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Technical Note

Attenuation anisotropy in shale at elevated confining pressures

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1. Introduction

Shale has been estimated to comprise approximately two-thirds of all sedimentary rocks [1]. Nevertheless, studies of the physical properties of shale are relatively uncommon compared to other sedimentary lithologies. Especially rare are studies of shale attenuation anisotropy at elevated confining pressure. An understanding of attenuation and attenuation mechanisms is particularly important for seismic exploration. VSP and cross well experiments have used attenuation information to help determine the lithology of subsurface formations [2-4]. Attenuation is also believed to have a significant affect on AVO responses [5], and may affect lithological interpretations based on AVO analyses. Measurements of attenuation have been correlated with fluid content (e.g. [6]) and porosity (e.g. [7]), and may be used to determine in-situ hydraulic properties. Seismic attenuation has also been linked to rock strength [8,9], and may be useful in relation to blasting, and the location of landslide material. Accurate values of attenuation are also necessary to estimate ground motion associated with earthquakes [10,11].

Shale has been shown to have significant velocity anisotropy (e.g. [12]) that persists at elevated confining pressure. It is unclear, however, whether attenuation displays the same anisotropic relationships with pressure. Previous studies of attenuation in shale have involved either measurements in a single direction, measurements at atmospheric pressure, or measurements on unsaturated samples only (e.g., [13–15]). This study provides the first measurements of shale attenuation in multiple directions, at elevated confining pressure, under both saturated and unsaturated conditions. Laboratory measurements have been made on four samples, up to 250 MPa. Velocity and attenuation have been measured parallel and perpendicular to bedding for all samples. One sample includes measurements made on cores at three additional angles to bedding. From this information, conclusions can be reached on attenuation mechanisms.

2. Previous studies of shale anisotropy

One of the first experimental studies on the physical properties of shale was by Kaarsberg [16], who measured compressional wave velocity in both artificial and natural shale samples in three mutually perpendicular directions. Two cores were taken in the plane of bedding and one was taken perpendicular to bedding. Velocity was measured at atmospheric pressure as a function of drying time. The samples were determined to be transversely isotropic (hexagonal symmetry), due to preferred mineral orientation.

Jones and Wang [17] reported compressional and shear wave velocities of Cretaceous shale as a function of confining pressure. Velocity measurements were made to 400 MPa at angles parallel and perpendicular to bedding, as well as at 45° to bedding, on both saturated and unsaturated cores. They found that velocities with vibration directions parallel to bedding were higher than those parallel to bedding, and concluded that this was due to preferred mineral orientation. Lo et al. [18] measured compressional and shear wave velocities for Chicopee shale to 100 MPa both parallel and perpendicular to bedding, as well as at 45° to bedding. They concluded that shale velocity anisotropy is due to preferred mineral orientation and cracks aligned parallel to bedding. Johnston and Christensen [12] combined measurements of velocity with X-ray diffraction measurements and SEM observations to relate velocity anisotropy to clay mineral orientation. "Orientation indices" were determined using an X-ray diffraction technique, and a positive correlation was found between the orientation of illite and chlorite mineral grains and velocity. Anisotropy at elevated pressures was,

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therefore, attributed to preferred mineral orientation rather than crack alignment. Velocity anisotropy in shale has also been related to thermal maturity as well as kerogen content and orientation [19,20].

Hornby et al. [21] use an anisotropic effective-medium approach to model the elastic properties of shales. Their analysis includes connected and distributed phases. Comparison with the laboratory results of Jones and Wang [17] demonstrates the validity of their model results.

More recently, the influence of pore fluid on elastic properties of shale has been investigated. Hornby [22] measured compressional and shear wave velocities up to 80 MPa on two fluid saturated shale samples under drained conditions. One sample is Jurassic outcrop shale that was recovered from under sea and stored in its natural fluid, and the other is Kimmeridge Clay taken from a North Sea borehole. Measurements were made on cores parallel, perpendicular, and at 45° to bedding. Values of anisotropy were up to 26% for compressional and 48% for shear wave velocity, and were found to decrease with increasing pressure. The effect of reduced porosity was, therefore, concluded to be more influential on anisotropy than increased alignment of minerals at higher pressure.

Compressional wave attenuation (α) anisotropy has been previously measured by Johnston and Toksoz [13] on saturated samples of Colorado oil shale. They measured Q both perpendicular and parallel to bedding as a function of confining pressure using a pulse transmission method. They found that values of Q were higher perpendicular to bedding ($\sim 21-27$) than parallel (~ 14), while velocity was higher parallel to bedding than perpendicular. Q and α are related by the following equation: $1/Q = \alpha V/\pi f$, where V is velocity and f is frequency. They postulate that Q is higher perpendicular to bedding due to relative shear deformation between the shale matrix and kerogen inclusions.

3. Experimental methods

3.1. Sample description

The NEW3, NEW5 and NEW7 shale samples that were used in this study are from the New Albany Shale, which has been previously studied by Johnston and Christensen [12]. The shale is located in the Illinois basin (USA), and is Devonian in age. Sample NEW3 is from the lowermost Blocher member of the New Albany shale, while samples NEW5 and NEW7 are from the Morgan Trail member [12]. The ANT1 sample is from the lower Antrim Shale, collected from a quarry in Northern Michigan (USA). The Antrim Shale is found throughout the Michigan Basin and is Upper Devonian in age. All of the shale samples are well indurated and have low porosity (<3%). Clay minerals consist mainly of illite, with minor amounts of chlorite, and non-clay minerals include quartz, pyrite and dolomite. The samples also contain small amount of organic material, which form thin laminae. Samples NEW5 and NEW7 have occasional thin carbonate laminae [12].

In this study measurements are reported for 16 cores taken from 4 different shale samples. Samples NEW5 and NEW7 both have one core at 0° and one at 90° to the axis of symmetry, which is perpendicular to the bedding plane (Fig. 1). ANT1 has 4 cores, two at 0° and two at 90° to vertical. Sample NEW3 has eight cores in five different directions, two at 0°, two at 20°, one at 45°, two at 72°, and two at 90° to the bedding plane. Each core was ~2.7 cm in diameter and ~1.5 cm in length. The core ends were trimmed to ensure that they were parallel to each other and perpendicular to the sides of the core. The core ends were polished flat.

The measurements of velocity and attenuation were conducted on the samples under both saturated and unsaturated conditions. Unsaturated conditions were achieved by simply air-drying the samples for several



Fig. 1. Core orientations in relation to bedding.

days. The fissile nature of the samples precluded oven drying. The samples were saturated in the following manner: A sponge was placed in the bottom of a jar, the jar was then filled with water to a level below the top of the sponge, the sample was then placed on the sponge. The samples were left on the sponge for at least 2 days before they were measured. This method was used due to the fissile nature of the samples that precluded using an immersion technique to saturate the samples. Samples showed an increase in weight upon saturation, which was consistent with 1–4% porosity.

3.2. Velocity measurements

Compressional wave velocity was measured on each core using a pulse-transmission technique [23]. The pulse transmission technique involves the use of four transducers, a mercury delay line, a pulse generator and an oscilloscope (Fig. 2). The pulse generator sends an electrical pulse simultaneously to the sending transducers on the mercury delay line and the sample assembly. The electrical pulse is converted to a mechanical pulse by both transducers and travels simultaneously through the column of mercury in the delay line and the sample. The signal is then received by transducers at the end of the delay line and the sample is sent to the oscilloscope. The length of the column of mercury is then adjusted until both signals arrive at the same time. The velocity of the sample can then be calculated since the length of the sample and mercury are known, as well as the velocity of mercury. Measurements were made in this way at increments of 20 MPa from 20 to 260 MPa then from 240 to 20 MPa. A more detailed description is available in Christensen [23].

3.3. Attenuation measurements

Measurements of P-wave attenuation were made using a pulse-echo technique [24,25]. This technique involves the usage of a 1 MHz piezoelectric transducer, a reference, and a backing piece (Fig. 3). Once again, a pulse generator is used to send an electrical pulse to the transducer, which converts the pulse to a mechanical one. The transducer in mounted on a tungsten-epoxy backing piece that effectively dampens the pulse and produces a more pure input signal. This pulse then travels through a brass reference plug to the samplereference interface, where it is reflected back to the transducer. The signal also travels through the sample and is reflected at the sample-backing piece interface. This reflected signal then travels through the sample and reference again and finally reaches the transducer. Both of the reflected signals are then recorded on a digital oscilloscope. The signals are then Fourier transformed, the spectral amplitudes of these reflections are compared, and attenuation is calculated using the equation:

$$\alpha(\omega) = 8.68/2L \ln[(R_{23}/R_{12})\{A_1(\omega)/A_2(\omega)\}(1-R_{12}^2)],$$

where $\alpha(\omega)$ is attenuation, *L* is the sample length, A_1 and A_2 are the spectral amplitudes of the reflections, and R_{12} and R_{23} are the reflection coefficients of the brass-rock and rock-steel interfaces [24,25]. Measurements were made at 10 MPa intervals, from 10 to 250 MPa.

Data runs were made on the cores from the NEW3 and ANT1 samples at least twice under both saturated and unsaturated conditions. In general, multiple runs produced values that were within 10% of each other. The reported measurements for the NEW3 and ANT1 samples consist of the average of the two measurements



Fig. 2. Schematic diagram of the velocity acquisition system.



made on individual cores, and the average of the measurements on cores in the same direction, if they exist. Only a single measurement was made on the NEW5 and NEW7 cores.

Wepfer and Christensen [24] cite an estimated accuracy of ± 0.05 db/cm for their pulse echo attenuation measurements. This value was determined by measuring the attenuation of an aluminum reference, and is only a upper bound on the accuracy estimate. Christensen and Shaw [26] estimate error in compressional velocity measurements to be ~1.0%. This estimate includes: sample length measurement error, temperature effects on the velocity of mercury, delay line calibration uncertainty, and first break picking errors.

4. Results

4.1. Velocity

The measured velocities as a function of pressure are shown in Fig. 4. The figure shows velocity measurements for both increasing and decreasing pressures. Values of velocity are always lower for increasing pressure. ANT1 0° and 90° values are average values for two cores, and NEW3 0°, 20°, and 90° values are also average values for two cores. All cores show an increase in velocity with increasing pressure. 90° cores (parallel to bedding) have higher velocities than 0° cores (perpendicular to bedding) by as much as 20%. Cores between 0° and 90° to bedding generally have velocities in-between those of 0° and 90° cores. Due to the low porosity of these samples, saturated and unsaturated velocities do not differ by more than 5%. Some cores have higher saturated velocities (i.e. NEW3-A1), while others have higher unsaturated velocities (i.e. NEW3-B4).

Velocity anisotropy is calculated using the equation:

$$\sqrt{Anisotropy} = [(V_{max} - V_{min})/V_{max}]100$$

 V_{max} is the fast velocity (90° core) and V_{min} is the slow velocity (0° core). Values of anisotropy vary between 14% and 32%, and decrease with increasing pressure, under both saturated and unsaturated conditions. There is no significant difference between the saturated and unsaturated velocity anisotropy.

4.2. Attenuation

The measured values of attenuation versus pressure for ANT1, NEW3, NEW5, and NEW7 under unsaturated conditions are shown in Fig. 5. Attenuation decreases with increasing pressure for all samples. The rate of decrease varies, with ANT1 cores decreasing $\sim 28\%$, NEW3 cores dropping $\sim 50\%$, NEW5 cores decreasing $\sim 40-50\%$, and the NEW7 cores decreasing $\sim 31-55\%$. The majority of the decrease occurs over the first 50 MPa of pressure increase for all samples except ANT1, which has a linear decline in attenuation.

The values of attenuation under unsaturated conditions for 0° and 90° cores from ANT1, NEW3, NEW5, and NEW7 are shown in Fig. 5. All of the cores have attenuation that is higher for the 0° cores than the 90° cores under unsaturated conditions. ANT1 shows attenuation that is ~1.0 db/cm higher for the 0° core than the 90° core.



Fig. 4. Measured values of compressional wave velocity versus confining pressure for cores parallel to and perpendicular to bedding from the four samples included in this study. Saturated and unsaturated values of velocity are included.

Attenuation anisotropy is calculated using the equation:

%Anisotropy = $[(\alpha_{per} - \alpha_{par})/\alpha_{per}]100.$

Here α_{per} is attenuation perpendicular to bedding (0°) and α_{par} is attenuation parallel to bedding (90°). Attenuation anisotropy decreases slightly with increasing pressure from 43% at 10 MPa to 36% at 250 MPa. NEW3 has attenuation that is ~1.0 db/cm higher for the 0° core at low pressure, and ~0.6 db/cm higher at high pressure. Anisotropy is ~33% over the entire pressure range. Attenuation for the 0° NEW5 core is ~2.5 db/cm higher than the 90° core at low pressure and ~1.0 db/cm higher at high pressure. Anisotropy decreases with increasing pressure from 106% at 10 MPa to 45% at 250 MPa. Finally, NEW7 has attenuation which is >4 db/cm higher for the 0° core than the 90° core at low pressure, but above 100 MPa the difference is \sim 1.5 db/cm. Anisotropy decreases with increasing pressure, from 64% at 40 MPa to 45% at 250 MPa.

Attenuation versus pressure for samples ANT1, NEW3, NEW5, and NEW7 under saturated conditions can be seen in Fig. 5. All of the samples have attenuation that decreases with increasing pressure. Rates of decrease are similar to those for the unsaturated measurements with the values dropping $\sim 37-55\%$ from 10 to 250 MPa. The values of attenuation anisotropy under saturated conditions differ from the anisotropy under unsaturated conditions. Samples ANT1 and NEW3 have attenuation values that are nearly identical for the 0° and 90° cores over the entire pressure range. NEW5 has attenuation that is $\sim 1.0 \text{ db/cm}$ higher for the 0° core below 50 MPa, but then is approximately equal to the 90° core at higher pressures. Finally, NEW7 has attenuation for the 0° core that is ~ 1.0 db/cm higher than the 90° core for the entire pressure range. NEW7 is



Fig. 5. Measured values of compressional wave attenuation versus confining pressure for cores parallel to and perpendicular to bedding from the four samples included in this study. Saturated and unsaturated values of attenuation are included.

the only sample to show significant anisotropy at high pressure, under saturated conditions. This anisotropy is $\sim 22\%$ and shows no pressure dependence.

Attenuation was also measured on NEW3 cores taken at 20°, 45°, and 72°. Unsaturated values of attenuation versus pressure for all of the cores are shown in Fig. 6. The plot shows that attenuation systematically increases as you go from parallel to perpendicular to bedding, over the entire pressure range. Fig. 6 shows attenuation versus pressure for the cores under saturated conditions. Here, no clear relationship between direction and attenuation exists, at any pressure.

The average values of attenuation of the saturated and unsaturated 0° and 90° cores are shown in Fig. 7. These values were calculated by taking the average of all of the 0° and 90° cores from all of the samples under both saturated and unsaturated conditions. All of cores show a decrease in attenuation with increasing pressure. The saturated 0° and 90° core averages and the unsaturated 0° core averages all decrease by ~50% from 10 to 250 MPa, while the unsaturated 90° core averages decrease by ~40% over the same pressure range. The unsaturated 0° cores have average values which are significantly higher than the 90° core averages. At low pressure, the 0° core average is ~2 db/cm higher than the 90° average, and is ~0.8 db/cm higher at high pressure. Values of attenuation anisotropy for the unsaturated average decrease from 46% at 10 MPa to 37% at 250 MPa. The saturated 0° and 90° cores have similar average values at high and low pressures, and differ by a maximum of 0.5 db/cm at 120 MPa. Attenuation anisotropy for the saturated samples shows no pressure dependence and ranges from 0% to 16%.

The average values of all of the cores under both saturated and unsaturated conditions are shown in Fig. 7. These values were calculated by taking using the



Fig. 6. Measured values of compressional wave attenuation versus confining pressure for cores at 0° , 20° , 45° , 72° and 90° from vertical for the NEW3 sample under unsaturated (a) and saturated (b) conditions.



Fig. 7. (a) Average compressional wave attenuation parallel to and perpendicular to bedding versus confining pressure under unsaturated and saturated conditions. (b) Average compressional wave attenuation versus confining pressure for unsaturated and saturated conditions.

following equation:

$$\alpha_{\rm ave} = (\alpha_{\rm a} + 2 \, \alpha_{\rm b})/3.$$

Here, α_a is the average value of attenuation for all of the 0° cores, and α_b is the average for all of the 90° cores.

This convention is used because the rocks are believed to be transversely isotropic, thus two principle axes have values equal to α_b and one has values equal to α_a . The saturated values of attenuation decrease by 50% from 10 to 250 MPa, while the unsaturated values decrease by 43%. Values of attenuation for the saturated cores are higher than those for the unsaturated cores. At low pressure the saturated values are $\sim 35\%$ higher than the unsaturated values and at high pressure they are $\sim 26\%$ higher.

5. Discussion

Attenuation in rocks is generally attributed to four different mechanisms: rock frame anelasticity, scattering, geometrical effects, and finally fluid interactions [27]. For unsaturated rock samples, only the first three mechanisms are important, however, for saturated rocks all four need to be considered. For this reason we will examine attenuation in the unsaturated samples first.

The mechanisms that contribute to attenuation in unsaturated rock samples are scattering, geometric effects and frame anelasticity [27]. Geometrical effects in the case of laboratory measurements involve the spherical spreading of the source wavelet. Spherical spreading effects are corrected for during the data processing procedure through the application of diffraction corrections [28,29].

Attenuation due to scattering can be due to thin bed layering or inclusions. The shale samples included in this study contain thin inclusions of organic material. In general, organic inclusions are $<5\,\mu$ m thick. This gives a wavelength (~4 mm) to scattering object diameter ratio of >800, and so the heterogeneous medium should behave as an effective homogeneous medium [30]. Quartz grains are generally also $<5\,\mu$ m in diameter, while groups of quartz grains may have diameters of up to 40 µm. The wavelength to object ratio for the quartz grain groups still produces a ratio of ~100 which is at the low end of the effective medium range. Scattering from inclusions and layering, therefore, should not make a significant contribution to attenuation for these samples.

Attenuation due to frame anelasticity can have several sources, one of which is friction on crack faces. Cracks in the shale sample from this study take two forms: large cracks aligned parallel to bedding, and randomly oriented microcracks in the quartz grain inclusions. Friction on crack surfaces can cause them to stay closed, resulting in a phase lag [31]. This phase lag, or hysteresis, results in attenuation of the passing compressional wave. Attenuation due to this mechanism will be larger for a compressional wave traveling perpendicular to crack surfaces than parallel because there is a much greater crack surface area for friction to occur on. Attenuation also occurs due to crack surfaces sliding against each other. In this scenario, the energy dissipation is related to the normal traction and displacement on the crack surface [32]. The attenuation due to this

mechanism will be maximized for cracks aligned subperpendicular to the direction of propagation. Attenuation due to these mechanisms will decrease with increasing pressure, as cracks become locked and can no longer move against each other. Both of these crack related mechanisms, hysteresis and frictional sliding, are consistent with attenuation that is higher perpendicular to bedding than parallel, and with decreasing attenuation with increasing confining pressure. This is consistent with the results from this study.

The presence of cracks can be related to the velocity versus pressure relationships for the samples. The velocities for the samples show a sharp increase over the first 50 MPa of pressure increase. Velocities continue to increase at a lower rate up to 260 MPa and do not asymptotically approach any value. This possibly indicates the presence of dual porosity, with the high aspect ratio cracks closing at low pressure and the low aspect ratio porosity closing at higher pressures. Another explanation for this behavior is increasing mineral moduli with increasing pressure. An increase of the bulk modulus of the clay minerals with increasing pressure may account for a portion of the velocity increase at high pressures, however an accurate estimation of this effect is not forthcoming due to a lack of information on the pressure dependence of moduli of clay minerals. Sample shortening also contributes to velocity increase with increasing pressure, however, it can account for $< \sim 1.0\%$ of the total velocity increase over the entire pressure range.

Another frame anelasticity attenuation mechanism is friction on mineral grain surfaces. Attenuation due to friction on grain surfaces has been described in terms of spherical grains sliding against each other [32]. Clay minerals posses a preferred orientation in shale, in which the clay minerals are aligned parallel to the bedding and therefore are more analogous to friction on crack surfaces. Since energy dissipation is related to normal traction on the mineral grain surfaces, attenuation should be higher in the direction perpendicular to bedding because there is a greater amount of grain contact surface area normal to the direction of compression. Once again, this is consistent with attenuation that is higher perpendicular to bedding.

Attenuation in saturated rocks may originate from mechanisms mentioned above, as well as ones related to fluid flow. There are two main types of attenuation mechanisms related to fluid flow, namely viscous flow [33] and squirt type flow [33]. Biot theory predicts that due to viscosity, pore fluids will move relative to the rock frame, as a compressional wave propagates through a fluid saturated rock. Motion of the fluid is parallel to the motion of the particle motion of the solid. The shear forces between the fluid and the matrix associated with this relative motion are the source of attenuation. Attenuation due to viscous flow will be the greatest when flat cracks are aligned parallel the vibration direction of a passing wave, because this provides the fluid with the longest path length along which to move.

The squirt flow mechanism, or dual porosity flow, requires the rock to have two types of porosity, soft and stiff [33,34]. Soft porosity is described as high aspect ratio pores, such as cracks, while stiff porosity is low aspect pores. As a compressional wave propagates through a rock, soft pores are closed and fluid is forced into stiff pores that remain open. This flow is not instantaneous, and may not be in the same direction as the passing wave, and thus energy is dissipated through shear forces associated with the fluid and frame. Attenuation due to this mechanism is maximized when flat cracks are aligned perpendicular to the vibration direction.

The measured values of attenuation for the saturated shale samples show little or no directional dependence. This is in contrast to the unsaturated measurements. which showed higher attenuation perpendicular to bedding than parallel to bedding. From this, it can be inferred that either the attenuation due to the frame anelasticity is the same for saturated and unsaturated measurements and attenuation due to fluid affects is lower perpendicular to bedding than parallel to bedding, or that frame anelasticity attenuation is not the same for saturated and unsaturated measurements. If the latter is true, then we cannot make any inference as to the contribution of either of the fluid flow mechanisms. It is unlikely that the contribution due to frame anelasticity remains constant, however, because the values of attenuation for the 0° cores under saturated conditions are similar to those under unsaturated conditions and thus there would have to be no fluid flow contribution.

Values of attenuation determined in the field generally consist of measurements made in three ways, surface-to-surface (refraction and reflection), surface to borehole (VSP), and borehole-to-borehole (cross-well). If the results determined in this study can be extended to measurements made in the field, then the following relationships can be applied for horizontally stratified bedding: Techniques that will measure attenuation parallel to sub-parallel to bedding include surface to surface (refraction), and cross well measurements. Surface to surface (reflection) and surface to borehole techniques will measure perpendicular to sub-perpendicular values of attenuation. If the formations are considered to be unsaturated, then the two groups of techniques will give inconsistent results, with the ones measuring perpendicular to bedding showing higher attenuation. It is more realistic, however, to assume that subsurface formations are saturated. In this case, there will be no directional dependence and the different techniques should give comparable results.

6. Conclusions

Compressional wave attenuation and velocity have been measured as a function of pressure on four shale samples. Measurements have included both saturated and unsaturated measurements up to 250 MPa confining pressure. For all samples, measurements were made both parallel and perpendicular to bedding. For one sample, measurements were made parallel and perpendicular to bedding, as well as at three intermediate angles. Attenuation versus pressure for each sample under saturated and unsaturated conditions is presented, as well as average values of attenuation for all of the samples studied.

Under unsaturated conditions, attenuation has been found to be significantly higher for propagation perpendicular to bedding, than parallel to bedding. Values of attenuation decrease with increasing pressure, and attenuation anisotropy shows a slight decrease with increasing pressure. The directional dependence of attenuation, and it's relationship with confining pressure indicate that attenuation is related to preferred crack and mineral orientation in the shale samples and that frictional sliding or hysteresis is the dominant attenuation mechanism.

Measurements of attenuation under saturated conditions show little or no directional dependence. Values of attenuation for some of the samples are similar to the values for the unsaturated cores perpendicular to bedding. The lack of directional dependence indicates that either Biot flow is more prominent than squirt flow, or that frame anelasticity is reduced under saturated conditions. These results indicate that with respect to attenuation, saturated shale in the subsurface may be treated as an isotropic media.

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