Seismic Attenuation Problem

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Statement of the problem: A subsurface reservoir full of hydrocarbons tends to be acoustically softer than if it is full of an incompressible fluid such as water. Theoretical models of seismic wave attenuation predict that a wave passing though such a reservoir should suffer more attenuation than in surrounding materials. It is proposed that this anomalously high attenuation can be detected in seismic data and used as an indicator of the presence of a hydrocarbon reservoir. The question at hand is: What reliable measure, made upon seismic reflection data, can be developed that indicates anomalous attenuation?

Background: A seismic wave loses energy as it propagates through the earth. The primary mechanisms are spherical divergence, scattering, and intrinsic attenuation. Spherical divergence is independent of frequency and a correction is commonly applied to seismic data. Scattering results from multiples that lag the primary seismic energy and tend to cause some cancellation of primary energy. This attenuation is frequency dependent and is difficult to separate from intrinsic attenuation. However intrinsic attenuation appears to dominate scattering attenuation. Intrinsic attenuation is energy loss due to friction. Grain to grain friction in sedimentary rock causes some attenuation. The major source of intrinsic attenuation in porous rocks such as sand, shale or carbonate occurs when motion of the rock and the fluid in the pores becomes uncoupled. The rock becomes anelastic as energy is lost due to fluid friction. The fluid motion is caused by pressure equilibration as the seismic wave passes through the rock (Pride et al 2003).

Knowledge of attenuation can be very useful in seismic data processing, as its removal increases resolution. But perhaps its greatest potential lies as a direct hydrocarbon indicator. Attenuation depends on fluid mobility (Batzle et al 2003, Kumar et al 2003). Fluid mobility depends on the viscosity and bulk modulus of the pore fluid, and the permeability of the rock. If the pore space is completely filled with fluid, the fluid has less mobility than if there is some gas saturation. It has been shown that attenuation is highest in a partially fluid saturated rock (Kumar et al 2003, Winkler and Nur (1982). Pride et al (2003) give a good overview of attenuation mechanisms and discuss the possibility of extracting information about the permeability of the rock. Pride and Berryman (2003) give a more detailed theoretical description of attenuation mechanisms.

Measurements of the loss Q are often made at a well using Vertical Seismic Profiles (VSP). Receivers record the seismic wavelet at many depths in the well. Q can be derived for the interval between two depths by using the spectral ratio of the amplitude spectra at the two depths. Quan and Harris (1997) used the decrease in average frequency as a seismic wave is attenuated to calculate Q. Much of our knowledge of attenuation comes from laboratory measurements (Kumar et al 2003). Attempts to extract attenuation from seismic data recorded at the surface have met with little success. A major stumbling block is that the amplitude spectrum of the seismic record contains the imprint of the amplitude spectrum of the earth's reflectivity as well as the amplitude spectrum of the seismic wavelet. Separation of the two spectra is difficult. Dilay et al (1995) observed changes in the amplitude spectra below a sand that was undergoing steam flood for enhanced oil recovery. Mitchell et al (1996) fit an exponential function to the amplitude spectra of several short time windows of the seismic data and compared the rate of decay of the spectra to measure attenuation in a gas filled sand. Dasgupta and Clark (1998) compared the rate of amplitude decay at 2 levels on pre-stack gathers to estimate Q. Hedlin et al (2001) observed an increase in attenuation (an anomalous decrease in average frequency) below an oil sand undergoing steam flood.

The ability to extract accurate values of attenuation or changes in attenuation using relatively short windows of seismic data could be very helpful in our search for gas reservoirs.

Theoretical Model (1D): The simplest possible case of interest is when the geological layers are all horizontal and the source and receiver are effectively coincident (Figure 1). The reservoir is idealized as a stratigraphic change from "regional" to "prospective". Let the source/receiver be initially at the coordinate origin. When the source/receiver pair is at a particular position, the resulting seismic recording is a digital time series called a "trace". Moving the source/receiver pair laterally, i.e. at constant z, to all points on a regular lattice acquires a seismic "section".

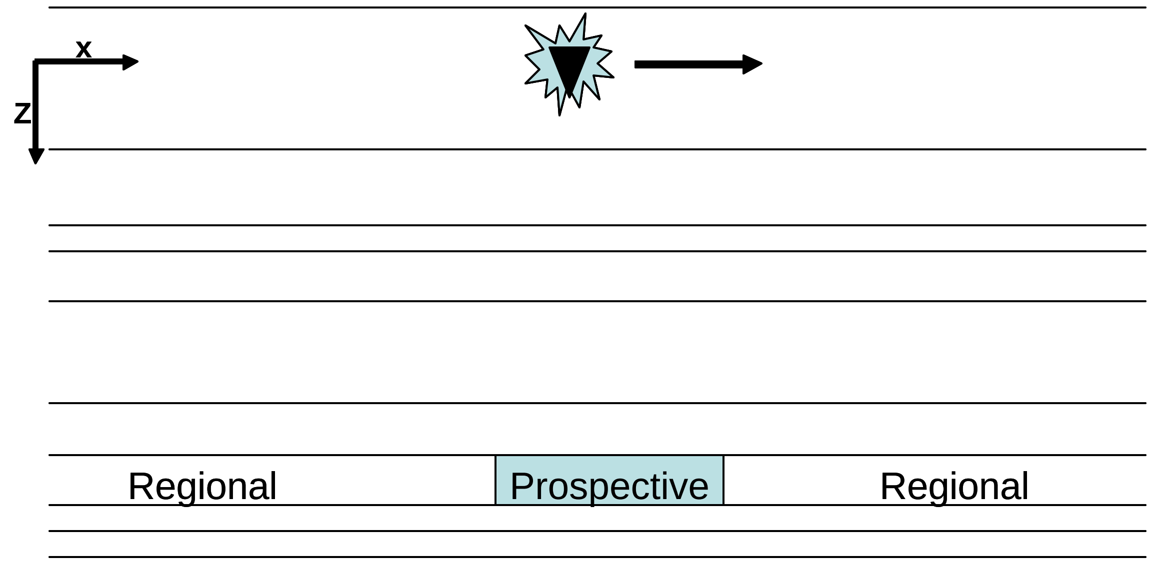

Figure 1. A horizontally layered geologic system is shown with a hydrocarbon reservoir denoted by “prospective” occurring as a change of properties within a layer. A coincident source/receiver are shown in the upper layer. A “zero offset” seismic survey is acquired by move the source/receiver pair in the direction of the arrow and recording a signal at regular intervals.

Though all rocks propagate seismic waves with some attenuation, the reservoir is assumed to be dramatically more “lossy” than is typical. The ability of a rock to attenuate seismic waves is usually measured by a dimensionless quantity called Q. Physically, Q is defined as the ratio of a waves energy to the energy dissipated per cycle of oscillation. If follows that a lossless material has a Q of infinity while a completely lossy material has a Q of zero. Rocks are found to have Q values in the range 10-400 with the typical sedimentary rock having a value near 100. The reservoir in question may have a Q of between 20 and 40 and be of the order of 20 meters thick.

There are many mathematical models of Q attenuation but most have a similar approximate behaviour. If $s_k(t)$ is the reflected waveform from the reflector at depth $z = z_k$ and recorded at $z = 0$, then the prediction is

$$\left|\widehat{s_k}\right| = r_k \left|\widehat{s_0}\right| e^{-2p f z_k / vQ} \tag{1}$$

where the “hat” denotes the Fourier transform from $t \to f$, v is the speed of the propagation of the seismic wave at frequency f, r_k is the reflection coefficient, and s_0 is the waveform emitted by the source. Though it turns out that v must depend upon frequency (dispersion) if we assume that it is approximately constant, then $2z_k / v = t_k$ and so we expect

$$\left|\widehat{s_k}\right| = r_k \left|\widehat{s_0}\right| e^{-p f t_k / Q}. \tag{2}$$

Of course, a seismic record contains a superposition of reflections from a great many impedance contrasts that will overlap temporally with one another. However, suppose we are lucky and can isolate the waveform for kth reflection from all others and similarly for another reflection from $z = z_j$. Then, the spectral ratio method estimates Q as follows:

$$a(f) = \ln\left|\widehat{s_k}\right| - \ln\left|\widehat{s_j}\right| = r_k - r_j + p f\left(t_j - t_k\right)/Q. \tag{3}$$

Thus the logarithm of the ratio of the spectra of the two reflected wavelets is predicted to be a linear function of frequency whose slope will estimate Q. In particular, if reflection k is from the top of the reservoir and reflection j is from the bottom, then we might hope by this method to estimate the Q value of the reservoir.

In practice, there are many difficulties with this method. First, it is never possible to isolate two reflections from all others. The complex superposition of many reflections in any temporal window means that there may be zeros in the magnitude spectra even if $\left|\widehat{s_0}\right|$ is everywhere positive. Also, temporal localization by windowing means that the spectral are convolved with the Fourier transform of the window. This introduces a bas as well as possible zeros. Furthermore, one cannot expect the linear relation in equation (3) to hold for all measured frequencies simply because of random noise and finite precision measurements. Even if the source radiates significant power at all measured frequencies, the exponential decay predicted by equation (2) will always drive some range of higher frequencies below the noise level. Finally, the reservoir will generally be quite thin so that the traveltime difference found in equation (3) will be small. These effects combine to have a severe degradation upon the ability to estimate Q by this method.

Possible Approaches: Perhaps the spectral ratio method can be improved though better estimation of the local spectra. Alternatively, perhaps there is some other attenuation measure, rather than Q, that can be more reliably estimated. Even if it is impractical to achieve an absolute measure, perhaps a relative measure that compares traces at the same stratigraphic level is possible.

Problem: To extract attenuation from seismic data.

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