Velocity and Attenuation Anisotropy in Reservoir Rocks

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Summary

Sedimentary rocks are generally characterized by textural anisotropy that gives rise to a directional dependence of acoustic velocities. This textural anisotropy in sedimentary rocks can lead to attenuation anisotropy. Our analyses of the directional dependence of velocity and attenuation in different reservoir rocks show that attenuation anisotropy can be quite large. Directional dependences of velocity and attenuation can be very different and are not influenced in the same manner by textural variations. Depending on the texture, the attenuation anisotropy can be opposite to the velocity anisotropy.

Introduction

Knowledge about the pore and confining pressure dependencies of the P-wave velocity (V_P) and quality factor (Q_P) in reservoir rocks is an important requisite for interpreting seismic measurements in terms of subsurface petrophysical parameters. Since permeability is a dominant factor in controlling loss mechanisms in porous media, a study of the quality factor (Q, or attenuation, Q^{-1}) is of special interest in seismic exploration for oil. Theoretical (Biot, 1956a, b; Akbar et al., 1993) and experimental studies (McCann and McCann, 1969; Klimentos, 1990; Prasad, 2003) have shown the importance of permeability in understanding wave propagation characteristics in porous media. Experimental studies on attenuation and velocity have shown the effect of pressure on crack closure and layering, however, a systematic study of attenuation anisotropy is lacking. For AVO analyses, Adriansyah and McMechan (1998) have shown that intrinsic and scattering attenuation can affect the AVO response. Thus, attenuation anisotropy becomes an important factor that needs to be considered for such investigations. Three main causes have been recognized for velocity anisotropy:

1. Preferential alignment of grains and cracks
2. Layering of materials of different acoustic impedance
3. Layers with different amounts of porosity

The question that remains to be answered is whether these factors affect attenuation in the same manner as they affect velocity. Specifically, the effect of permeability anisotropy on attenuation has not been studied systematically. We have investigated the effect of layering and permeability on both, velocity and attenuation on a set of sandstones as functions of confining pressures up to 25 MPa. The sandstones were very similar in mineralogy and porosity. Permeability, however, varied with direction and between samples. The measurements made in two directions, parallel and perpendicular to borehole axis show different effects of anisotropy on velocity and attenuation.

Experimental Procedure

Cylindrical core samples with 25 mm diameter and 20-30 mm length were prepared with their faces parallel to within 100 µm. Two samples were prepared from each core: parallel to the borehole axis (called vertical) and perpendicular to the borehole axis (called horizontal). The pulse transmission technique was used for P- and S-wave velocity (V_P, V_S, respectively) measurements. Quality factor (Q_P, Q_S) was calculated using the spectrum division method (Toksöz et al., 1979; Sears and Bonner, 1981).

Bulk and grain densities and porosity were measured using a Helium porosimeter. Difference in porosity values measured in two cores from same depth gave an indication of small-scale heterogeneities in the samples. The microstructure of the samples was examined with optical microscopy, CT-scanning, and scanning acoustic microscopy. Mineralogy was determined by XRD analyses of the sample powders. Klinkenberg-corrected air permeability was measured in horizontal and vertical directions.

Samples Used

We have analyzed fluvial sandstone samples from a producing oil field. The chalk, limestone, and sandstone data were taken from Prasad and Manghnani (1996). The Prasad and Manghnani data was measured in two directions simultaneously on the same sample. Measurements on the fluvial sandstones were made on oriented samples.

Results

Porosity, Permeability, and Texture: Figure 1 and Tables 1 and 2 shows XRD mineralogy, permeability and texture from CT scans in two directions for the fluvial sandstones. The samples are very similar in mineralogy and in porosity: They are fairly clean sandstones consisting of quartz and feldspars with clay contents between 5 – 10%. Porosity ranged between 19–25%. The main difference lies in permeability and in permeability anisotropy. Permeability values varied between 0.1 and 1000 mD and permeability anisotropy values ranged between 0 – 200%. In most cases, the permeability anisotropy could be correlated to the density variations revealed by CT scans. Under optical microscopy, the permeability variations (and corresponding density layers) were found to be due to alternate layers of coarse and fine-grained sands. Horizontal alignment of the more porous, coarser grained layers gave a higher permeability in that direction. In some cases, the cause for permeability anisotropy could not be recognized on the CT scans, which showed a very homogenous texture. CT scans of some samples (10 and 21) revealed large-scale density variations. These structures, seen as bioturbations and shell fragments under an optical microscope, were larger than the dominant ultrasonic wavelengths.

Table 1. Porosity and permeability in the sandstone samples. hor = horizontal, vert = vertical. Differences in the vertical and horizontal porosity are due to small-scale heterogeneity in the core. The samples were cleaned prior to measurements.

Sample Id	Permeability (mD)		Porosity (%)		Grain density (g/cm^3)
	Hor	Vert	Hor	Vert	
10	68	3.9	23.9	25.2	2.6
11	295	41	23.4	26.9	2.62
12	818	426	25.2	29.2	2.61
15	7.6	7.6	19.8	24.3	2.64
19	91	36	22.4	25.6	2.63
21	1.4	0.21	19.1	22.3	2.62
24	1030	677	26.9	26.2	2.62
25	67	0.84	20	18.8	2.53
26	39	45	20.1	26.3	2.64
28	22	1.5	23.2	23.6	2.64

Table 2. Density and porosity variations in the limestone samples from Prasad and Manghnani (1996). Note low grain density in the chalk samples implying that porosity is underestimated.

Sample Name	depth (m)	Density (g/cm3)		Porosity (%)
		Bulk	Grain	
Sandstone				
Berea	quarry	2.3	2.59	21.18
Chalk				
#10185.6	3104.6	2.46	2.504	3.24
#10185.9	3104.7	2.40	2.688	13.7
#10351	3150	2.44	2.509	4.67
#10438	3180	2.37	2.603	14.7
Limestone				
#4782	1450	2.72	2.84	6.75%
#4701	1430	2.62	2.86	12.8%
Dolomite				
#3200	3200	2.21	2.82	33.4%

Based on the microstructure observed in CT scans and the permeability measurements, the samples were separated into the groups specified in Table 3: Sandstones had heterogeneous, layered, or homogenous textures. The carbonate samples consisted of low and high porosity chalks, limestones with vuggy porosity, and a high porosity dolomite (Table 3).

Table 3: Textural properties. The symbols "V" and "H" denote vertical and horizontal measurements; no symbol implies same behavior is observed in both directions. The textural groups for the carbonate samples are derived from Prasad and Manghnani (1996).

Group	Texture	Samples
Sandstones		
1.	Heterogeneous texture	10, 21
2.	Layers + high permeability anisotropy	11, 25H, 28H
2a.	Low permeability	15, 25V, 28V
3.	Homogeneous	12, 24, 26
Chalks		
1.	Very low micritic porosity	10185.6, 10351
2.	Medium porosity	10185.9, 10438
Limestone		
1.	Vuggy porosity	4701, 4782
Dolomite		
1.	High porosity	3200

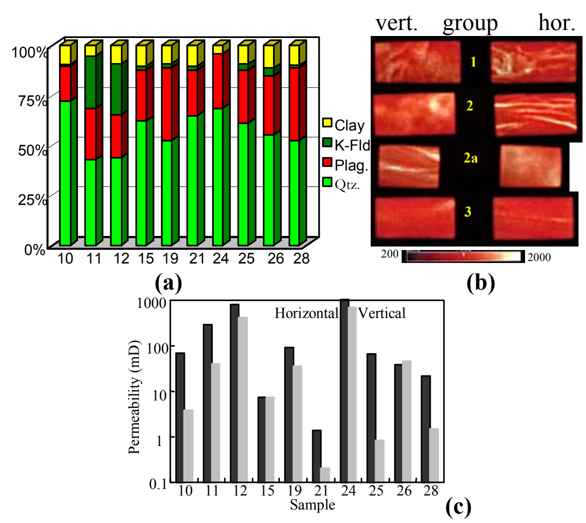

Figure 1: (a) Mineralogy (b) microstructural variations from CT scans, and (c) permeability anisotropy in the fluvial samples. The samples groups based on permeability and microstructural variations are marked in Figure 1b. hor = horizontal, vert = vertical.

Velocity Anisotropy: Figure 2 shows the effect of pressure on V_P for representative samples from the three fluvial sandstone groups. The samples show a general increase in V_P with pressure. Groups 1 and 2 show V_P anisotropy at higher pressures also, mainly due to textural differences. In some cases, a large V_P anisotropy at low pressure decreases to near zero at 25 MPa. In Group 2 samples, V_P anisotropy remains high at 25 MPa confining pressure. The chalks (Figure 3) showed high V_P anisotropy. There is very little change in V_P and in V_P anisotropy with pressure for the low porosity chalks. The increase in V_P and decrease in V_P anisotropy with pressure in the high porosity chalk is due to closing of a visible crack. In the limestones (Figure 4), V_P increases very rapidly with pressure. An initially high V_P anisotropy decreases to almost zero beyond 25 MPa. Apparently, the microcracks responsible for V_P reduction and anisotropy close at this pressure. In the high porosity sandstone and dolomite (Figure 4), V_P increases with pressure and V_P anisotropy is low, about 4%.

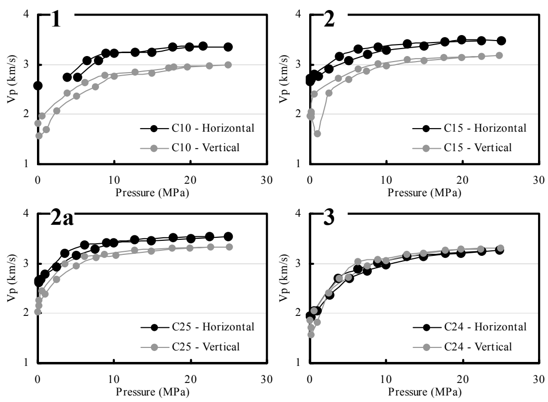

Figure 2: V_P -pressure variations in vertical and horizontal directions for samples in the textural groups marked by numbers. Black symbols show measured values in horizontal direction, gray in vertical direction.

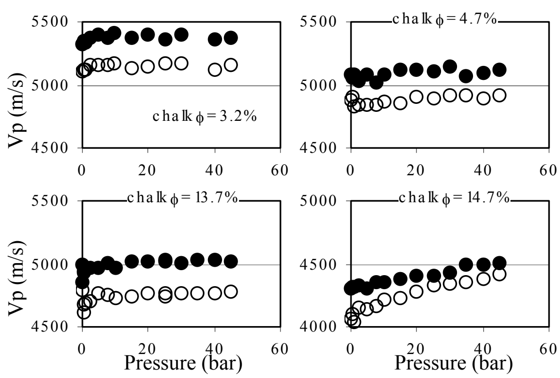

Figure 3: V_P variation with pressure in chalks. Solid symbols mark values measured in the horizontal direction and open symbols in vertical direction.

Attenuation Anisotropy: Figure 5 shows the effect of pressure on Q_P for the fluvial sandstones. The Q_P – pressure behavior is typical within each group. Thus

- Group 1. Q_P is low and remains constant.
- Group 2. Q_P increases with pressure. The increase is larger for the low velocity direction and leads to a negative Q_P anisotropy.
- Group 2a Q_P increases equally in both directions with pressure.
- Group 3. Q_P anisotropy is low and positive.

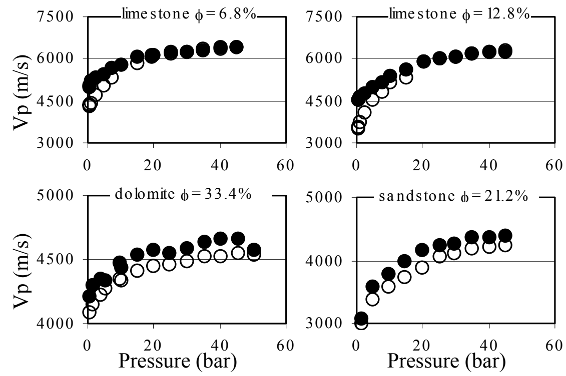

Figure 4: V_P variation with pressure in limestones and dolomite. Solid symbols mark values measured in the horizontal direction and open symbols in vertical direction.

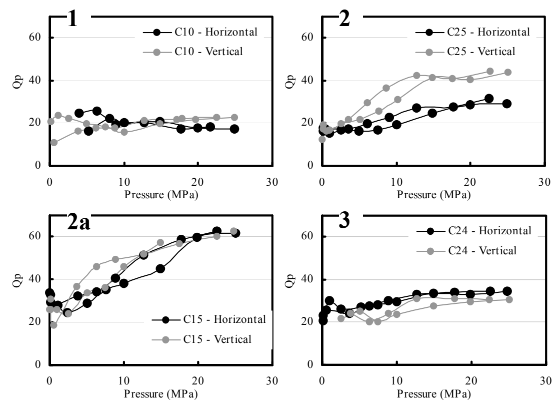

Figure 5: Quality factor-pressure variations in vertical and horizontal directions for samples in the textural groups marked by numbers. Black symbols show measured values in horizontal direction, gray in vertical direction.

Figures 6 and 7 show the effect of pressure on quality factor for the carbonates. Similar to velocity, the low porosity chalks (Figure 6) do not show much change in quality factor anisotropy with pressure. In the high porosity chalks, quality factor increases with pressure.

In the limestones (Figure 7), Q_P is very low and stays constant with pressure. In the high porosity sandstone and dolomite, Q_P increases with pressure. The Q_P anisotropy is also increases with pressure, with the increase being larger for the low velocity direction, leading to a negative attenuation anisotropy.

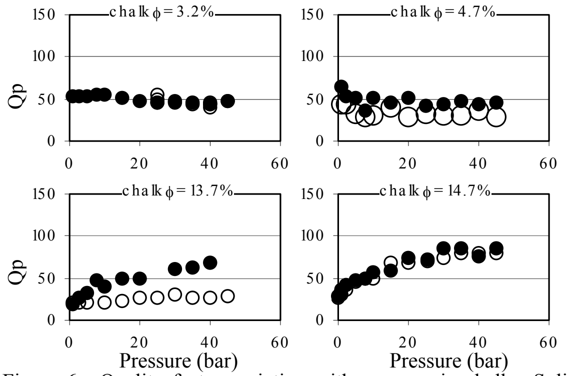

Figure 6: Quality factor variation with pressure in chalks. Solid symbols mark show values in horizontal and open symbols in vertical directions.

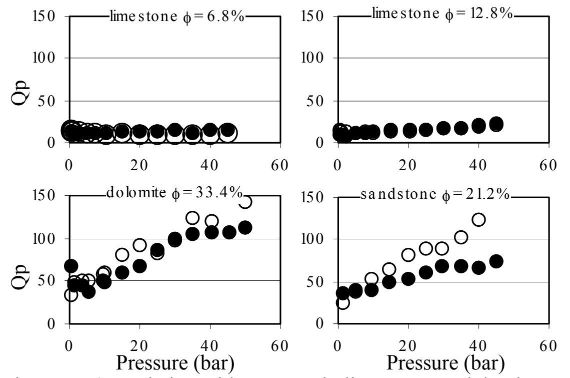

Figure 7: Q_P variation with pressure in limestones, a dolomite, and a sandstone. Solid symbols mark values measured in the horizontal direction and open symbols in vertical direction.

Conclusions

A summary of the textural properties and their relations to the ultrasonic properties is given in Table 4.

Table 4: Summary of the textural and ultrasonic properties of the fluvial sandstones and carbonates.

Group	Texture	Ultrasonic properties
Sandstones		
1.	Heterogeneous texture	Low Q_P, no change with pressure: scattering losses dominate
2.	Layers + high permeability anisotropy	Negative Q_P- anisotropy, appears to increase with pressure. Large, positive V_P anisotropy
2a.	Low permeability	High Q_P values which increase with pressure.
3.	Homogeneous	Positive and low V_P and Q_P anisotropy

Table 4 (contd.): Summary of the textural and ultrasonic properties of the fluvial sandstones and carbonates.

Chalks		
1.	Micritic texture, layers with equal impedance	Constant V_P-anisotropy, low Q_P-anisotropy
2.	Partially connected pores	V_P and Q_P increase with pressure
Limestone		
1.	Vuggy porosity, cracks	Low Q_P, no change with pressure: scattering losses dominate, high, V_P anisotropy decreasing with pressure
Dolomite		
1.	Connected pores, low impedance contrast	Negative Q_P- anisotropy

We find that not only velocity but also attenuation shows a directional dependence dependent on texture. Depending on texture, attenuation anisotropy can be opposite to the velocity anisotropy.

References

Adriansyah, McMechan, G.A., 1998, Effects of attenuation and scattering on AVO measurements: Geophysics, 63, 2025 – 2034.

Akbar, N., Dvorkin, J., and Nur, A., 1993, Relating P-wave attenuation to permeability: Geophysics, 58, 20--29.

Biot, M. A., 1956a, Theory of propagation of elastic waves in fluid saturated porous solids. I: Low frequency range: J. Acoust. Soc. Amer., 28, 168 - 178.

Biot, M. A., 1956b, Theory of propagation of elastic waves in fluid saturated porous solids. II: High frequency range: JASA, 28, 179 - 191.

Klimentos, T., McCann, C., 1990, Relationships between compressional wave attenuation, porosity, clay content and permeability of sandstones: Geophysics, 55, 998 – 1014.

McCann C., McCann, D. M., 1969, The attenuation of compressional waves in marine sediments: Geophysics, 34, #6, 882-892.

Prasad, M., Manghnani, M. H., 1996, Velocity and impedance microstructural anisotropy in reservoir rocks: Expanded Abstracts of 1996 SEG Annual Meeting.

Sears, F. M., and Bonner, B. P., 1981, Ultrasonic attenuation measurement by spectral ratio utilizing signal processing techniques: IEEE Trans. on Geoscience and Remote Sensing, GE-19, 95 - 99.

Toksöz, M. N., Johnston, D. H., and Timur, A., 1979, Attenuation of seismic waves in dry and saturated rocks, I. Laboratory measurements: Geophysics, 44, 681--690.

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