MECHANISM OF ATTENUATION OF COMPRESSIONAL AND SHEAR WAVES
FOR DRY, WATER AND BENZENE SATURATED ROCKS.

by

Christophe Gonguet

Ingénieur de L'Ecole Nationale Supérieure de Géologie
Nancy, France
(1983)

SUBMITTED TO THE DEPARTMENT OF
EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in
Earth and Planetary Science

at the

© MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1985

Signature of Author............................................................
Department of Earth, Atmospheric, and Planetary Sciences
May, 1985

Certified by................................................................. M. Nafi Toksoz
Thesis Advisor

Accepted by................................................................. Theodore R. Madden
Chairman
Departmental Committee on Graduate Students
DISCLAIMER OF QUALITY

Due to the condition of the original material, there are unavoidable flaws in this reproduction. We have made every effort possible to provide you with the best copy available. If you are dissatisfied with this product and find it unusable, please contact Document Services as soon as possible.

Thank you.

Due to the poor quality of the original document, there is some spotting or background shading in this document.
Table of Contents

ABSTRACT........................................................................................................................................... 3

ACKNOWLEDGEMENTS...................................................................................................................................... 4

Chapter 1. INTRODUCTION.................................................................................................................................. 5

Chapter 2. LABORATORY MEASUREMENTS AND SAMPLE DESCRIPTION

A Experimental technique........................................................................................................................................... 8

B Samples studied................................................................................................................................................... 10

Chapter 3. DETERMINATION OF ATTENUATION COEFFICIENT

A Spectral ratio technique
   A.1 Analytical presentation ................................................................................................................................. 13
   A.2 Practical problems ........................................................................................................................................ 15
   A.3 Comparison with other techniques .................................................................................................................. 17

B Rise time technique
   B.1 Analytical presentation ................................................................................................................................. 17
   B.2 Practical problems ........................................................................................................................................ 19
   B.3 Comparison with other techniques .................................................................................................................. 20

C Sources of error
   C.1 Spherical spreading ....................................................................................................................................... 22
   C.2 Sidewall reflections and geometrical artifacts .............................................................................................. 27
   C.3 Scattering by grains ....................................................................................................................................... 27
MECHANISM OF ATTENUATION OF COMPRESSIONAL AND SHEAR WAVES FOR DRY, WATER AND BENZENE SATURATED ROCKS.

by

Christophe Gonguet

Submitted to the department of Earth, Atmospheric and Planetary Sciences on May, 1985 in partial fulfillement of the requirements for the degree of Master of Science in Geophysics

Abstract

The spectral ratio method is used to calculate the quality factor (Q) in porous rock samples at ultrasonic frequencies (0.3 - 1.5 MHz). The data were collected using the pulse transmission technique with aluminum used as a high Q standard. The data set consists of dry, water and benzene saturated rocks at differential pressures from zero to one kilobar. Four sandstones, Berea, Kayenta, Navajo and Weber, in addition to Bedford limestone, Webatuck dolomite and Westerly granite are studied. Water and benzene were chosen as pore fluid saturants to contrast the effects of two different pore fluids (density, compressibility, viscosity, dielectric constant, and wetting properties) at ultrasonic frequencies. The main features observed are: 1) The quality factor Q increases with increasing confining pressure; at low pressures the rate of increase is larger. 2) Q for saturated samples is generally lower than for dry samples. This effect could be counterbalanced by a "crack-healing" effect for rocks which have a high crack-porosity and low pore-porosity. 3) The introduction of a fluid saturant into a dry rock increases S-wave attenuation more than P-wave attenuation. 4) We observe that benzene saturated attenuations are higher than water-saturated values at lower pressures, and conversely slightly lower at higher pressures. This observation is well correlated with a similar behavior of the benzene- and water-saturated results for non-linear stress-strain and velocity curves. The difference between benzene- and water-saturated attenuations is generally not important, it is larger for rocks with a higher clay content. (5) Bulk and extensional attenuations are useful to discriminate between compressional and shear attenuation and therefore enhance the effects of fluid saturants. (6) The rise time technique and the spectral ratio technique are in relatively good agreement. The rise time technique requires a precise determination of the constant c in order to adjust well to the spectral ratio technique. However, rise time attenuations are easier to calculate for very high attenuations.

Thesis Supervisor: M.N. Toksöz
Title: Professor of Geophysics
Acknowledgements

The completion of this work was made possible because of some self determination and a great deal of stimulation, support and fundamental insight by my advisor, Prof. Nafi Toksöz, and by Dr. Karl Coyner and because of a generous financial aid from the oil company TOTAL.

I am also grateful for all the good friends I made in the departement and at ERL in particular, who made this working environment something exciting and enjoyable.

Finally, I must thank my parents, uncle Louis and aunt Juliet who encouraged and supported me all the way, giving to me this unique opportunity of discoveries and enrichment.
CHAPTER 1:

INTRODUCTION

The contribution of pore fluid to attenuation in rocks has been a subject of interest and intensive study (Bulau et al., 1984; Murphy, 1982; Spencer, 1981; Winkler and Nur, 1979; Mavko and Nur, 1979; Johnston et al., 1979; Johnston and Toksöz, 1980; O'Connell and Budiansky, 1977; Biot, 1956a,b; Wyllie et al., 1962).

Pore fluid can contribute to attenuation in many ways: inertial decoupling, pressure induced flow; viscoelastic relaxation; local flow between adjacent pores ('squish flow'); and wetting of grain surfaces that can contribute to chemical and physical attenuation mechanisms. Although these mechanisms have been studied extensively, neither the experimental data nor the theoretical studies have been able to determine quantitatively the relative significance of different mechanisms (see summary in Toksöz and Johnston, 1981). Attenuation in fully or partially saturated rocks is greater than attenuation in dry rocks. For dry rocks, attenuation \( (Q^{-1}) \) varies by orders of magnitude whether the rock is "air dry" (containing at least a monolayer of water) or totally outgassed by high-vacuum and thermal pulsing (Pandit and King, 1979; Clark et al., 1980). These data confirm the role of water on the scale of monolayer thicknesses.

Going from air-dry to fully fluid saturated case, attenuation increases (Johnston et al., 1980; Toksöz et al., 1979; Winkler and Nur, 1979). The largest effect of saturation occurs in \( Q_s \). In the air-dry case \( Q_p \approx Q_s \) and, in fully saturated case \( Q_s < Q_p \). Partial saturation may reduce \( Q_p \) relative to full saturation, but this effect is generally small (Winkler and Nur, 1979; Johnston and Toksöz, 1980; Frisillo and Stewart, 1980;
There is little experimental data on attenuation with fluids other than water and brine. Wyllie et al., (1962) measured resonant bar attenuation in alundum rods (25% porosity) saturated with soltrol and water and found that attenuation was lower with soltrol saturation. Nur and Simmons (1969) measured the relative change in ultrasonic signal amplitudes transmitted through glycerin- and water-saturated Barre granite as a function of temperature and concluded that a resonant peak existed as a function of fluid viscosity. Spencer (1981) measured the low-frequency phase-lag between stress and strain in Navajo sandstone with a sequence of different fluids and correlated increasing attenuation with larger reductions in surface free energy of silica when immersed in the various fluids, with water being the highest. Bulau et al., 1984, measured resonant bar attenuation with water and iso-octane and noted that attenuation with water was higher.

To evaluate whether water versus another type of liquid pore fluid affects ultrasonic attenuation significantly, we made a systematic study of the dynamic bulk and shear moduli, $(K, \mu)$, and the quality factors, $Q_p$ and $Q_s$, $Q_K$ and $Q_\mu$, in dry, water and benzene-saturated rock samples. Measurements are made over a hydrostatic confining pressure range up to 1 kbar. Rock samples include sandstones (Berea, Kayenta, Navajo and Weber), a limestone (Bedford), a dolomite (Webatuck) and a fine grained granite (Westerly). The measurements are made at ultrasonic frequencies (300-1500 kHz).

The effects of water versus benzene on P- and S-wave velocities and dynamic and shear moduli have been discussed by Coyner and Cheng (1985). In short, the differences between velocity measurements with benzene and water are not easily interpreted strictly on the basis of density, compressibility, or viscosity differences. At
low pressures water-saturated P- and S-wave velocities are higher than benzene-saturated values. At high pressures (greater than about 300 to 500 bars) in the sandstones the water-saturated velocities tend to fall below the benzene-saturated values. Conversion of velocities into dynamic shear and bulk moduli as a function of pressure indicates that the effect is concentrated in the shear modulus. Water-saturated bulk moduli are consistently higher than benzene-saturated values while water-saturated shear moduli, initially slightly higher at low pressures, fall below benzene-saturated values and even the dry shear moduli at higher pressures.

In this study a portion of the signal waveforms collected by Coyner (1984) were analyzed for P- and S-wave ultrasonic attenuation with the hope that a similar effect would be measured. Contrary to what was expected, benzene-saturated attenuation is higher than with water, particularly at low pressures for the P-wave, when most cracks have not been closed and the different bulk properties of water and benzene have a predominant effect. At high pressures water-saturated attenuation tends to be slightly higher although the amount is on the order of experimental error.
CHAPTER 2:

LABORATORY MEASUREMENTS AND SAMPLE DESCRIPTIONS.

A. Experimental technique

In this study we determine attenuation of P- and S-waves using ultrasonic pulse transmission.

The experimental arrangements shown schematically in Figure 1, representing a sample loaded in the high pressure apparatus. In this method, a jacketed sample is placed in the pressure vessel with source and receiver transducer attached. The source and receiver piezoelectric crystals are contained within a titanium alloy housing.

The main characteristics of this experimental combination are:

(i) The samples used are cylinders 2 inches in length and 3 inches in width

(ii) Independent hydrostatic confining pressure and pore pressure or vacuum are applied. The differential pressure was chosen to vary from 25 to 1000 bars, by increments of 25 bars up to 250 bars, then by increments of 50 bars up to 500 bars and finally by increments of 100 bars up to the maximum pressure. Pore pressure for the fluid saturated samples was maintained at 100 bars.

(iii) The ceramic transducers are isolated from pressure, thus avoiding effects on the source spectrum caused by the change of pressure.

(iv) At any given time or pressure, P or either S-wave can be recorded.

(v) The experiment is computer monitored.

The design of this apparatus and all the measurements were completed by Karl Coyner (Phd thesis, 1984). A more detailed description is available in his PhD thesis. In addition
to these specifications, it may be useful to remark that two perpendicular S-wave recordings were made at each pressure. In this study only one of those has been used, but the processing of both recordings reveal some anisotropic attenuation if for instance the rock microfractures are preferably oriented in some direction (Lo, Coyner, Toksöz, 1985). Furthermore, we only used the transmitted events for attenuation measurements, while P and S-waveforms have been recorded for all all first order reflected events, reflecting from the titanium plates - sample core interfaces. A study of attenuation would therefore be possible by comparatively measuring amplitudes for events with and without reflection or by using the phase velocity determination and the method described by Winkler and Plona, 1982. A specific manipulation was conducted in order to estimate the travel time through the titanium plates at all pressures, taking the coupling effects into account, by measuring the delay time, with visual threshold detection, from source to receiver, for aluminum samples of decreasing thickness, finally interpolating the results to a zero-length aluminum core. The results agree well with the approximate calculation of \( \Delta t \) using \( \Delta l = 3.6 \text{cm} \) and \( v_P = 6.07 \text{ km/sec}, v_S = 3.13 \text{ km/sec}. \)

Ultrasonic P- and S-wave signals are propagated through cylindrical cores or rock. An aluminum cylinder, same size as the sample, is used as a high-Q standard for calculation of the spectral ratio. Center frequencies of the signals are approximately 400 to 850 KHz depending on pressure and sample. Temperatures are laboratory ambient. Confining pressures are systematically cycled up to levels of 1000 bars and pore pressures are either vacuum (20 \( \mu \) m Hg) or 100 bars for the benzene and water saturations. The difference between confining and pore pressures is taken to be the "effective" pressure in determining attenuation. Each sample was first measured vacuum dry over a cycle of confining pressure, then saturated with benzene reagent.
(100 bars) and again measured over a cycle of confining pressure. Samples were then removed from the sample apparatus, soaked and washed with acetone, and dried for at least 24 hours in a vacuum at 80°C. Next the sample was re-jacketed, measured dry again as a check for repeatability, and then measured over a cycle of confining pressure after saturating with water at 100 bars pore pressure.

Specially developed transducers provide broadband P and S-waves. Examples of waveforms for dry, benzene and water saturated Kayenta sandstone at 100 and 500 bars, for Westerly granite at 100 bars are shown in Figures 2, 3 and 4.

The experimental procedures used for both the sample and the aluminum reference are similar. Therefore, we have relative measurement of attenuation and such we minimize the effects of the transducer, the coupling between transducer, titanium holders and the sample. The Q of aluminum is about 150,000 (Zemanek and Rudnick, 1961), roughly 3 to 4 orders of magnitude higher than those of rocks in this study, and is constant with frequency (Savage and Hasegawa, 1967).

B. Samples studied

Table 1: Rock Samples in this Study

The standard characteristics of the rocks studied are given in next table:
Table 1

<table>
<thead>
<tr>
<th>Rock</th>
<th>Density (g/cc)</th>
<th>Grain Size (mm)</th>
<th>Porosity (%)</th>
<th>$K_s$ (Mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westerly Granite (blue)</td>
<td>2.641</td>
<td>0.75</td>
<td>0.8</td>
<td>0.56</td>
</tr>
<tr>
<td>Webatuck Dolomite</td>
<td>2.846</td>
<td>0.45</td>
<td>0.5</td>
<td>0.97</td>
</tr>
<tr>
<td>Bedford Limestone</td>
<td>2.360</td>
<td>0.75</td>
<td>11.9</td>
<td>0.65</td>
</tr>
<tr>
<td>Weber Sandstone</td>
<td>2.392</td>
<td>0.05</td>
<td>9.5</td>
<td>0.385</td>
</tr>
<tr>
<td>Navajo Sandstone</td>
<td>2.316</td>
<td>0.15</td>
<td>11.8</td>
<td>0.36</td>
</tr>
<tr>
<td>Berea Sandstone</td>
<td>2.197</td>
<td>0.1</td>
<td>17.8</td>
<td>0.39</td>
</tr>
<tr>
<td>Kayenta Sandstone</td>
<td>2.017</td>
<td>0.15</td>
<td>22.2</td>
<td>0.33</td>
</tr>
</tbody>
</table>

In addition to the information contained in the above table, it is useful to point out some extra characteristics of these rocks:

Westerly granite: this is a fine grained equigranular, biotite granite of very uniform texture and grain size.

Webatuck dolomite: this metamorphic foliated dolomite has a very low pore porosity and a relatively abundant amount of cracks (confer to the low Poisson's ratio for dry sample). The matrix structure is susceptible of collapsing at very high pressure, after all the pores have been closed.

Bedford limestone: this is a coarse-grained, poorly-sorted, well cemented calcarenite, brecciated limestone with fossil debris. The rock contains almost no cracks and is very stiff. Accordingly, Poisson's ratio is nearly constant along pressure
variations. The pores have a high aspect ratio.

Weber sandstone: this is an extremely fine grained sandstone and probably should be called a siltstone; it contains a substantial amount of cracks, more near grain boundary cracks than all the other sandstones studied here. It is finely layered and the cylindrical core sample has been cut with its axis perpendicular to the bedding. This anisotropy has been the source for underestimating compressional velocity (measured perpendicular to the bedding), and overestimating shear velocity (the shear stresses and displacements are measured parallel to the bedding). Henceforth we obtained negative Poisson's ratio for the dry sample at pressures below 250 bars. This nonphysical result was corrected by increasing slightly the values of the compressional velocities in order to better interpret the results of attenuations for bulk and Young's moduli, where Poisson's ratio is introduced in the calculation of these variables.

Navajo sandstone. this is a very clean, well-silicified and isotropic sandstone. The compacity of the rock is reflected in the Poisson's ratio which is nearly unaffected by pressure increase.

Berea sandstone: this is a well sorted, fine-grained, submature protoquartzite containing less than 10% of fine-grained clays. This is the only rock where the core sample has been cut with its longitudinal axis parallel to the bedding orientation.

Kayenta sandstone: this is a very friable rock, coarser grained than the Berea, higher in porosity and not as well cemented. Poisson's ratio varies a lot below 250 bars, in particular for the dry sample. Therefore, we conclude that the rock may contain a fair amount of cracks.
A Spectral ratio technique

A.1 Analytical presentation

Attenuation values were first measured using the spectral ratio technique (Toksoz et al., 1979).

For plane waves, wave amplitudes can be expressed as:

\[ A_1(f) = G_1(f, x) e^{-\alpha_1(f)z} e^{i(2\pi ft - k_1 x)} \]  

(1)

and

\[ A_2(f) = G_2(f, x) e^{-\alpha_2(f)z} e^{i(2\pi ft - k_2 x)} \]  

(2)

where \( A \) = amplitude, \( f \) = frequency, \( z \) = distance of propagation, \( k = 2\pi f / v \) = wavenumber, \( v \) = velocity, \( G(f, x) \) is a geometrical factor which includes beam spreading. Subscripts 1 and 2 refer to the reference and the rock sample respectively. \( \alpha(f) \) is the attenuation factor and related to \( Q \) by

\[ \alpha = \frac{\pi f}{Qv} \]  

(3)

Taking the ratio of amplitudes given by equations (1) and (2) and the natural logarithm of this ratio gives

\[ \ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G_1}{G_2}\right) = (\alpha_2 - \alpha_1)z. \]  

(4)
If we assume that $\alpha$ is a linear function of the frequency, i.e., constant $Q$, then

$$\alpha(f) = \gamma f,$$

(5)

where $\gamma$ is a constant, and

$$Q = \frac{\pi}{\gamma v}.$$  

(6)

We can rewrite (4) as

$$\ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G_1}{G_2}\right) = (\gamma_2 - \gamma_1) zf,$$

(7)

The term $\ln(A_1/A_2)$ is the ratio of the spectral amplitudes of the reference to the sample. The term $\ln(G_1/G_2)$ may be frequency dependent because of beam spreading.

$$F(f) = (\gamma_2 - \gamma_1)zf,$$

(8)

where $F(f) = \ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G_1}{G_2}\right)$. Since $Q$ of the standard is very high, $\gamma_1$ can be taken equal to 0.

For plane waves the geometric factors $G_1$ and $G_2$ have similar frequency dependence, $\ln(G_1/G_2)$ is independent of frequency.

In practice, a window is selected over the signals, aluminum and sample, and then Fourier transformed. The natural log of the amplitude ratios are computed versus frequency. Attenuation constant, $\gamma$, is determined over the frequency interval where both the sample and reference spectra have adequate power (i.e., when signal to noise ratio is high). An example of spectra, the ratio, and frequency window over which a least squares linear fit is made are shown in Figure 2. The data quality is good for all samples.
A.2 Practical problems

Some of the problems occurring are directly related to the field of digital signal processing. One of the objectives is to obtain the best resolution in frequency domain, where the amplitude ratio is to be calculated at each frequency. In order to increase the sampling density in of the frequency spectra without losing information we zero-padded the time domain series of point and took a longer FFT (Fast Fourier Transform algorithm), up to 1024 points where in most cases the minimum was 256 points. In addition we undersampled the time domain signal by a factor of 10, without approaching the Nyquist frequency too closely: we operate on signals recorded over 4 to 5 microseconds, we select a rectangular window containing the first 3 half-cycles of the pulse, we sinus-tape the edges of this window; we now have about than 400 points over 3 to 4 microseconds, the initial digitization frequency is thus around 100MHz; the signal does not contain any information above 1.5 MHz, then the Nyquist frequency is below 3MHz and we see that a 10 to 1 compression of the signal cannot cause any aliasing problem.

The rectangular window has been chosen rather than a Blackman or a Hamming window since the signal is relatively noise free and the zero-crossings of the initial waveform are non ambiguous.

The next problem is to determine over which portion of the amplitude spectra the ratio is to be calculated and a line to be adjusted to the data in the least-square sense. Ideally we would like to take the longest window, where the signal to noise ratio is reasonable and at the same time get the best fit. The windowing process should thus respect the following conditions

(i) The spectral window should be centered around the common area limited by the two amplitude peaks (aluminum and rock).

(ii) We should get the best numerical adjustment in order to satisfy to the predicted
linear theory.

(iii) Between different pressures and between different saturation conditions for the same sample of rock, the window determination should be consistent so that the results are comparable.

One choice was to select this window visually, while respecting the above criteria. This the time consuming solution. The other solution was to automatize the computer program completely. The interpolated slope of the fitted line is then taken to be a weighted average of the slope values from three overlapping windows defined as such: The first one is between the 50% levels of the peak amplitudes on both sides of the peaks. (This level values are taken on the average from the two peaks: aluminum and rock sample). The next two windows are taken respectively between the [20% - 50%] and [50% - 20%] level amplitudes astride the common area of the peaks. The weighting factor is taken to be the correlation factor for the fit on each window. The averaged slope is normalized by dividing the sum of the weighted slopes by the sum of the weighting factors.

It is difficult to provide an estimation of the accuracy of the spectral ratio measurements. This accuracy depends mainly on the quality of the least square fit between the spectral amplitude ratio and a straight line. As addressed above, the choice of a spectral window is essential in this sense. In the absolute, the relative error in calculating the slope is greater for smaller slope and therefore very low attenuation values, like those encountered for Webatuck dolomite are to be interpreted with caution.

Finally, in order to obtain interpretable results, we must insist on the importance of the standardization of the method: the experimental conditions should be kept constant (temperature, source spectrum, sample length, initial signal filtering and recording) as well as the processing techniques, particularly for the spectral window determination.
A.3 Comparison with other techniques

Little comparative information is available in the literature about the comparison of the different methods of attenuation measurements in the ultrasonic field, in terms of accuracy, reliability and limits of the methods. However, it appears that the spectral ratio is well suited for laboratory measurements because the signals are relatively free of noise and the single pulse events easy to identify. Nevertheless, the accuracy becomes uncertain for high quality factors, since they correspond to very small slopes where there becomes to be numerical problems in estimating that slope. Within the limits of this study, we did not find any Q below 7, but we suspect that for very low Q's, for instance below 5 the broadening of the pulse.

B Rise time technique

B.1 Analytical presentation

This method is based on the quantification of the change in the shape of the transient waveform propagating through the rock, modification which is due to anelastic absorption.

Gladwin and Stacey (1974), have proposed a linear relationship between Q, the quality factor, and \( \tau \), the rise time: \( \tau \) increases linearly with the distance from the source and the slope of this linear relationship is inversely proportional to Q. This is valid only if we assume a constant-Q or nearly constant-Q over the frequency range concerned.

Therefore, they derive the equation, valid for an impulsive source:
\[ \tau = \tau_0 + \frac{C \tau}{Q} \]  

\( T \) being the travel time from the source.  
\( \tau_0 \) is the rise time at the source or before propagation in the studied attenuative media.  
\( \tau_0 \) and \( C \) are two source dependant parameters.  
In our case, the distance of propagation in the rock medium is close to 2 inches, the measured travel times vary between 8 and 20 microseconds.  
Kjartanson's work (1979), yields a value for \( C \) of .298 for measurements of acceleration pulse rise times and for \( Q \) factors higher than approximately 10 as is generally the case in this study. The ceramic transducers are sensitive to pressure variations and hence to accelerations in the particle movements.  
Note that the value of \( \tau_0 \) must be strongly dependent upon the high frequency component of the initial source impulse since at \( T=0 \), there must be a non zero rise time.  
In our experimental setting, a titanium plate is interposed between the source and the rock, thus \( \tau_0 \) is different from 0, as would be the case if the source was perfectly impulsive and the source was directly in contact with the rock or the titanium had no relevant attenuation. Furthermore we are interested over obtaining a \( Q \)-value relative to the aluminum standard, for which the same linear relationship is also valid:  
\[ \tau(\text{aluminum}) = \tau_0(\text{aluminum}) + \frac{C \tau}{Q}(\text{aluminum}) \]  
\( Q \) is very large, around 150,000, then the second term in this equation is negligible in front of the other two terms. We deduce that \( \tau_0(\text{aluminum}) = \tau(\text{aluminum}) \) at each working pressure.  
\( \tau(\text{aluminum}) \) has been measured for the entire range of differential pressures used in this work, with the same source and apparatus as for the rock samples, therefore we will assume \( \tau_0(\text{Rock}) = \tau(\text{aluminum}) \) at the same pressure.  
\( \tau_0 \) is also corrected for the small discrepancy existing in terms of sample length.
between aluminum reference and rock core. This correction corresponds at most to 8% of the initial value of \( \tau_0 \).

The rise time parameter is calculated using two different techniques:

(i) using the definition from Gladwin and Stacey (1974), with \( \tau \) being the ratio of the maximum ordinate of the first peak to the maximum slope in the first quarter cycle of the recorded pulse.

\[
\tau = \frac{u_{\text{max}}}{(du/dt)_{\text{max}}}
\]  

(ii) using the definition from Blair and Spathis (1982), with \( \tau \) being the time difference between 10% and the 90% amplitude levels of the pulse onset.

\[
tau = \frac{u_{90\%} - u_{10\%}}{\Delta t}
\]

The use of the two definitions yield values of \( \tau \) that agree within 10% of error for all data and within 5% variation in most cases. Therefore, we shall limit all further discussion on Q-values to the results obtained by applying Gladwin and Stacey's definition. As a remark we could state that the common C-value of .298, that was used in both cases has been calculated analytically by Kjartanson (1979) for the restricted case of Gladwin and Stacey's definition for \( \tau \), thus some divergence between our two series of results is not surprising.

**B.2 Practical problems**

In order to gain precision on the measurement of the rise time, we adjusted a fifth degree polynomial to the first period of the waveform. This accounts for the fact that the discrete nature of the signal (sampled every 1.0 to 2.0 nanoseconds according to the rock) and the short duration of each period (less than 2 microseconds), makes it difficult to find the exact point of steepest tangent, or the 100%, 90% and 10% peak
amplitude levels. The point of steepest tangent and the point of maximum amplitude are then easily determined by finding the roots of the second and first derivatives of the polynomial.

This method was relatively simpler to implement than the previous one. For the spectral ratio technique, the sensitive part was the selection of a spectral window, where to observe a linear adjustment. For the rise time technique, the sensitive part is to determine the point of maximum slope, under the assumption that the shape of the pulse is not distorted by the recording system. The signal shape is more faithfully reproduced on a broad-band system, where the energy is not delayed by the phase response of the instrument. But again this is a relative measurement method: The value of $\tau$ considered is the differential with the aluminum standard.

B.3 Comparison with other methods

We compared the results provided by the spectral ratio and rise time techniques. The agreement is good provided that we chose the appropriate value of the constant $C$ for the latest method. In the next table we give the $C$-value that provides attenuation coefficients $Q$'s with an identical mass on the range of pressures considered, for both rise-time and spectral-ratio techniques. Together with this estimation of $C$ which practically corresponds to the best coincidence between the two group of values, we give the deviation for the those two groups, considering rise-time attenuation coefficients calculated with the corrected $C$ constant. We observe that rise time measurements provide attenuations that are higher in the case of S-waves for Webatuck dolomite. The reliability of this result is uncertain but the measurement is probably more accurate than for the spectral ratio technique since in this iast case the incertitude on the measurements of very small slopes (corresponding to very high $Q$'s) is very large.
We will discard the results from Webatuck dolomite for the calculation of an average value of C, because it is difficult to normalize the rise time Q-values to the very high Q-values obtained by spectral ratio analysis. In this respect, the rise time technique seems to give more plausible results than the spectral ratio technique for high quality factors (above 200).
From this values, we conclude that the average C-value is .40 for P-waves, and .24 for S-waves. Those two values are in a 5 to 3 ratio with each other. This result is purely informative and has little physical significance. It is more interesting to point out that the estimated C-values are higher for P than for S-waves, and higher for dry than for saturated rocks. From Kjartanson (1979), we observe that the value we considered for C is based on a Nearly-Constant-Q assumption (NCQ), and accordingly it appears that C calculated is independant of Q for any Q greater than 20. In conclusion, normalizing rise-time to spectral ratio values is not necessary legitimate. However, if we take the spectral ratio calculations as a reference, it appears that the divergence of C from the theoretical value of .298 could be explained by the non rigorous validity of the NCQ hypothesis.

It is interesting to note that the beam spreading effect due to a non strictly plane wave, as well as the scattering effects should not affect the rise time measurements since they do not affect the pulse shape or its time duration. Finally, the rise-time method has the clear advantage over spectral methods that the measurement may be done on a clearly defined phase of the waveform (Gladwin and Stacey,1974).

**C Sources of error**

**C.1 Spherical spreading**

In this experiment the transducer diameter is 2.5 cm (1 inch), and the sample diameter is 7.62 cm. As a result the energy beam spreads and this spreading is dependent on wavelength. Seki et al., (1956) and Papadakis (1975) studied the beam spreading problem for a cylindrical source. They found that amplitude decrease due to
beam spreading is about 1 db per $a^2/\lambda$, where $a$ = source diameter and $\lambda$ = wavelength.

Calculation of the diffraction correction: Due to the short wavelengths, it is required that the opposite faces of the sample be flat and parallel. Truell et al., 1969, have shown that the limit to the deviation from parallel faces depends on $Q^{-1}$ for the studied material and on the frequency. We assume that both source and receiver transducers are coaxial, have the same circular shape and same dimensions, that the source behaves pistonlike, uniformly and harmonically, that the electrical response of the receiver is proportional to the average pressure over the surface of the transducer at a given time. Diffraction occurs when the product $ka$ gets large, i.e., the wavelength is much shorter than the radius of the source (the source therefore has a radiation pattern, the displacements are dependant on the angle of emergence).

If $k$ is the wavenumber, $a$ is the source diameter; in our case $k = \frac{2\pi}{\lambda} = 5$ mm for $v_p = 5.0$ km/sec and $f = 1$ Mhz, $a = 25$ mm, thus $ka = 10 \pi = 31.4$, the transducer diameter is about 3 to 4 times the wavelength.

The diffraction correction could be made for each data point in the term $ln(G_1/G_2)$, but since this correction is nonmonotonic in nature, it is contrary to our linearity assumption. Therefore this correction is to be made after $Q$ is calculated.

We will use the following table given by Seki et al.
<table>
<thead>
<tr>
<th>S</th>
<th>d (dB)</th>
<th>S</th>
<th>d (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.868</td>
<td>1.8</td>
<td>2.600</td>
</tr>
<tr>
<td>0.3</td>
<td>1.070</td>
<td>2.0</td>
<td>2.478</td>
</tr>
<tr>
<td>0.4</td>
<td>1.198</td>
<td>2.2</td>
<td>2.386</td>
</tr>
<tr>
<td>0.5</td>
<td>1.342</td>
<td>2.4</td>
<td>2.358</td>
</tr>
<tr>
<td>0.6</td>
<td>1.554</td>
<td>2.6</td>
<td>2.404</td>
</tr>
<tr>
<td>0.7</td>
<td>1.548</td>
<td>2.8</td>
<td>2.536</td>
</tr>
<tr>
<td>0.8</td>
<td>1.776</td>
<td>3.0</td>
<td>2.708</td>
</tr>
<tr>
<td>0.9</td>
<td>1.910</td>
<td>3.2</td>
<td>2.904</td>
</tr>
<tr>
<td>1.0</td>
<td>1.848</td>
<td>3.4</td>
<td>3.118</td>
</tr>
<tr>
<td>1.1</td>
<td>1.862</td>
<td>3.6</td>
<td>3.364</td>
</tr>
<tr>
<td>1.2</td>
<td>2.014</td>
<td>3.8</td>
<td>3.607</td>
</tr>
<tr>
<td>1.4</td>
<td>2.453</td>
<td>4.0</td>
<td>3.862</td>
</tr>
<tr>
<td>1.6</td>
<td>2.664</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this table, S is the distance between source and receiver measured in units of \( \frac{a^2}{\lambda} \), a is the diameter of the transducers (2.5 cms in our case), d is the drop in amplitude measured in dB.

This loss, as can be readily seen from the values is not linear. Indeed the curve, d as a function of S, although overall approximately monotonic (tends to be exponential), presents local minima, at S= 0.73, 1.05, 2.4.

at a given frequency:

\( d_1 \) being the drop in amplitude in dB for the rock sample,
$d_2$ being the drop in amplitude in dB for the aluminum reference. Therefore $d_1$ and $d_2$
are negative quantities.

\[
-d_2 - d_1 = 20 \log \left( \frac{A'_2}{A_2} \right) - 20 \log \left( \frac{A'_1}{A_1} \right) \tag{13}
\]

\[
d_2 - d_1 = 20 \log \left( \frac{A'_2}{A'_1} \right) \tag{14}
\]

then \[
\frac{A'_2}{A'_1} = \frac{A_2}{A_1} \frac{d_2 - d_1}{10^{20}} \tag{15}
\]

\[
\ln \left( \frac{A'_2}{A'_1} \right) = \ln \left( \frac{A_2}{A_1} \right) + \ln \left( 10^{\frac{d_2 - d_1}{20}} \right) \tag{16}
\]

At a given frequency, we get the correction to apply to the natural logarithm of the
spectral ratio. We can calculate this term at both extremities of the spectral window
where the linear interpolation is made. This correction comes in terms of adding or
subtracting a normalized value to ordinate for the interpolate line at both ends of the
window, an addition occurring when the correction due to diffraction is larger for the
aluminum and on the other hand, a substraction is made when diffraction effect is
prominent for the rock sample. Finally, the slope is recalculated from:

\[
slope_{corrected} = \slope_{initial} + \frac{\Delta z_{max} - \Delta z_{min}}{\Delta f} \tag{17}
\]

with

\[
\Delta z_{min} = \Delta \ln \left( \frac{A'_2}{A'_1} \right) \quad \text{at } f_{min} \tag{18}
\]

and

\[
\Delta z_{max} = \Delta \ln \left( \frac{A'_2}{A'_1} \right) \quad \text{at } f_{max} \tag{19}
\]

$\Delta f = f_{max} - f_{min}$ is the frequency span corresponding to the spectral window. Then we
can recalculate $Q$ from:

$$Q = \frac{\pi x}{v \text{ slope}}$$  \hspace{1cm} (20)

We deduce:

$$Q_{\text{corrected}} = \frac{\pi x}{Q_{\text{initial}} + v \text{ slope}}$$  \hspace{1cm} (21)

We chose to make our corrections over the standard frequency range, on a window centered around .8 MHz and with 1 MHz width. It is noted that the titanium plate holders introduce by themselves a drop in amplitude of 2 dB (20.6%) and 1.55 dB (16.3%) for P-waves respectively at 0.3 and 1.3 MHz, and .9 dB (9.8%) and .8 dB (8.8%) for S-waves at the same frequencies; the velocities for this metal being 6.07 km/sec for compressional waves and 3.12 km/sec for shear waves, the total interposed thickness being 3.6 cms. However, we do not correct for this contribution to the total spreading since it does not introduce a differential effect between the aluminum reference and the rock sample.

The correction should be greater for samples with slower velocities such as porous sandstones, since the difference in velocities with aluminum is greater. Indeed, we found a correction smaller than 2% in most cases, in the range of pressures considered, except for Berea, Navajo and Weber sandstones, in laboratory dry state where the relative contribution of beam dispersion to P-wave attenuation reaches 10 to 17% decrease of the $Q$-value at the higher pressures. For the fastest rocks considered, Westerly granite and Webatuck dolomite, the correction corresponds to a $Q$-increase due to velocities relatively higher than for the aluminum reference (for the aluminum, $v_P=6.42 km/sec$, $v_S=3.04 km/sec$) in the case of the dolomite and due to velocities comparable with aluminum for the granite with in addition a slightly longer travel path (increased by 2.1%).
C.2 Sidewall reflections and other geometric artifacts

The geometry of the samples (2" long by 3" large), was designed to avoid sidewall reflections, even if we take the beam spreading effect into account. The samples are also considered as homogeneous and isotropic and thereby no inside reflection occurring on occur on a bedding interface, should take place. Nor any major crack was detected in those samples. Furthermore the time domain signals as well as their frequency spectra do not show any apparent superimposed event.

C.3 Scattering by grains

In this study, rocks with larger grain size are the Westerly granite and the Bedford limestone. Both contain grains with an average size of 0.75 millimeters. When we compare the wavelength of the pulses (dominant wavelength, $\lambda = 6$mm for P-waves in granite) with the size of the grains, we find that the rayleigh condition: $ka < 0.1$ ($k$ being the real wavenumber and $a$ the size of the grains), is not met in the strict sense. Thus there may be some contribution due to scattering. Another rule of the thumb is that $\lambda a < 3$, $\lambda$ being the wavelength. This latter condition is generally satisfied. Based on these, we can say that scattering may be present but its effect is probably small. We consider this effect to be negligible.

C.4 Effects of noise

The recorded signals are represented in Figures 2 to 4 for Kayenta sandstone and Westerly granite. It can be readily seen that they are at least visually free of noise. The same conclusion can be drawn when looking at the shape of the spectra.
additional information seems to come only at frequencies below 100 or 200 kilocycles or above 2 megahertz. However, we observe some variation in the results according to how many arches (half-cycles), we process into the Fourier transform for the spectral ratio method, or on how many of these arches we try to fit a fifth degree polynomial in the case of the rise time method. We cannot assert whether the difficulty to find a perfectly linear portion on the spectral ratio, on the larger possible section of the spectrum peak, is due to numerical noise or to noise attributable to the recording instruments or is inherent to the technique. To give an idea of the quality of the spectral ratio fit, we get on the average a correlation coefficient of .99 for the fit in the window corresponding to the 50% -50% levels of the peak amplitude, which corresponds to about 50 points scattered on a range covering 0.8 megahertz.
CHAPTER 4: RESULTS AND INTERPRETATION

A. Spectral ratio attenuation - results

A brief lithological description of the samples studied is given in chapter 2-C. The properties of the saturating fluids are given in Table 4, chapter 4.

In order to separate the P-wave attenuation into bulk and shear attenuation (Spencer, 1979) we calculated $Q_E$ and $Q_K$ using observed $Q_p$, $Q_S$, and Poisson's ratio $\nu$ from the velocity data. $K$ and $Q$ refer respectively to bulk and Young's moduli.

\[
Q_E = \frac{(1+\nu)}{(1-\nu)(1-2\nu)} + \frac{2\nu(2-\nu)}{Q_P Q_S} \tag{22}
\]

\[
Q_K = \frac{(1+\nu)}{3(1-\nu)} - \frac{2(1-2\nu)}{2Q_P Q_S} \tag{23}
\]

with

\[
\nu = \frac{\beta_2 - 2\xi_2}{2(\beta_2 - \xi_2)} \tag{24}
\]

At first we present all the main features observed on the displays of $\frac{1000}{Q_P}$, $\frac{1000}{Q_S}$, $\frac{1000}{Q_K}$, $\frac{1000}{Q_E}$ versus differential pressure (difference between confining and pore pressure). We consider the effects of pressure, fluid saturation versus dry, benzene versus water saturation, shear versus compressional contribution towards absorption.
**Weber sandstone**

As for all sandstones studied, pressure dependence is greatest for benzene saturated attenuations and smallest for dry attenuation. Here, dry S-attenuation is almost independant of pressure, while dry K-attenuation is strongly dependant on pressure variations.

At highest pressures, saturation affects more shear than bulk or compressional attenuation: at 1000 bars, saturated shear and Young's attenuations are twice the dry attenuations, while compressional and bulk attenuation are less affected.

Benzene attenuation is greater than water attenuation for all Q variables. The divergence between benzene and water decreases to almost zero towards the highest pressures (over 800 bars). At 800 bars, we observe a cross-over for S-attenuation, above this pressure benzene S-attenuation becomes slightly smaller than water S-attenuation. This last observation is made almost within error limits for our measurements. If we compare bulk attenuation to P- and S-attenuation, the difference between water and benzene is enhanced. In addition water attenuation unexpectedly falls lower than dry attenuation. Except for the water-dry reversal for bulk attenuation, all other attenuation coefficients are greater for benzene and lower for dry and the difference is quite important at the low pressures.

P and S-wave attenuations are similar for benzene saturation, S-attenuation is greater than P-attenuation for water saturation (the difference becomes negligible at high pressures) and P-attenuation is greater than S-attenuation for the dry case. The same observations can be made between K- and E-attenuations.

Finally, we notice that in the dry case, there is the greatest difference between K- and S-attenuation: at all pressures, dry K-attenuation is more than twice dry S-attenuation.

**Navajo sandstone**
A single fluid saturation was measured, using benzene as fluid saturant. This rock has the lowest attenuation of all our sandstones. For all type of attenuations, 1000 $Q^{-1}$ values for benzene are well above dry values. At 1000 bars, benzene S-attenuation is three times dry S-attenuation and benzene P-attenuation is two times dry P-attenuation. Pressure dependence, at least for the lower pressures ($P < 250$ bars), is greater for dry P- and K-attenuation than for dry S-attenuation. For dry S-attenuation, the pressure dependence is almost linear.

All P-attenuations are greater than S-attenuations. (The difference becomes negligible for benzene saturation when pressure is close to the lowest values). The same results are also valid when we compare K and E-attenuations.

**Berea sandstone**

The first observation we can make is that for all measurements of attenuation, dry values are significantly lower than saturated values (even at the higher pressures). Pressure dependence is greater for saturated values. The greater dry attenuation pressure dependence can be observed for S-attenuation, the least for K-attenuation (almost constant values at all pressures in this last case) and intermediate values are found for P-attenuation.

Benzene and water attenuations are comparable. The deviation is nearly within error limits but, nevertheless we are able to observe a cross-over feature occurring at 250 bars for $Q_S$ and $Q_E$ and 450 bars for $Q_P$ and $Q_K$: at lower pressures, benzene saturation is greater and at higher pressures, water saturation is greater. This cross-over is less obvious for P and even more for K-attenuations than for S- and E-attenuations.

S-attenuation is greater than P-attenuation for saturated data. The same is true for dry data below 500 bars. Above this threshold, dry P and S values are identical. The same comparison can be made for K- and E-attenuations respectively.

-31-
**Kayenta sandstone**

The pressure dependence is remarkably similar for all different Q's calculated. The data curves are parallel to each other. As for other sandstones, benzene saturation has the greatest pressure dependence and dry the lowest one. As for Berea sandstone, saturated attenuations are well above dry attenuations at all pressures. The increase in attenuation due to fluid saturation is proportionally larger for S-waves than for P-waves, especially at high pressures.

Benzene saturated attenuations are greater than water saturated attenuations. The difference is more noticeable for P and K-attenuations rather than for S and E-attenuations. In these last cases, the benzene-water deviation disappears above 300 bars, but we do not observe a real cross-over as for other sandstones.

In the case of K-attenuation, water saturated and dry attenuations are nearly identical, dry attenuation tends to be greater than water saturated attenuation at low pressures. This observation is to be associated with the inversion in K-attenuations between dry and water saturated case for Weber sandstone.

Dry P-attenuation is slightly higher than dry S-attenuation. On the opposite, water saturated P-attenuation is lower than water saturated S-attenuation. Benzene saturated attenuations are identical for P and S-waves. The same observations can be made between K and E-attenuations.

**Bedford limestone**

First, we can observe a very similar and almost linear pressure dependence for all saturations and for all attenuation parameters. Then we can point out the small difference between water and benzene saturations.

Saturated attenuations are always greater than dry attenuation. The presence of fluids increases mostly shear attenuation. Benzene saturated values are greater than water
saturated values for P and K-attenuations. As for Weber sandstone and to a lesser extent for Kayenta sandstone, dry K-attenuation is greater than water K-attenuation. For S and E-attenuations, a cross-over can be observed: Benzene is more attenuative than water below 200 bars and conversely at pressures above 200 bars.

Attenuation is significantly greater for P than for S-waves at all saturations. Identically, K-attenuation is greater than E-attenuation.

**Webatuck dolomite**

The only fluid saturant used for measurements was benzene. The first observation we can make is that dry P and K-attenuations are much greater than corresponding benzene saturated attenuations, particularly at pressures below 200 bars. Above 300 bars, benzene P and K-attenuations become slightly higher than dry P and K-attenuations. For S and E-attenuations, the result is opposite below 250 bars. Above 400 bars the values are so low (Q is of the order of 1000), that we cannot compare dry and saturated values accurately.

The effect of pressure variations is negligible above 400 bars.

For the dry measurements we observe that the pressure dependence is greater for P-attenuation than for S-attenuation and that P-attenuation is greater than S-attenuation; identically, K-attenuation is greater than E-attenuation. For the benzene saturated measurements, the pressure dependence has an opposite behavior: it affects more S and E-attenuations than P and K-attenuations. Furthermore, S-attenuation is greater than P-attenuation below 200 bars, and conversely above 200 bars. The same result is observable for E and K-attenuation.

**Westerly granite**

The pressure dependence is greater for S,E than P,K-attenuations for saturated
measurements, greater for P,K than for S,E-attenuations for dry measurements. Saturated attenuations are higher than dry attenuations for S and E measurements, lower than dry attenuation for P and K measurements below 175 and 400 bars respectively, greater than dry P and K-attenuations above 200 and 400 bars respectively.

A surprising behavior can be observed for dry K-attenuations where the attenuation is increasing with pressure. Similarly to Weber sandstone and to a certain extent to Kayenta sandstone and Bedford limestone, we observe a dry K-attenuation greater than water and benzene saturated K-attenuation, at for pressures lower than 400 bars. Above 400 bars, dry K-attenuation becomes slightly lower than water and benzene attenuations.

1000/Q_p never gets below 20 for dry measurements when it is well under 5 for Webatuck dolomite. P-attenuations present no difference between water and benzene saturations. S an E-attenuations exhibit a difference between water and benzene saturations that decreases with increasing pressure, this deviation becomes negligible above 500 bars. For dry data water saturated measurements, P and K-attenuations are higher than S and E-attenuations respectively. For benzene saturated measurements, the same result is true above 350 bars.

B. Effects of fluid saturants

Many authors agree with the fact that frictional grain sliding alone does not account significantly in the mechanism for stress wave attenuation in saturated porous rocks. A major argument for this assertion is that frictional attenuation being non linear in strain, we will not observe a Q dependence on strain for strains lower than 10^{-6}.
Therefore pore fluids control attenuation even in laboratory-dry rocks. The question remains whereas what are the particular interactions of fluids pore or crack surfaces which contribute to the stress wave energy dissipation. Tittmann et al. (1980), suggest that at the molecular level the energy loss can be ascribed to stress-induced diffusion of absorbed polar fluid, the energy being dissipated in the breakage of hydrogen bonds between the surface hydroxyls and the fluid molecules, i.e. the silanol and the water molecules in the case of silicates. The removal of water molecules from the surface of grains increases surface free energy and thereby stiffens the mineral at the grain contacts. Murphy (1982) regroups under the qualification of micro capillary hysteresis the phenomena of bond breaking at the grains surfaces or the viscous dissipation as a fluid film moves over surfaces asperities in the case of incomplete saturation. These mechanisms take place mostly for relatively low partial pressures of fluid as is probably the case of our laboratory-dry rocks although the experimental zero-pore pressure is as low as 20μ of Hg and the dry samples have been thoroughly dried during 24 hours in a vacuum at 80°C.

At significant saturations (we insured total saturation as much as possible, by applying a hydrostatic pore-pressure of 100 bars), Murphy (1982) tells us that frequency dependant flow mechanisms are probably predominant. Biot (1956) suggested an oscillation of the pore walls in their plane, inducing fluid, diffuse vorticity and thereby energy dissipation, but this mechanism which predicts a strong frequency dependance centered around 10^4–10^6 Hz and Q_p<Q_s is certainly quantitatively minor compared to the fluid squirt or squish mechanism: the dissipative fluid flow is generated by a local pressure field from the compression of grain contacts and fine capillaries. Since cracks have different orientations to the passing wave or different aspect ratios, the squirt occurs when those cracks undergo a differential compression. This mechanism should cause more shear than compressional attenuation (Winkler, 1979). Accordingly, Winkler
finds fully saturated bulk attenuations greater than dry bulk attenuations. At full saturation, the bulk compression losses are smaller than the shearing losses, because shear stress provides stronger gradients between adjacent contacts or capillaries with different orientations and aspect ratios while longitudinally the compressibility of pores and thus the pore pressure gradient is small. Hence this mechanism explains $Q_S < Q_p$.

Bulau et al. (1984), confirm the existence of a viscous dissipation mechanism with a characteristic relaxation time proportional to pore fluid viscosity. The utilization of a non-polar saturating liquid, iso-octane yields significantly lower attenuation, showing that near-surface processes as surface-adsorbed molecular effects are non negligible. They measured attenuation over a wide range of frequencies and fluid viscosities, for Coconino sandstone which is similar to Navajo sandstone. A graphic representation is given of log($1000/Q$) as a function of log($f \eta$). The attenuation corresponding to our frequency range (centered around 0.8 Mhz) and to the viscosities for the pore fluids we consider, water ($\eta=1.00210^{-2}$ Poises) and benzene ($\eta=6.0210^{-2}$ Poises) are found to be respectively 23 and 28, at an effective pressure of 1000 psi (about 70 bars). Our results yield a $1000/Q$ value of 48 for benzene saturated Navajo sandstone at 75 bars. Therefore attenuation for benzene saturated Coconino sandstone appears to be greater than for the same sandstone water saturated. We do not have water saturated measurements for Navajo sandstone, but the results for the other sandstones also show a greater attenuation for benzene fluid than for water saturating fluid at the same effective pressure. A water-glycerol mixture was used as pore fluid saturant on the Coconino sandstone. A viscous dissipation mechanism with a characteristic relaxation time was used with a good agreement to describe the results. Nevertheless, with a non-polar fluid (iso-octane), the attenuation was found to be significantly lower than values predicted from simple frequency-viscosity scaling, as is the case for water-glycerol system. This was explained by the presence of near surface processes.
attenuation mechanism which also depends on partial-saturation (Mavko and Nur, 1979) may be present. This may explain the higher P-wave attenuation but not the higher S-wave attenuation, which has not been observed in partially-saturated rock at ultrasonic frequencies (Spencer, 1979; Johnston, 1978). It is clear that no single mechanism alone could explain our results, we may have to consider various contributions to attenuation, including in the case of benzene, partial saturation and presence of water in thin cracks and pores and possibly as a monolayer coating on silicates (particularly clay minerals).

The interpretation of our data raises a number of questions that need to be addressed. (1) Coyner, 1984, pointed out that the shear-modulus in the water saturated sandstones fell below the benzene-saturated values at the higher pressures. The water-saturated bulk modulus is always larger than the benzene-saturated bulk modulus. This was explained as a water "softening" of the water-saturated shear modulus which was not apparent in the water-saturated bulk-modulus. This "cross-over" feature is also observed for our attenuation data. It is prominent for Berea sandstone and Bedford limestone. The observation diverges with Coyner's remark in the sense that the cross-over is also slightly visible for P- and K-attenuations, although it is less visible than for S- and E-attenuations and it occurs at a higher effective pressure for P- and K- than for S- and E-attenuations. The same cross-over appears for the velocity data: water saturated velocities are higher than benzene saturated velocities at lower pressures, and this difference is reversed above a threshold pressure which is about the same as the cross-over pressure for shear-moduli and attenuation measurements. As for attenuation, a cross-over is also observed for P-wave velocity measurements although the phenomenon has a smaller amplitude and at higher pressures.

(2) The comparison of the attenuations for all sandstones shows that benzene saturated attenuation is higher than water-saturated attenuation in the case of
Kayenta and Weber sandstones, while for Berea sandstone as well as for Bedford limestone water- and benzene-saturated attenuation measurements yield approximately the same values.

One explanation could be that both Weber and Kayenta sandstones contain a fair amount of clays (about 15%) compared to Berea (about 5%) or Navajo sandstones (less than 1%) and Bedford limestone has no clay content. The effect of clay content on attenuation may be that clay-water interaction could result in a stiffening of the rock structure (swelling of hydratated clays) while benzene non polar molecules do not wet the clay surfaces. Another explanation is that Weber and Kayenta sandstones have much more cracks than Berea sandstone or bedford limestone: this can be seen by looking at the volume of microstrain on static stress-strain curves. The microstrain volume is not an exact measurement of an hypothetical cracks volume, it reflects more the reduction and flattening of asperities at grain contacts while pressure is increasing. Nonetheless, the volume of microstrain for the sandstones is approximately 6000 10^{-6} for Weber, 5200 10^{-6} for Kayenta, 3500 10^{-6} for Berea, 700 10^{-6} for Navajo and less than 100 10^{-6} for Bedford limestone. Benzene, due to its lower viscosity induces more attenuation than water particularly at low pressures, when the porosity due to cracks is important as is seen for Weber and Kayenta sandstones (although Weber and Kayenta sandstones have very different average grain size: 0.15 mm for Kayenta and 0.05 mm for Weber sandstone, which means that the difference in terms of permeability and hydraulic radius must be greater than just in terms of porosity, \( \phi \) for Kayenta sandstone is 22.2%, \( \phi \) for Weber sandstone is 9.5%).

(3) We also observe that fluid saturated P- and K-attenuations are less than dry P- and K-attenuations for Webatuck dolomite and Westerly granite, at lower pressures. This effect may be due to the low porosities of these rocks, respectively 0.5 and 0.8%, and consecutively their permeability must be small. Henceforth, the effect of fluid
saturation could be a crack healing effect. The elastic coupling between grains across cracks may be improved as well as the wave scattering effect may be reduced by the presence of fluid. As a matter of fact, this affects only compressional and bulk attenuations, for which the propagated wave is most likely to close cracks.

(4) We finally address the possibility of an eventual partial saturation in the case of clay rich sandstones, as an explanation for the higher attenuations observed for benzene saturation than for water-saturation as is seen for Kayenta and Weber sandstones. It is unlikely that partial saturation is responsible for this observation since S-wave attenuation is affected when it should not be as much (Frisillo and Stewart, 1980). In addition, the 100 bars pore pressure maintained along the saturated measurements should insure a complete saturation.

C. Comparison with other ultrasonic determinations.

If we compare our results for Berea sandstone with other authors, we observe: Jones and Nur, 1983, found at 220° C, fluid saturant $\eta = 0.95c$poises, $1000/\xi$ varies from 45 at 25 bars to 18 at 200 bars, for 100 and 80 at the same pressures in our measurements. Winkler, 1983, measured attenuation on a Berea sample with 20.3% porosity (our sample had 17.8% porosity), 2.65 density (2.20 for us), 150-200 $\mu$ average grain size (100 $\mu$ for us), and found brine saturated $1000/\xi$ values varying from 85 at 25 bars to 10 at 400 bars, compared to 95 and 40 at the same pressures for our data. Dry attenuations are found to be much lower (less than 20), but no numerical value is given in the frequency range where we performed our measurements. Tittman et al., 1981, measured $1000/\xi_E$ at a central frequency of 7 KHz for Berea sandstone and found, in dry conditions, 12 at 25 bars and 5 at 700 bars (against 35 and 13 for us) and under saturation 110 at 25 bars and 30 at 700 bars (against 45
and 30 for us). They conclude that attenuation caused by fluid flow is strongly frequency dependent and increases with frequency. Thus the discrepancy with our results could be explained by the much higher frequency we have been using. We can point out that, aside from the shift in absolute value between their measurements and ours, the shape and slopes of the curves (attenuation versus pressure) are very similar. At last, we compare our results with values from Spencer, 1979. Spencer computed \( \frac{1000}{Q_K} \) and \( \frac{1000}{Q_E} \) from the P- and S-attenuations obtained by Johnston, 1979, measured on Berea sandstone. The results are as follows: dry P-attenuation is slightly lower than in our case, brine saturated P-attenuation is higher. S-attenuation is identical to our results for both dry and brine saturated measurements. The results differ significantly when it comes to K-attenuation. Adversely from our results, Spencer finds saturated K-attenuations greater than dry K-attenuations. Spencer proposes the following explanations for the low (even negative) dry K-attenuations he obtains: he suggests that the drying process might have increased the defects in the adhesion between grains or that the fluid saturated core is not perfectly elastic: fluid flow increases S-attenuation but not P-attenuation as much.

We can also compare our results for Navajo with Spencer, 1981. E-attenuation \( \frac{1000}{Q_E} \) is found to be equal to 150 for dry and 130 for water saturated sample. Their conclusion is that a small amount of water can reduce the stiffness as much as full saturation: water molecules by bonding to the surface, reduce the surface free energy and thus generate frequency dependent softening in rocks. We notice that the reduction of water-saturated shear modulus so apparent in the velocity data for the sandstones is not strongly reflected in the shear attenuation. The high-pressure low P- and K-attenuations in benzene saturated Webatuck dolomite may reflect unrelaxed stresses in the fluid at ultrasonic frequencies (O’Connell and Budianny, 1977; Murphy, 1982). Crack geometry and surface interactions between water and matrix minerals
(silica, feldspar and clay versus carbonates) apparently play an important role.
<table>
<thead>
<tr>
<th></th>
<th>unit</th>
<th>benzene</th>
<th>water</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>g/cc</td>
<td>.87</td>
<td>.99</td>
</tr>
<tr>
<td>velocity</td>
<td>km/sec</td>
<td>1.295</td>
<td>1.497</td>
</tr>
<tr>
<td>viscosity(1)</td>
<td>cpoises</td>
<td>.602</td>
<td>1.002</td>
</tr>
<tr>
<td>compressibility(2)</td>
<td>Mbar$^{-1}$</td>
<td>96.70</td>
<td>45.24</td>
</tr>
<tr>
<td>bulk modulus</td>
<td>Kbar</td>
<td>12.1</td>
<td>22.3</td>
</tr>
</tbody>
</table>

(1) measured at 100 bar, 20°C
(2) measured at 1 bar, 25°C
(3) measured at 100 bars, 20°C

All other parameters are at conditions of temperature (20 C) and pressure (1 bar).
CHAPTER 5 : CONCLUSIONS

Our measurements of ultrasonic attenuation for several rocks as a function of pressure for vacuum dry, water and benzene saturated conditions confirm previous observations while raising questions concerning water versus non-aqueous pore fluid saturants. Our observations show that for the Kayenta, Berea, Weber and Navajo sandstones, benzene-saturated attenuation, in particular for P-wave, is larger than water-saturated attenuation. For the S-wave the same relationship holds although the differences are less. In addition, as pressure increases the differences decrease. Crack geometry and surface interactions between water and matrix minerals (quartz, feldspar, clay, and carbonates) may play an important role in how fluids affect attenuation. The fluid properties are also essential: viscosity is a determinant factor for the fluid flow and fluid squirt mechanisms, molecular electrical properties may have a great contribution to attenuation relatively to the wetting capacity, grain surface softening and full or partial saturation of cracks and pores. In this respect, even under petroleum saturation, we can suspect that some residual water occupying large aspect ratio pores and cracks and adsorbed on minerals, still plays a major role towards attenuation.
References


Blair, D.P., 1982, Measurement of rise times of seismic pulses in rock, Geophysics, 47, 1047-1058


Blair, D.P., 1984, Rise time of attenuated seismic pulses detected in both empty and fluid-filled cylindrical boreholes, Geophysics, 49, 398-410


Budiansky, B., Sumner, E.E., Jr., O'Connell, R.J., Bulk thermoelastic attenuation of composite materials, J. Geophys. Res., 89, 10343-10348


Kjartanson E., 1979, Constant Q-wave propagation and attenuation, J. Geophys. Res., 84, 4737-4743


Savage, J.C. and Hasegawa, H.S., 1967, Evidence for a linear attenuation mechanism: Geophysics, 6, 1003-1014

-46-


Spencer, T.W., Sonnad, J.R., Butler, T.M., 1982, Seismic Q- stratigraphy or dissipation, Geophysics, 47, 16-24


FIGURE CAPTIONS

Figure 1: Experimental apparatus used to measure the velocities and record the waveforms for the aluminum standard and the rock samples, with variable confining pressure and pore pressure.

The next four figures represent examples of recorded waveforms.

Figure 2: P- and S-wave signals transmitted through Kayenta sandstone at 100 bars net confining pressure for dry, benzene and water-saturations.

Figure 3: P- and S-wave signals transmitted through Kayenta sandstone at 500 bars net confining pressure for dry, benzene and water-saturations.

Figure 4: P- and S-wave signals transmitted through Berea sandstone at 100 bars net confining pressure for dry, benzene and water-saturations.

Figure 5: P- and S-wave signals transmitted through Westerly granite at 100 bars net confining pressure for dry, benzene and water-saturations.

Figure 6: Spectral ratio (long-short dash) with amplitude spectra for aluminum (dashed line) and vacuum dry Kayenta sandstone (solid line) at 500 bars confining pressure.

The next 49 figures consist in a series of measurements for the 7 rocks studied. For each rock the results are presented in this order:
- Poisson's ratio as a function of net confining pressure, for dry, water* and benzene-saturations.
- P-wave attenuation measurements versus confining pressure compared between spectral ratio (sr) and rise time (rt) techniques, for dry, water* and benzene-saturations.
- S-wave attenuation measurements versus confining pressure compared between spectral ratio (sr) and rise time (rt) techniques, for dry, water* and benzene-saturations.

- P-wave attenuation measurements versus confining pressure from spectral ratio technique, for dry, water* and benzene saturations.

- P-wave attenuation measurements versus confining pressure from spectral ratio technique, for dry, water* and benzene saturations.

- S-wave attenuation measurements versus confining pressure from spectral ratio technique, for dry, water* and benzene saturations.

- K-attenuation measurements versus confining pressure from spectral ratio technique, for dry, water* and benzene saturations.

- E-attenuation measurements versus confining pressure from spectral ratio technique, for dry, water* and benzene saturations.

* Water saturation has not been measured for Navajo sandstone and for Webatuck dolomite.

Figures 7 to 13: Previously indicated measurements for Weber sandstone.

Figures 14 to 20: Previously indicated measurements for Navajo sandstone.

Figures 21 to 27: Previously indicated measurements for Berea sandstone.

Figures 28 to 34: Previously indicated measurements for Kayenta sandstone.

Figures 35 to 41: Previously indicated measurements for Bedford limestone.

Figures 42 to 48: Previously indicated measurements for Webatuck dolomite.

Figures 49 to 55: Previously indicated measurements for Westerly granite.
In the next six figures the P- and S-attenuations measurements versus confining pressure are compared between the four sandstones for the saturations available.

**Figure 56:** Dry P-wave attenuation for the four sandstones.

**Figure 57:** Dry S-wave attenuation for the four sandstones.

**Figure 58:** Water saturated P-wave attenuation for three sandstones.

**Figure 59:** Water saturated S-wave attenuation for three sandstones.

**Figure 60:** Benzene saturated P-wave attenuation for the four sandstones.

**Figure 61:** Benzene saturated S-wave attenuation for the four sandstones.
Figure 1.
KAYENTA SANDSTONE (100 bars)

Figure 2.
Figure 3.
BEREA SANDSTONE (100 bars)

Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8.
Figure 9.
Figure 10.
Weber Sandstone

- Benzene
- Water
- Dry

Figure 11.
Figure 12.

Weber Sandstone

□ Benzene
○ Water
△ Dry
Weber Sandstone

- Benzene
- Water
- Dry

Figure 13.
Figure 14.
Figure 15.

Navajo Sandstone

- Benz. SR, RT
- Dry SR, RT

Attenuation, 1000/QP

Pressure, MPa
Figure 16.
Figure 17.
Figure 18.
Figure 19.

Navajo Sandstone

- Benzene
- Dry

Attenuation, 1000/OK

Pressure, MPa
Figure 20.

-70-
Berea Sandstone

- Benzene
- Water
- Dry

Poisson's ratio

Pressure, MPa

Figure 21.
Figure 22.
Figure 23.
Figure 24.
Figure 25.
Figure 26.

Pressure, MPa

Attenuation, 1000/°K

Berea Sandstone

- Benzene
- Water
- Dry
Figure 27.
Figure 28.
Figure 29.

Kayenta Sandstone

- Benz. sr&rt
- Water sr&rt
- Dry sr&rt

Attenuation, 1000/\alpha p

Pressure, MPa
Figure 30.
Figure 31.
Figure 32.
Figure 33.

Attenuation, 1000/\Omega_k

Pressure, MPa

Kayenta Sandstone

- Benzene
- Water
- Dry
Figure 34.
Figure 35.
Bedford Limestone

- Benz. sr&rt
- Water sr&rt
- Dry sr&rt

Figure 38.
Figure 37.
Figure 39.
Figure 40.
Figure 41.
Figure 42.
Figure 43.
Figure 44.
Figure 45.
Figure 46.
Figure 47.
Figure 48.
Figure 49.

Pressure, MPa

0.0  0.1  0.2  0.3  0.4  0.5

Poisson's ratio

Dry
Water
Benzene
Granite
Westley
Westerly Granite

- Benz. sr&rt
- Water sr&rt
- Dry sr&rt

Figure 50.
Figure 51.
Figure 52.
Figure 53.

Pressure, MPa

Attenuation, 1000/ΩS

- Westerly Granite
- Benzene
- Water
- Dry
Westerly Granite

- Benzene
- Water
- Dry

Figure 55.
Figure 56.
Figure 57.
Figure 58.
Figure 59.
Figure 60.
Figure 61.