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Effects of Pore Pressure on Compressional Wave Attenuation in a Young Oceanic Basalt

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Abstract. Laboratory data are reported for ultrasonic compressional wave attenuation (α_p) as a function of pore pressure in a Juan de Fuca Ridge dredge basalt. Four experiments have been made to determine the relationships between attenuation and quality factor (Q_p) and confining and pore pressures in the shallow ocean crust. Attenuation was measured at 1) a constant differential pressure of 40 MPa; 2) confining pressures to 120 MPa and atmospheric pore pressures; 3) a constant confining pressure of 50 MPa while varying pore pressures; 4) a constant confining pressure of 100 MPa while varying pore pressures. For atmospheric pore pressures, α_p ranges from 1.64 dB/cm to 7.08 dB/cm (Q_p = 24 to 10). In addition, attenuation increases systematically with increasing pore pressure and decreasing differential pressure (confining pressure - pore pressure). Results from DSDP and ODP downhole packer experiments suggest that the hydrostatic pore pressure regime may best approximate *in situ* conditions for young oceanic crust. Hydrostatic pore pressures (@ 5000 meters depth) reduce Q_p as much as 35% from normal atmospheric pressure conditions; therefore, pore pressures generated in the upper oceanic crust may be responsible in part for the observed low seismic Q_p within layer 2A. Q_p measurements at elevated pore pressures agree well with seismic Q_p data.

Introduction

Due to the growing number of field studies investigating seismic attenuation in oceanic crust (e.g., Lewis and Jung, 1989; Jacobson and Lewis, 1990; Goldberg and Yin, 1994; Christeson et al., 1994; White and Clowes, 1994; Wilcock et al., 1995), laboratory measurements characterizing acoustic absorption in oceanic lithologies under *in situ* conditions have become paramount. Although some have investigated attenuation in basalt (e.g., Gordon and Davis, 1968; Herminghaus and Berckhemer, 1974; Tittmann et al., 1977; and Weiner et al., 1987), only three laboratory studies have measured attenuation in oceanic rock (i.e., Wepfer and Christensen, 1990; 1991; and Goldberg et al., 1992). Over the past two decades, many studies have shown, either directly or indirectly, that the effect of decreasing differential pressure is to increase the ultrasonic wave attenuation in sandstones (e.g., Johnston and Toksoz, 1980; Winkler and Nur, 1982; and Green and Wang, 1993). However, no laboratory study has investigated pore pressure effects on attenuation in oceanic basalts. Understanding the effect of pore pressure on attenuation is crucial in helping constrain seismic Q_p data for young oceanic crust (i.e., laboratory studies under confining pressures alone may not accurately characterize the *in situ* rock properties of shallow ocean crust). In particular, information on Q_p as a function of differing pore pressure regimes (hydrostatic, underpressure, overpressure) may shed light on the parameters responsible for the low Q_p of oceanic layer 2A.

In this study, α_p and Q_p are reported at varying confining and pore pressures for a basalt from the Juan de Fuca Ridge. The sample is from the western edge of the median valley of the Juan de Fuca Ridge and was dredged from a depth of 2470 meters. It is a fresh tholeiite in the form of a well-developed pillow (Christensen, 1970, 1984), and its abundant low aspect-ratio porosity (2.5%) makes it an ideal sample for pore pressure studies.

With the innovation of downhole packer experiments, direct measurements of oceanic layer 2A pore pressures have been possible at Deep Sea Drilling Project (DSDP) Hole 504B near the Costa Rica Rift (Anderson et al., 1985) and Ocean Drilling Program (ODP) Site 1026B on the Juan de Fuca Ridge (Fisher et al., 1997). Data recorded for DSDP Hole 504B suggest an underpressure pore pressure regime in the uppermost 100m of basalt. Estimates of pore pressure conditions in this hole are 0.8 - 1.2 MPa below hydrostatic pressure (Anderson et al., 1985). Similar data from ODP Leg 168, Hole 1026B, suggest an overpressured environment, which deviates only 0.02 - 0.03 MPa from hydrostatic (Fisher et al., 1997). Since the ODP Leg 168 hole is located near the dredge site of our Juan de Fuca Ridge sample, *in situ* pore pressure conditions will be considered approximately hydrostatic.

Laboratory Measurements

A pulse-echo technique (Wepfer and Christensen, 1990) was used to measure compressional wave attenuation. In this method, a 1 MHz pulse is delivered to a stacked rock and reference sample assembly, and energy reflections from the sample-reference interface and reference-backing piece interface (Figure 1) are recorded. Ultrasonic compressional wave spectral amplitudes are calculated from full reflection traces of both the rock and aluminum reference samples after a 3μs window has been applied. The p-wave attenuation coefficient (α_p) is calculated from the spectral amplitude of the rock sample relative to the non-attenuating aluminum reference (Q_p > 10,000) amplitude spectrum. Q_p is then derived from α using

$$\frac{1}{Q_p} = \frac{\alpha V}{\pi f}$$

(e.g., Tang et al., 1988), where V is phase velocity and f is

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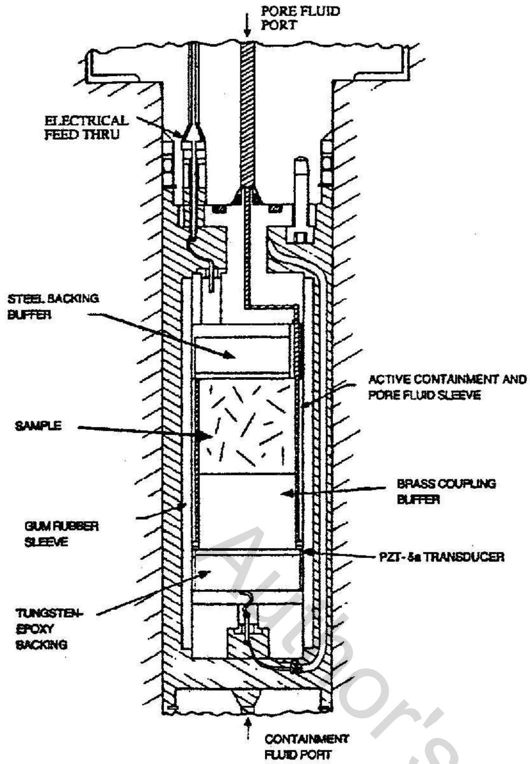

Figure 1. Pressure vessel endcap and sample assembly used to measure ultrasonic wave attenuation as a function of confining and pore pressures.

frequency. In the determination of Q_p, group velocities, measured separately for our sample (Christensen, 1984), were substituted for phase velocities. The accuracy of measuring α_p using this technique is estimated to be ±0.05 dB/cm (Wepfer and Christensen, 1990).

For α_p measurements, the sample assembly used by Wepfer and Christensen [1990] was modified to include a containment sleeve and pore fluid input (Christensen, 1984), which is required to control pore pressures in the sample (Figure 1). Distilled water was used as the pore pressure medium, and the sample was evacuated for several hours before the pore fluid was introduced and the rock was saturated. Confining and pore pressures were generated independently to 120 MPa using separate fluid pressure pumping systems (Christensen, 1984), while waveforms were recorded along random paths of increasing and decreasing confining and pore pressures. The latter procedure eliminates hysteresis effects that might occur when data sets are recorded with successive increases or decreases in pressures. All measurements were recorded after pressure conditions had equilibrated for several hours.

Four experimental runs were performed to determine the relationships between attenuation, Q_p, confining pressure, and pore pressure. First, attenuation was measured while varying confining pressures and maintaining atmospheric pore pressure conditions (Figure 2a). This experiment simulated measurements conducted under drained conditions where rock pore fluid pressure is not controlled and assumed to be atmospheric. Next, compressional wave attenuation was measured at a constant differential pressure of 40 MPa (Figure 2b). At every increment (10 MPa) of increasing or decreasing confining pressure between 50 and 120 MPa, the independently generated pore pressure was 40 MPa less than confining. Finally, two runs were made at constant confining pressures while varying pore pressures. Figures 2c and 2d show attenuation data obtained for these runs at confining pressures of 50 MPa and 100 MPa, respectively.

Results

Attenuation data is presented under atmospheric pore pressure conditions in Figure 2a. Here attenuation decreases nonlinearly with increasing confining pressure. This attenuation-pressure relationship is consistent with velocity-pressure data obtained for many rock types (e.g., See Birch, 1960). The α_p values at the lowest and highest confining pressures in Figure 2a constitute the upper and lower bounds for attenuation in our sample at 7.1 dB/cm and 1.6 dB/cm, respectively. Although the attenuation-pressure data for this experiment was provided to recover the maximum and minimum values for our data set and to demonstrate the similarities with velocity-pressure relationships, the pressure conditions are not representative of *in situ* conditions.

Attenuation data in Figure 2b, measured at a constant differential pressure of 40 MPa, forms a linear relationship with confining pressure. The slope of the attenuation-pressure curve is small (-0.0033dB/cm / MPa) with values ranging from 3.5 dB/cm to 3.2 dB/cm over the entire experiment. In this data run, attenuation closely approximates data obtained at a confining pressure of 40 MPa and atmospheric pore pressure (Figure 2a). Constant differential pressure data demonstrates that pore pressure is of equal importance to confining pressure in determining rock attenuation in our sample.

Figure 2c and 2d represent α_p under elevated pore pressure conditions. Both data sets show an increase in attenuation with increasing pore pressure (decreasing differential pressure). But data at a constant confining pressure of 50 MPa displays a linear relationship with pore pressure, while attenuation values at a constant confining pressure of 100 MPa form an exponential relationship with pore pressure. This phenomenon is the result of varying differential pressure between the two experiments. At lower differential pressures, microcrack porosity is dominant, and the closing of these pores with increasing differential pressure gives attenuation the observed linear relationship. At higher differential pressures (left side of Figure 2d), microcrack closure has occurred and attenuation becomes asymptotic near 0 MPa pore pressures. Compressional wave velocities, Q_p, and α_p are presented in Table 1 for both experiments at elevated pore pressures. Q_p shows the opposite pore pressure dependence as α_p and reaches values of 11 and 17 at a hydrostatic pore pressure of 50 MPa and confining pressures of 50 and 100 MPa, respectively. A hydrostatic pore pressure of 50 MPa is used as one possible *in situ* pressure condition. Q_p is also tabulated for possible underpressure and overpressure conditions at 5000 meters water depth, while results calculated for hydrostatic pore pressures are considered most representative of *in situ* conditions.

Both Q_p and α_p have been shown to depend strongly on pore pressure, and it is evident from ODP and DSDP down-hole packer experiments that *in situ* conditions for young oceanic crust may best be approximated by a hydrostatic pore pressure gradient (Anderson et al., 1985 and Fisher et al., 1997). Q_p values at hydrostatic pore pressures are low (11-17 @ 5000 meters depth) for our Juan de Fuca Ridge basalt and less than Q_p values measured for the same rock under drained

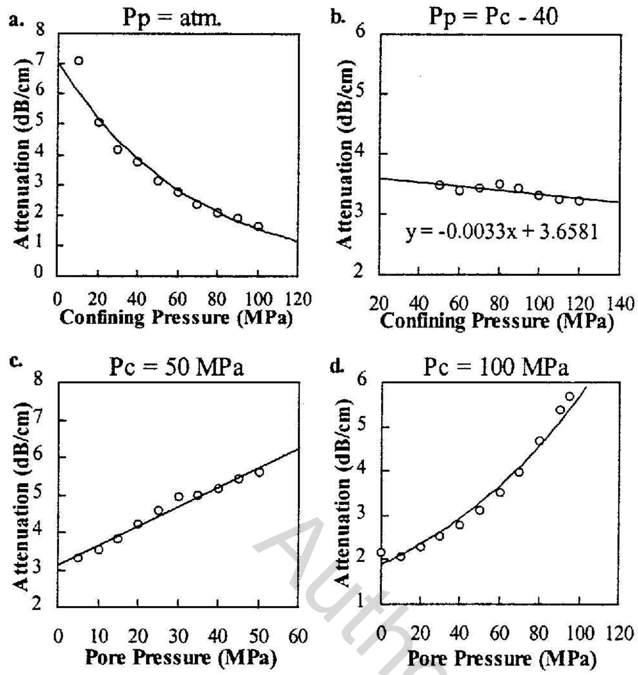

Figure 2. Juan de Fuca Ridge basalt compressional wave attenuation at various confining and pore pressures. Pp = Pore pressure and Pc = confining pressure. Differential pressures decrease from left to right in c and d.

(saturated) pore pressure conditions (Wepfer and Christensen, 1990). Wepfer and Christensen [1990] reported α_p values ranging from 3.7 dB/cm (Q_p = 15) at 40 MPa confining pressure to 1.6 dB/cm (Q_p = 31) at 100 MPa confining pressure for the Juan de Fuca Ridge basalt. These values are consistent with our measurements at atmospheric pore pressures (Figure 2a) but are considerably less than our α_p measurements at elevated pore pressures (α_p = 5.59 - 3.11 dB/cm @ P_p = 50 MPa, Table1). Minimum pore pressures are generated when using saturated samples, and consequently, α_p values are lower than for measurements at elevated pore pressures. For confining pressures of 50 MPa and 100 MPa, our Q_p measurements are 35 and 29% lower than data recorded for drained pore pressures, respectively (Table1). Therefore, data at elevated pore pressures represent a lower bound for the ultrasonic Q_p of oceanic Layer 2A.

Discussion

A compilation of recent seismic Q_p experiments in the upper oceanic crust is shown in Table 2. The Q_p values reported in Table 2 range from 10 to 100, while all but two studies have minimum Q_p values near 10 associated with shallow crustal levels. Our data agree well with these seismic Q_p values for oceanic Layer 2A; although, data published by White and Clowes [1994] and Jacobson and Lewis [1990] give somewhat higher minimum values (Q_p = 20). The study conducted by White and Clowes is included in Table 2, because it represents an upper bound for seismic Q_p in oceanic Layer 2; however, it is not considered comparable to our Q_p data due to the depth at which Q_p was measured (Layer 2-3 boundary). In addition to the absence of data describing *in situ* pressure conditions for this deep ocean crust, prolific fracturing, which couples crustal pore fluids to ocean column pressures, may not be present in the deep crust. The Q_p values reported by Jacobson and Lewis [1990] are for Layer 2A; however, their profile was conducted 13 km off axis of the Juan de Fuca Ridge and may demonstrate lateral variations in Q_p away from ridge crests.

In both the field and laboratory, many investigators have postulated that the dominant mechanisms of elastic wave absorption in rock are frictional energy loss, scattering, geometric spreading, and pore fluid-rock interaction (e.g., Gordon and Davis, 1968; Dvorkin and Nur, 1993; Christeson et al., 1994; and Goldberg and Sun, 1997). Among the most important physical parameters affecting these mechanisms are temperature, confining pressure, and pore fluid content and pressure (Brace, 1972; Jones and Nur, 1983; and Wepfer and Christensen, 1991). Comparison of ultrasonic Q_p data with seismic Q_p data in Table 2 suggests that the mechanical parameters affecting seismic loss mechanisms in oceanic Layer 2A may be important in ultrasonic measurements as well (e.g., pressure regimes). Because no clear explanation exists which bridges the gap between low and high frequency attenuation mechanisms, it is difficult to relate Q_p data at the different scales. Additionally, zones of high attenuation within Layer 2A may contain alteration mineralogy (Swift et al., 1998), which may not be sampled at the ultrasonic scale. Even though separate attenuation mechanisms undoubtedly dominate over seismic and ultrasonic frequency ranges due to sampling scale differences, physical parameters must not be overlooked as important factors affecting the low Q_p of oceanic Layer 2A.

Conclusions

The first laboratory compressional wave attenuation measurements in an ocean basalt at elevated pore pressures have been presented. It has been demonstrated that attenuation is strongly dependent upon confining pressure conditions. In addition, attenuation has been shown to increase rapidly with increasing pore pressure (2.17 dB/cm @

Table 1. P Wave Attenuation (α_p), Quality Factors (Q_p), and Group Velocities (V_p) for Basalt at Constant Confining Pressures of 50 MPa and 100 MPa

	Pore Pressure MPa	Pc = constant @ 50 MPa			Pc = constant @ 100 MPa		
		Vp	αp	Qp	Vp	αp	Qp
Underpressured	0				5.56	2.17	24
	5	5.38	3.31	17			
	10	5.34	3.54	16	5.63	2.07	25
	15	5.35	3.80	15			
	20	5.25	4.21	13	5.51	2.30	23
	25	5.20	4.58	12			
	30	5.27	4.94	12	5.47	2.52	21
	35	5.39	4.99	12			
	40	5.28	5.15	12	5.42	2.79	19
	45	5.20	5.40	11			
Hydrostatic	50	5.15	5.59	11	5.35	3.11	17
Overpressured	60				5.28	3.51	16
	70				5.18	3.99	14
	80				5.12	4.67	12
	90				5.12	5.40	11
	95				4.96	5.70	10

Table 2. Seismic Q_p data for the upper oceanic crust.

Reference	Location	Oceanic Layer	Reported Qp
Wilcock et al., 1995	East Pacific Rise (9^0 30' N)	2A	10 to 20
Christeson et al., 1994	East Pacific Rise (9^0 30' N)	2A	11 to 20
White and Clowes, 1994	Endeaver Segment, Juan de Fuca Ridge	layer 2-3 boundary	20 to 100
Jacobson and Lewis, 1990	13 km east of Juan de Fuca Ridge	2A	20 to 50
Lewis and Jung, 1989	30 km north of Blanco Fracture Zone-Juan de Fuca Ridge intersection	2	10 to 16

P_p=atm. and P_c=100MPa to 5.70 dB/cm @ P_p = 95MPa and P_c=100MPa) and change minimally at a constant differential pressure. It is evident from these empirical relationships that pore pressure conditions must be considered to accurately characterize the rock attenuation properties of the shallow crust. Hydrostatic pore pressure conditions, which best approximate in situ conditions for oceanic Layer 2A, raise α_p as much as 69% and lower calculated Q_p values by 35% in our example at 5000 meters depth. Low Q_p values (11-17) agree remarkably well with seismic Q_p values reported for oceanic Layer 2A. However, low Q_p field measurements associated with young oceanic crust may be related to phenomena not present on an ultrasonic scale (e.g., abundant fracturing or large-scale heterogeneities). Nevertheless, pore pressure conditions can not be overlooked as controlling parameters for Q_p values on all scales.

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