in Figure 9 is obtained by assuming that µsat(T) 6= µdry. This line fits the P-wave velocities of the experiment data of sample 3A much better. The introduction of such non-constant shear modulus into the Gassmann equation needs, however, further measurements, e.g., by including S-wave data, which was not available in the present study. The application of the relationship in Equation (6) should nevertheless demonstrate that factors involving shear weakening/strengthening, i.e., µsat 6= µdry, might be relevant for temperature-dependent rock properties. Possibly, it can be related to the opening of new microfractures during the temperature increase. It is well known that microfractures exhibit an anisotropic feature to the rock properties and, indeed, under the presence of anisotropy the shear modulus becomes fluid dependent (Berryman, 2006, see also references there).

On the other hand, a reasonable result shown in Figure 7 indicates that the assumption of the Gassmann equation works reasonably well for basalt material (sample 58). Generally, since deviations from the Gassmann relationship may indicate a shear modulus dependence on temperature, e.g., through the temperature-dependent fluid properties as has been discussed in the previous paragraph, it is supposed that the grain material of basalt exhibits a more homogeneous structure compared to hyaloclastite. The results for both materials do, nevertheless, demonstrate the usefulness of temperature-dependent fluid substitution modeling using the Gassmann equation.

4. TEMPERATURE DEPENDENT SEISMIC ATTENUATION

Figure 10(a) shows selected waveforms measured on sample 3A. In this figure, the waveform amplitude follows a systematic trend consistently with temperature changes. The amplitude increases first from 50 to 125 ◦C and then starts to decrease afterwards up to a temperature of 250 ◦C. In 283 the following section we use these waveform amplitudes to determine the wave attenuation and then relate its temperature dependence to the thermophysical characteristics of the fluid. The attenuation, expressed as an inverse *Q* factor, Q^{-1}, (Figure 10(b)) is related to complex effects of thermophysical characteristics of the fluid. Figure

3(b) shows the water viscosity and velocity as a function of temperature. These data was taken from NIST Standard Reference Database (Lemmon et al., 2005).

Due to the temperature-dependent viscosity and velocity of fluid, it is more likely that the increase of *Q* factor (decrease of attenuation) in the temperature range *50-125* °C is related to a quick decrease of viscosity. When considering Figure 4 (right) where the fluid internal energy or entropy increases with the temperature, it may indicate that the fluid experiences an equilibrium perturbation from its fully fluid state. It may also indicate a spontaneous change of intrinsic physical characteristics of the fluid during the course of temperature change. Together with the decrease of fluid density, it might be an indicator of creating steam bubbles (even very small). We think that the decrease of *Q* factor (increase of attenuation) in the temperature range above 125 °C is more likely due to the presence of steam bubbles. The presence of steam bubbles, even in a very small part, is sufficient to decrease the velocity as shown in Figure 7 and 8.

5. CONCLUDING REMARKS

This work presented results of applying the fluid substitution analysis to predict the seismic properties (velocity and attenuation) as a function of temperature under simulated reservoir conditions using the Gassmann equation. To include the temperature effect in the Gassmann equation, assumptions have been made: 1) the grain/mineral and dry bulk moduli (initially in the absence of microfractures) are independent of temperature; 2) the temperature dependence follows solely from the thermophysical characteristics of the saturating fluid through the fluid bulk modulus and fluid density. Therewith, a temperature-dependent fluid substitution modeling using the Gassmann relationship has been realized.

Laboratory measurements showed that P-wave velocities decrease with increasing temperature in a systematic way. This trend in seismic velocity with temperatures is related to the fluid characteristics. Using the temperature dependent Gassmann equation it is suggested that the presence of bubbles can reduce the effective elastic properties of rocks as shown for the hyaloclastite (sample 3A).

The Q factor behaves almost in the same way with temperature as the seismic velocity, except in the lower temperature range. The increase of the Q factor with temperature is related to a rapid viscosity decrease. The decrease of the Q factor at higher temperatures may indicate the presence of bubbles decreasing the effective elastic properties. It should be mentioned that, in the current study, the role of rock alteration and the contribution of primary and secondary minerals to the effective seismic properties was not investigated in details. Only an effective property (quasi-homogeneous) grain mineral has been assumed which results in the application of the Gassmann equation using only one value of Kg. For the basalt material (sample 58) this approximation works reasonably well as the primary composition of basaltic rocks in Iceland is relatively uniform comprising calcic plagioclases, clinopyroxene, olivine and magnetite ilmenite (Fridleifsson, 1991; Bakht, 2000). For the hyaloclastite material (sample 3A) the standard appli360 cation of the modified temperature-dependent Gassmann equation works only for lower temperatures but not for higher ones which indicates the deviation to the assumption of a homogeneous grain material. As reported by Bakht (2000, and see also references there), volcanic glass (the main mineral component of hyaloclastite) is more susceptible to secondary alteration, than olivine followed by plagioclases, pyroxene and the ore minerals. Possibly, besides the creation of a small fraction of bubbles, the higher degree of secondary mineral alteration in hyaloclastite is able to explain that the Gassmann relationship does not work for all temperatures for hyaloclastite compared to basalt. It is worth to note that the deviation to the assumption used for the application of the Gassmann equation may be compensated by involving a patchy fluid saturation due to the presence of bubbles and a pore-fluid enhanced shear modulus as shown in Figures 8 and 9. The way how such approaches are implemented in the current study may give the modality for the prediction of a temperature dependence of seismic properties.

The results shown here indicate that both velocity and attenuation may be diagnostic for the temperature conditions of a reservoir. The Gassmann equation applies reasonably well for the sample material investigated in the present study and can help explain the contribution of grain/mineral and fluid bulk modulae changes with temperatures to velocity and attenuation. This finding demonstrates that the application of a seismic exploration method, particu393 larly the Gassmann fluid substitution modeling, may be useful for the characterization and interpretation of geothermal reservoir systems using seismic velocity and attenuation data.

6. ACKNOWLEDGEMENTS

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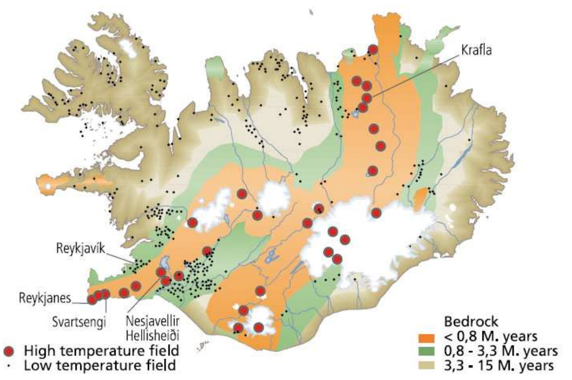

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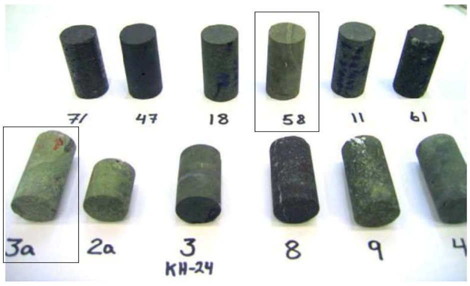
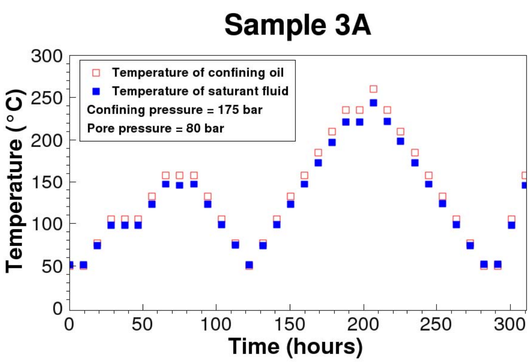


(b)

Figure. 1. a) The location of geothermal fields from which the sample under investigation came from. b) Core samples from different alteration zones in Iceland.



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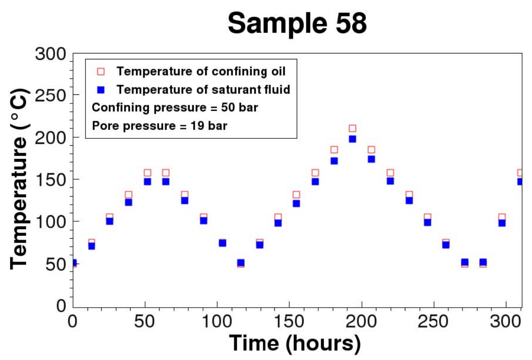
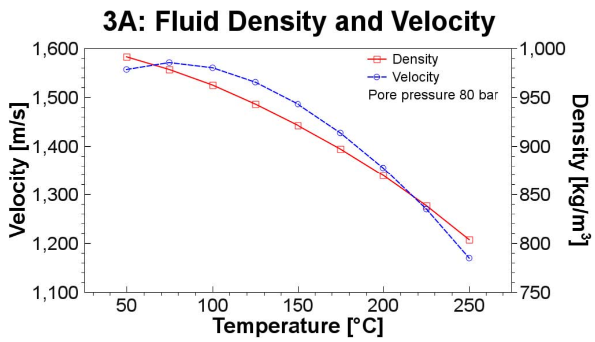
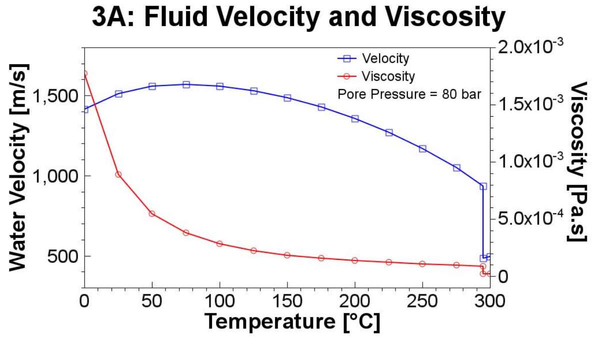


(b)

Figure.2. Temperaturehistory of sample3A (a) and 58 (b), respectively.



(a)



(b)

Figure. 3. Thermophysical characteristics of low salinity water as a function of temperature at 80 bar fluid pressure: a) Density and velocity; b) Velocity and viscosity. The data in Figure 3 came from the fluid thermophysical database provided by the National Institute of Standards and Technology (NIST) (collected from numerous laboratory measurements by Lemmon et al. (2005)). Note that the jump at T =295° C indicates the fluid-steam phase transition.

Table 1. The petrophysical characteristics of samples 3A and 58 prior to the laboratory measurements. (1) Data taken from Fl´ovenz et al. (2005); (2) data of National Energy Authority and Iceland Geo Survey; (3) measurements made and shared by E. Spangenberg at GeoForschungsZentrum Potsdam, Germany.

Sample Description	Sample ID	
	58	3A
Depth [m] (1)	187	795
Material (1)	Basalt	Hyaloclastite
Alteration zone (1)	Smectite	Chlorite
Present in-situ temperature [°C] (1,2)	160	200
Sample length [mm] (3)	40	40
Sample diameter [mm] (3)	30	30
Estimated in-situ fluid conductivity at 25°C [μ S/cm] (1)	780	808
Porosity [%] (3)	20.0	20.7
Pore volume [cm] (3)	5.6	6.0
Density [g/cm^3] (3)	2.37	2.15
Pore pressure [bar]	19	50
Confining pressure [bar]	80	175

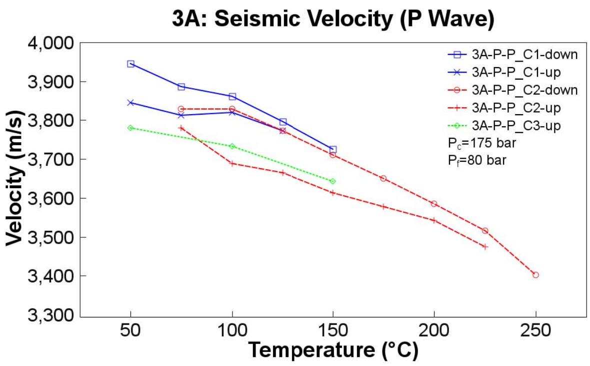


Figure. 4. Temperature dependent P wave velocities of sample 3A.

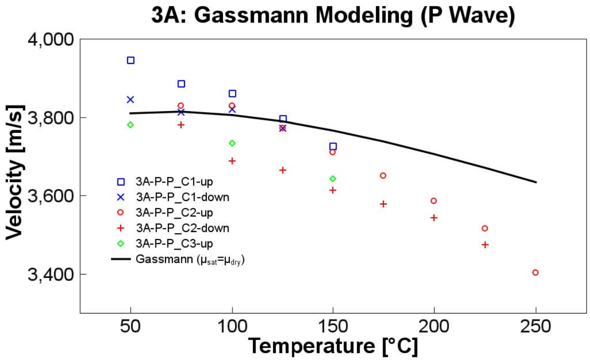


Figure. 5. Results of temperature-dependent Gassmann fluid substitution for sample 3A.

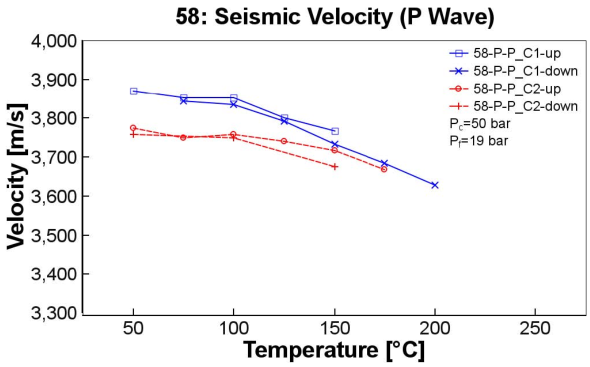


Figure. 6. Temperature dependent P wave velocities of sample 58.

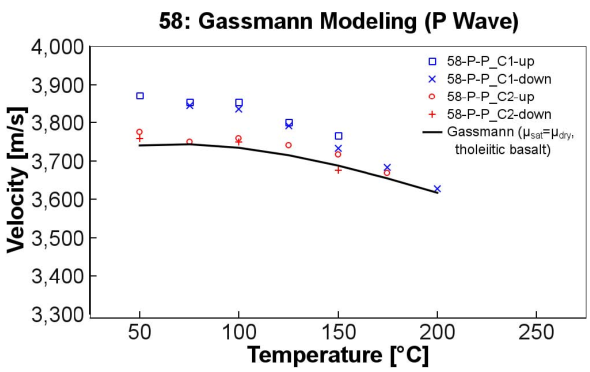


Figure. 7. Results of the fluid substitution analysis using the Gassmann equation for sample 58.

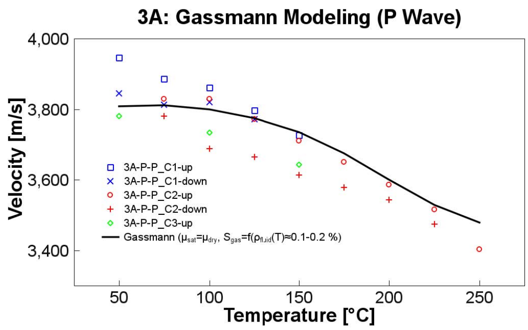


Figure. 8. Results of temperature-dependent Gassmann fluid substitution by incorporating a small fraction of bubbles for sample 3A.

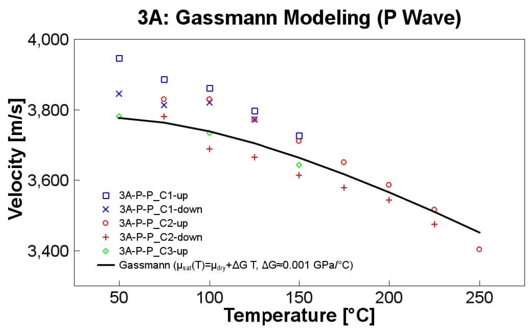
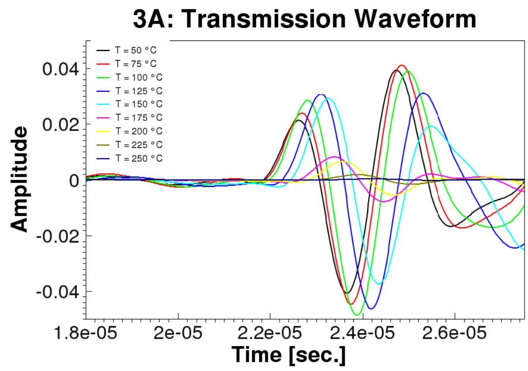
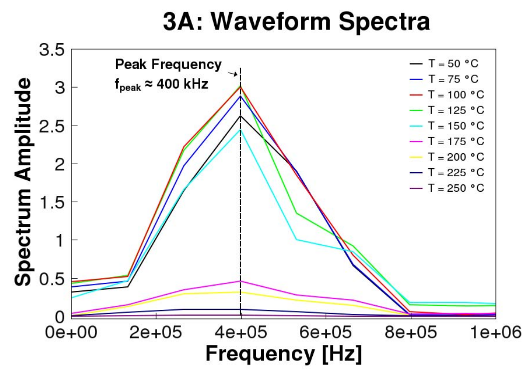


Figure. 9. Results of temperature-dependent Gassmann fluid substitution with μ_{sat} (T) ≠ μ_{dry} for sample 3A.



(a)



(b)

Figure.10. Transmission waveforms (a) and their corresponding spectra (b) measured on sample 3A.

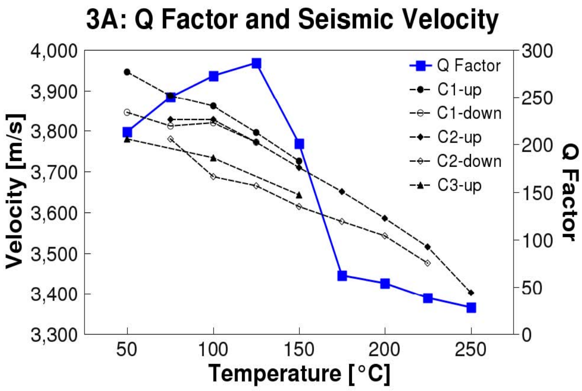


Figure. 11. Q factors calculatedfrom the transmission waveforms of sample3A (Figure 10(a)) overlain on the P-wave velocities.