Seismic velocities of halite salt: anisotropy, dispersion, temperature and stress effects

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Summary

We have made various laboratory measurements on halite salt. Most of the effects of crystal defects and inter-crystal cracks on P-wave velocity can be removed after high pressure annealing. The temperature effect on seismic velocities of halite salt is dominant relative to the stress effect. We did not observe azimuthally anisotropy on the halite salt sample. We analyzed that the directional velocity variations are not indication systematic anisotropy, instead they are most likely caused by crystal-scale heterogeneity. No significant dispersion of seismic velocities is observed from the low frequency measurement.

Introduction

Laboratory measurement data on rock physics properties of underground salt rocks are rare. Although salt rock cannot store petroleum itself, it is found that underground salt is often closely related to high productive petroleum reservoirs because creeping deformation of salt can be beneficial to formation of potential oil and gas traps. The dimensions of the underground salt can be significant. For accurate delineation of structures of the reservoirs associated with underground salt, we need more understanding of the seismic properties of underground salt.

The naturally formed single halite crystal has cubic shape and has cubic velocity anisotropy (Sun, 1994). After creeping deformation, the halite salt usually has polycrystal structure (Lebensoh, et al., 2003). LandrØ et al. (2011) has observed moderate velocity anisotropy in the salt outcrop at Cardona, Catalonia in Spain. Since underground salt can occur in a wide range of depths and temperatures, in this study, we will first try to measure the stress and temperature effects on seismic velocities of halite salt, then will try to observe the existence of velocity anisotropy on the halite salt sample. Finally, low frequency measurement is conducted to test frequency dependency of seismic velocities.

Sample preparation and description

The halite salt core (Figure 1) comes from a underground salt dome in Louisiana, the North America. Although halite salt is much softer than common rocks (halite has Mohs hardness around 2-2.5), preparation of samples for laboratory measurement is quite time consuming. We have to cut through the brittle halite crystals which are much larger than the grains of common clastic rocks. Also water cannot be used in drilling the plug. These properties make sample preparation for lab measurement a very expensive process. To make sample for traditional ultrasonic velocity measurement, we first cut the core into gross cylindrical shape, and then use lathe to shape it into perfect cylindrical shape. Figure 1 shows the halite salt core and the sample made from it. The halite sample has glass luster, the whitish spots indicate defects in the crystals or opening of inter-crystal cracks. The bulk density of the halite is 2.165 g/cc. The porosity is too low to be reliably measured by the helium porosity meter, it is assumed to be zero. We did not

Figure 1: Halite salt core (left, with diameter about 4″)and sample (right, with diameter of 1-1/2″ and length of 2″) made from it for ultrasonic and low frequency measurement s

make chemical analysis of mineral composition of halite sample, bus as Martinez (1991) pointed out that the Gulf Coast domes are remarkably pure rock salt (NaCl) or halite in chemical composition.

Core damage, hysteresis and stress effect

The core damage during coring process can be observed from the whitish spots on core surface (Figure 1). Damages can also occur during the preparation of samples for lab measurement. It is reported that due to plastic deformation, this damages might be recoverable by annealing under high pressure (Lebensohn, et al., 2003). To observe the real stress effect on seismic velocities, we need first to stabilize the halite sample and let it partially recover from damages from coring and sample preparation. In Figure 2, we monitor P-wave velocities under 3 circles of stress loading and unloading. Except of the first pressure loading processing, the effect of stress on P-wave velocity is not significant. The velocity increasing during the first pressure

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loading process might be primarily caused by closing of inter-crystal cracks. Part of the inter-crystal cracks might be annealed under high pressure, so the P-wave velocity cannot drop down to the initial low value when the pressure is decreased to the same level. Obvious hysteresis is observed, which might be related to plastic deformation.

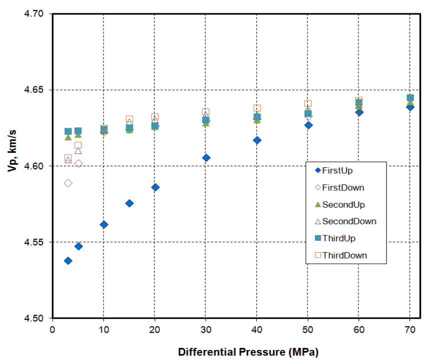

Figure 2: Stress effect on halite sample (Second pressure circle is 12 hours after the first pressure circle, the pressure circle is 24 hours after the second pressure circle, after measurement of each pressure circle, the sample stay under differential pressure of 3 MPa until next measurement of next pressure circle)

Figure 3: Dent of pore pressure line pattern on halite sample after measurement of 3 testing circles

There is good repeatability between measurements of the second and third pressure circles. After the sample is stabilized, the stress effect is not significant, which should be more close to in situ conditions.

Figure 3 shows the halite sample after stress effect measurements. The titanium buffers used in the ultrasonic measurement has Mors hardness scale of 7. It is much harder than the halite salt, so there is obvious dent of pore pressure line pattern on the end surface, which causes the actual signal travel path be shortened by 0.1 mm. There are no observable diameter changes on the sample.

Temperature and stress effects

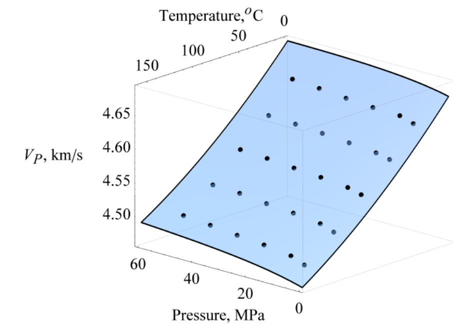

Figure 4: Temperature and pressure effects on P-wave velocity

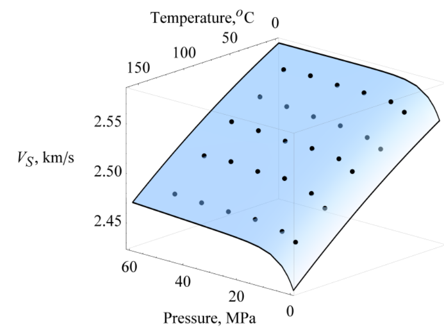

Figure 5: Temperature and pressure effects on S-wave velocity

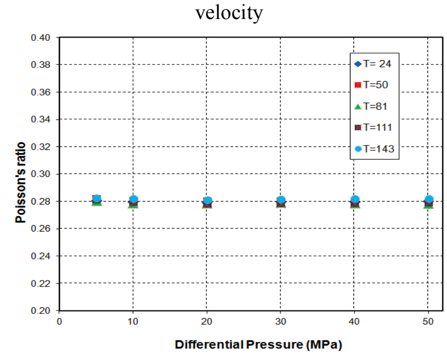

Figure 6: Temperature and pressure effects on Poisson's ratio of halite.

The pressure range of our measurement is from 5 MPa to 50 MPa, and the temperature range is from 24 ^oC to 143^oC. Duration of the ultrasonic velocity measurement on the halite sample is about 10 hours. At each temperature, we first increase the pressure to 50 MPa and then decrease the pressure sequentially and record the travel times at each pressure, and then we increase the temperature to the next

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temperature. The time of heating and velocity measurement for each temperature is about two hours.

Figures 4 and 5 show the measured effects of differential pressure and temperature for P-wave velocity and S-wave velocity respectively. It can be seen that at the temperature and pressure ranges where the measurement is conducted, the temperature effect is more significant than the pressure effect for both P-wave velocity and S-wave velocity. For practical application, we have set up following empirical relations by non-linear regression fitting of the measurement data:

$$V_P = 4.6910 - 0.01918\, e^{-0.05164\,\mathrm{P}} + 1.3265 \times 10^{-6}\,\mathrm{P\,T} - 0.001707\,\mathrm{T} + 2.3893 \times 10^{-6}\,\mathrm{T}^2$$

$$V_S = 2.5830 - 0.03440 e^{-0.2081\,\mathrm{P}} + 9.8889 \times 10^{-7}\mathrm{P\,T} - 0.0006058\,\mathrm{T} - 9.6832 \times 10^{-7}\mathrm{T}^2$$

where P has unit of MPa and T has unit of Celsius degree. The fitting surfaces are also shown in Figures 4 and 5. The R^2 regression coefficients are 0.999 and 0.992 for Vp and Vs data respectively. Figure 7 shows the effects of temperature and pressure on Poisson's ratio. At the temperature and pressure ranges where the measurements are conducted, the variation of Poisson's ratio is negligible.

Velocity anisotropy/heterogeneity

We have designed a benchtop rotational velocity measurement system (Figure 7) to measure azimuthal velocity anisotropy on circle A and circle B on the cylindrical sample (as shown Figure 8). The idea is that if there is systematic anisotropy, we should be able to observe similar directional velocity variation trend. We first conduct the rotational velocity measurement around the top circle (circle A), the signal traces are shown in Figure 9 (traces in black). Although the signal traces are generally good for time picking, under the same pressure condition, the waveforms around the first break time are not consistent. This reminds us the sample has accidentally fallen on the desktop before rotational velocity measurement. The damage is obvious from the whitish part at the top end of the sample. So we put the sample in pressure vessel again and let it stay under 60 MPa for 5 hours, and then take it out. As shown in Figure 8, the color of the damaged part is more close to the other part, the sample seems to be partially recovered or annealed under high pressure. We did the rotational velocity measurement again on the same rotational position. The red traces in Figure 9 show the repeated measurement result. It can be seen the quality of the signals are substantially improved. The first break signal is clearer and the wave forms are more consistent.

We continue the rotational velocity measurement on circle B. Figure 10 shows the comparison of the trace signals around circle A and circle B. The wave signals are generally consistent, but the first arriving times at different directions has no similar pattern between circle A and circle B. Figure 11 shows the polar plot of measured velocity around both circle A and circle B. First, it can be seen the velocity variation is small, less than 5%; second, there is no similar directional velocity variation trend between A and B. Thus no systematic velocity anisotropy is

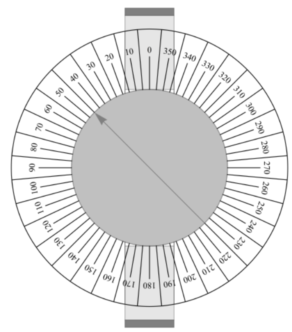

Figure 7: Diagram of rotational benchtop velocity measurement.

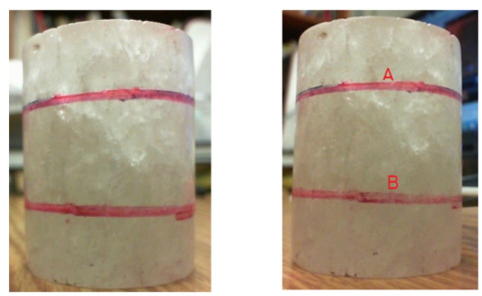

Figure 8: Halite sample before (left) and after (right) high pressure annealing

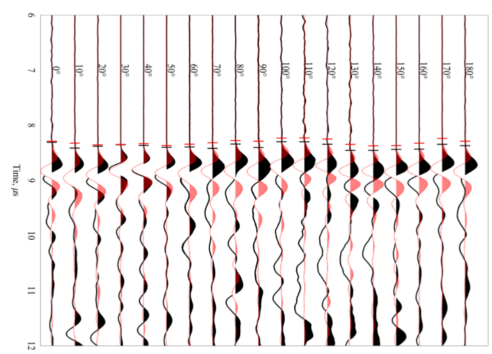

Figure 9: Comparison of P-wave signal traces around circle A before (balck traces) and after (red traces) high pressure annealing .

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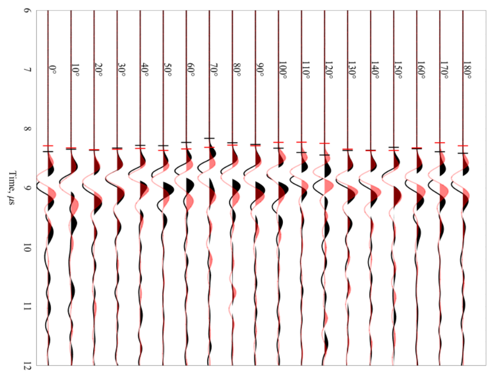

Figure 10: Comparison of P-wave signal traces around circle A (Red) and circle B(Black)

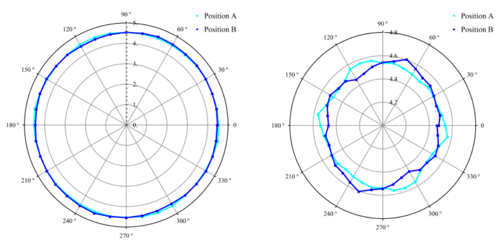

Figure 11: Comparison of P-wave velocities at different azimuths around position A and position B, no consistent velocity anisotropy is observed(Left: real scale polar plot; Right: distorted polar plot).

observed from our measurement.

The distance between the two red circles in axial direction is about 2 cm, which is about the median size of halite crystals. Quite possibly, the small velocity variation in different directions and the different variation trends between circle A and circle B are caused by different combinations of halite crystals through which the wave signals pass. The wavelength of seismic wave going through salt body is much longer than the sizes of salt crystals, thus the local heterogeneity should have negligible effect on seismic wave velocities. It should be proper to treat creeping deformed halite salt as homogeneous medium for seismic exploration.

Low frequency measurement

Imaging around creeping deformed salt is one of the most challenging tasks in seismic data processing. The difficulty is caused by geometric complexity and significant impedance contrast between salt and surround lithologies, and it is also suspected that the creeping deformed salt might cause significant attenuation of seismic wave. Thus we have conducted velocity dispersion measurement on the

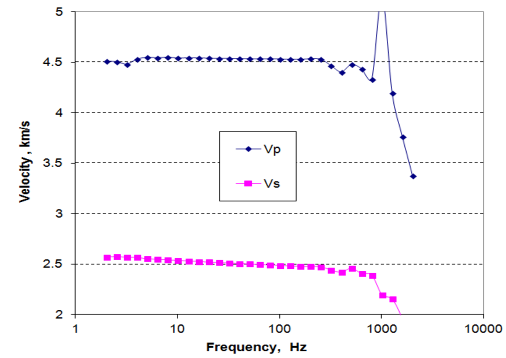

Figure 12: Low frequency measurement

halite salt sample using the low frequency system built by our lab (Yao, 2013). The measurement is conducted on room temperature and pressure conditions. As shown in Figure 12, in seismic frequency range, the P-wave velocity has no trend of increasing with frequency and the S-wave velocity even slightly decreases with frequency, which might be caused by measurement uncertainty. The P-wave velocities measured at seismic frequency ranges are consistent with those from benchtop measurements, so there should be no significant dispersion of P-wave velocity at frequency range between seismic frequency and ultrasonic frequency.

Conclusions

The temperature effect on seismic velocities of halite salt is dominant relative to the stress effect. For laboratory measurement of the elastic properties of salts, it is important to check possible damages of the salt sample and let the sample stay at underground stress condition for a certain time to recover from possible damages. We did not observe azimuthal anisotropy on the halite salt sample. The velocity variations in different directions observed in laboratory are most likely caused by crystal-scale heterogeneity, the velocity anisotropy of halite salt experienced significant creeping deformation should be negligible for seismic exploration. No significant dispersion of seismic velocities is observed from the low frequency measurement.

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EDITED REFERENCES

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