Estimating Compressibility from Seismic Data

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Abstract

Seismic techniques can be used to generate elastic rock parameters of interest in engineering applications. For example, compressibility of the reservoir and surrounding rock is estimated from seismic data using amplitude inversion of the results of AVO (Amplitude Versus Offset) analysis. An example of the application of this technology is shown for a carbonate pinnacle reef reservoir in central Alberta, Canada.

Introduction

Engineering applications frequently require information about the elastic properties of the reservoir and surrounding rocks. Geophysicists routinely generate information about these properties during seismic processing. However, the terminology used by the two disciplines is different and so each may be unaware of the possible benefits to be derived from the other. Geophysicists use seismic velocities to stack and migrate seismic data and they gather information about the shear wave properties of the rocks through AVO (Amplitude Versus Offset) analysis. Through simple mathematical operations (e.g. Wang and Nur, 1992) the seismic velocities and shear wave properties can be converted to parameters of interest to engineers, such as compressibility, Young's modulus and Poisson's ratio. This paper shows an example of such a conversion for a Devonian pinnacle reef reservoir in Alberta, Canada. In this case, compressibility is estimated by an AVO analysis of pre-stack seismic data followed by an amplitude inversion of the AVO result. This methodology can be extended to the estimation of other elastic rock properties of interest in engineering studies.

Theory

Gray et al's (1999) AVO Equation 1 describes how to estimate the reflectivity of the bulk modulus or "incompressibility reflectivity" from seismic data. This equation can be recast to estimate the "compressibility reflectivity". The recast equation is shown below as Equation 1, where C is compressibility, μ is rigidity, ρ is density, α is compressional-wave velocity and β is shear-wave velocity. The symbol Δ indicates a differencing operator, (i.e. $\Delta C_i = C_i - C_{i-1}$), and the bar indicates an averaging operator, (i.e. $\overline{C} = \dfrac{C_i + C_{i-1}}{2}$).

$$R(\theta) = \left(-\frac{1}{4} + \frac{1}{3}\frac{\overline{\beta}^2}{\overline{\alpha}^2}\right)\left(\sec^2\theta\right)\frac{\Delta C}{\overline{C}} + \left(\frac{\overline{\beta}^2}{\overline{\alpha}^2}\right)\left(\frac{1}{3}\sec^2\theta - 2\sin^2\theta\right)\frac{\Delta\mu}{\overline{\mu}} + \left(\frac{1}{2} - \frac{1}{4}\sec^2\theta\right)\frac{\Delta\rho}{\overline{\rho}} \qquad (1)$$

Gray (2002) showed how to convert these estimates of the contrast (reflectivity) of the elastic properties into estimates of the actual elastic properties of the rock. This same methodology can be applied to estimate compressibility, C, from the compressibility reflectivity, $\Delta C/C$, estimated using Equation 1. Applying a post-stack amplitude inversion technique (e.g. Lindseth, 1979) to the compressibility reflectivity results in an estimate of compressibility. The output of the inversion is an estimate of the total compressibility of the earth at every sample in the seismic volume. For example, following Lindseth's formulation, where the i^th reflectivity value, $r_i = \Delta C_i/C_i$, then the i^th compressibility value, C_i, can be estimated iteratively by:

$$C_i = C_{i-1}\frac{1 + r_i}{1 - r_i} \qquad (2)$$

There are many post-stack amplitude inversion methods available (e.g. Russell and Hampson, 1991) and most of these can be used as an alternative to the method suggested here.

Example

An example is shown of a Devonian Reef located at Erskine, Alberta, Canada. This reef is a now-depleted oil reservoir that produced a total of 36000 m^3 of oil between 1968 and 1992. Veritas acquired a 3D seismic survey over part of this reef complex in 1983. These seismic data are employed here to estimate the compressibility of the reservoir rocks. Anderson and Gray (2001) interpreted these data and showed that the seismically-derived elastic properties of the rock are useful in identification of these Devonian reefs.

The reflectivity of the compressibility along a line that passes through two pinnacle reefs and close to two wells is shown in Figure 1. This reflectivity of the compressibility is inverted using a model-based inversion available in off-the-shelf post-stack inversion software (Russell and Hampson, 1991) and the result is an estimate of the compressibility of the entire section, including the reservoir (Figure 2). The reflectivity of the compressibility is calculated using AVO through a least-squares fit of the pre-stack data (Figure 3) to Equation 1.

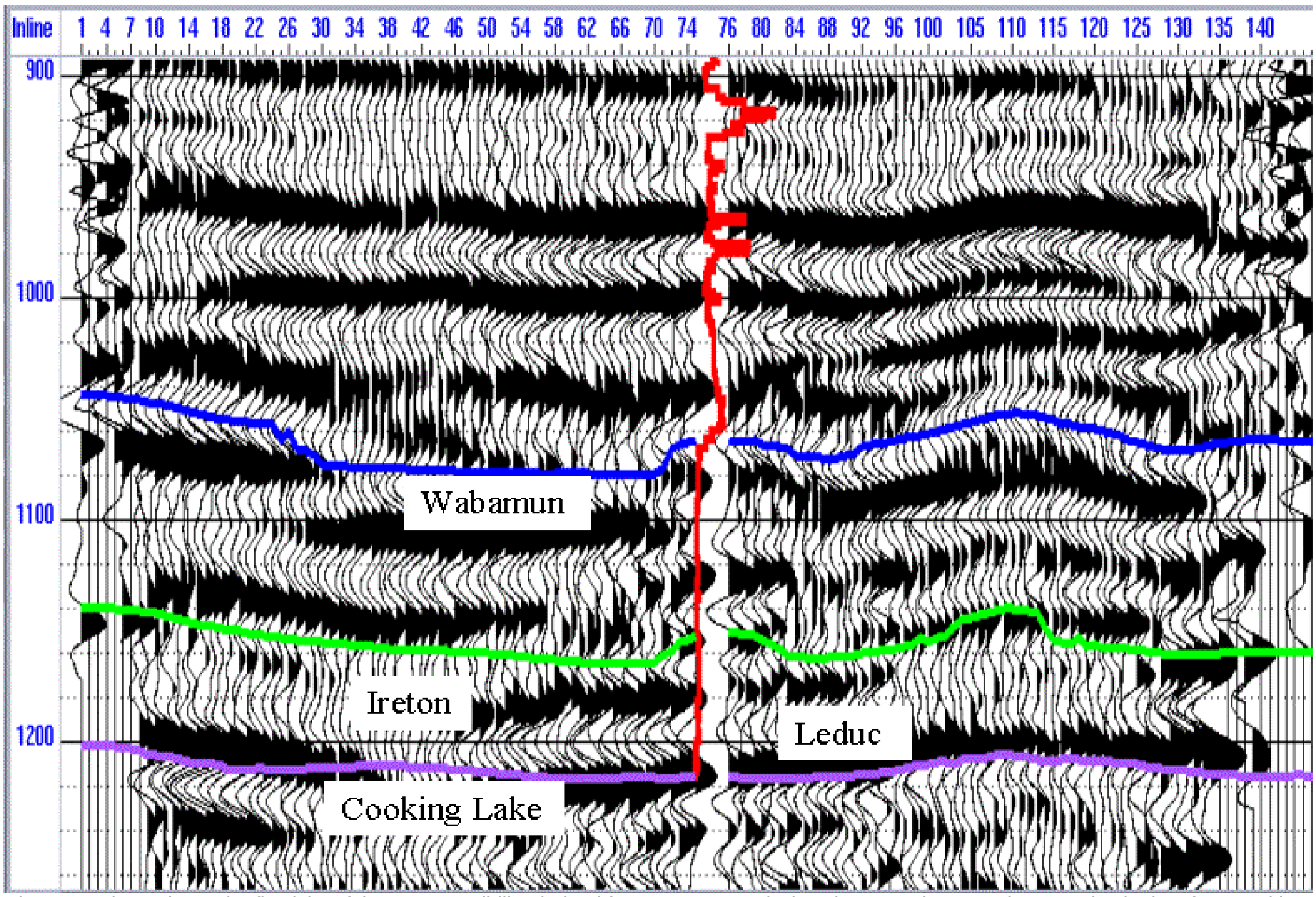

Figure 1: The estimated reflectivity of the compressibility derived from an AVO analysis using Equation 1 on the 3D seismic data from Erskine, Alberta. The reservoir is a Devonian-age Leduc pinnacle reef that sits on the Cooking Lake carbonate platform.

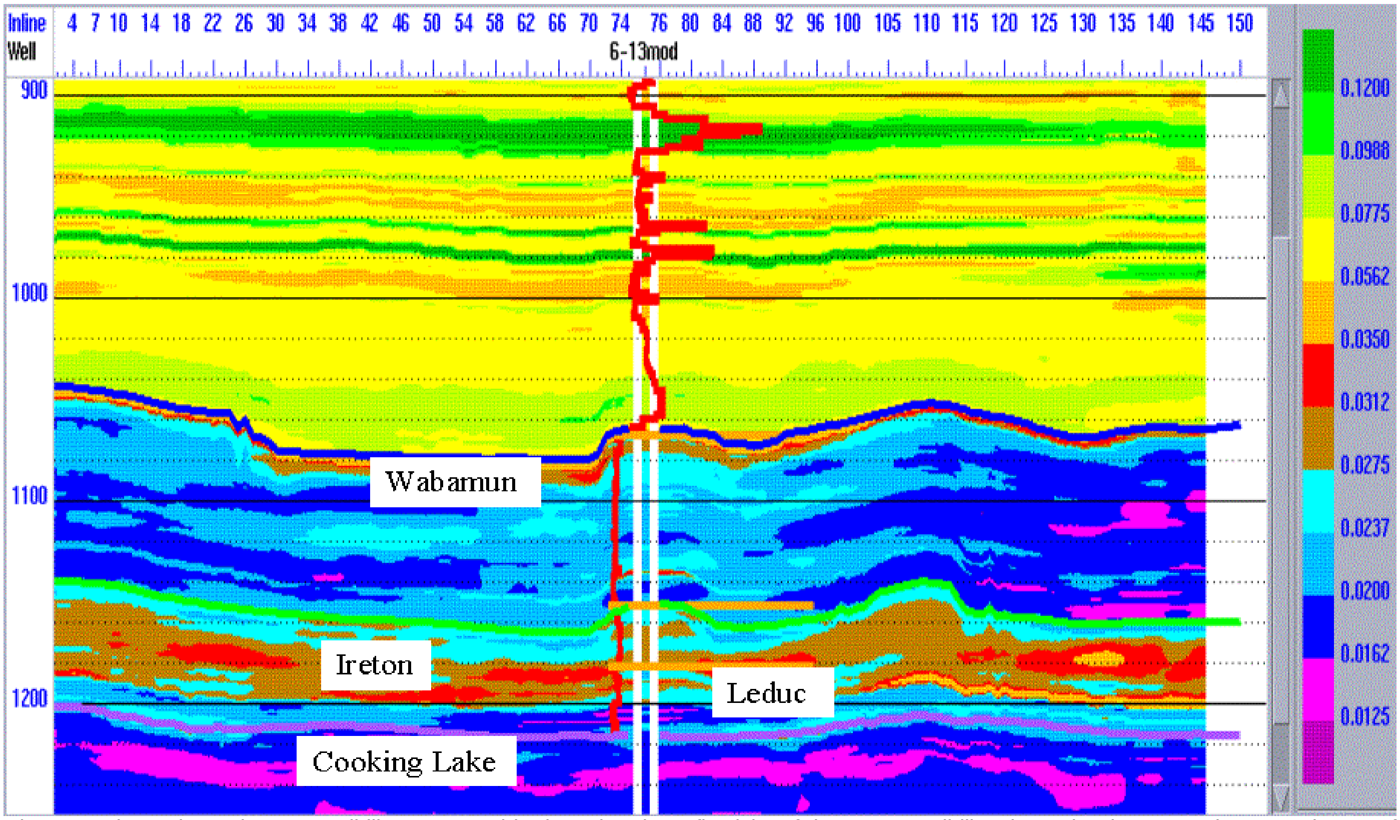

Figure 2: The estimated compressibility generated by inverting the reflectivity of the compressibility shown in Figure 1. The Devonian Reef (Leduc top to end of well) shows lower compressibility (blue) than the surrounding shales of the Ireton (brown). Note that the compressibility of the entire section is estimated, both above and below the reservoir.

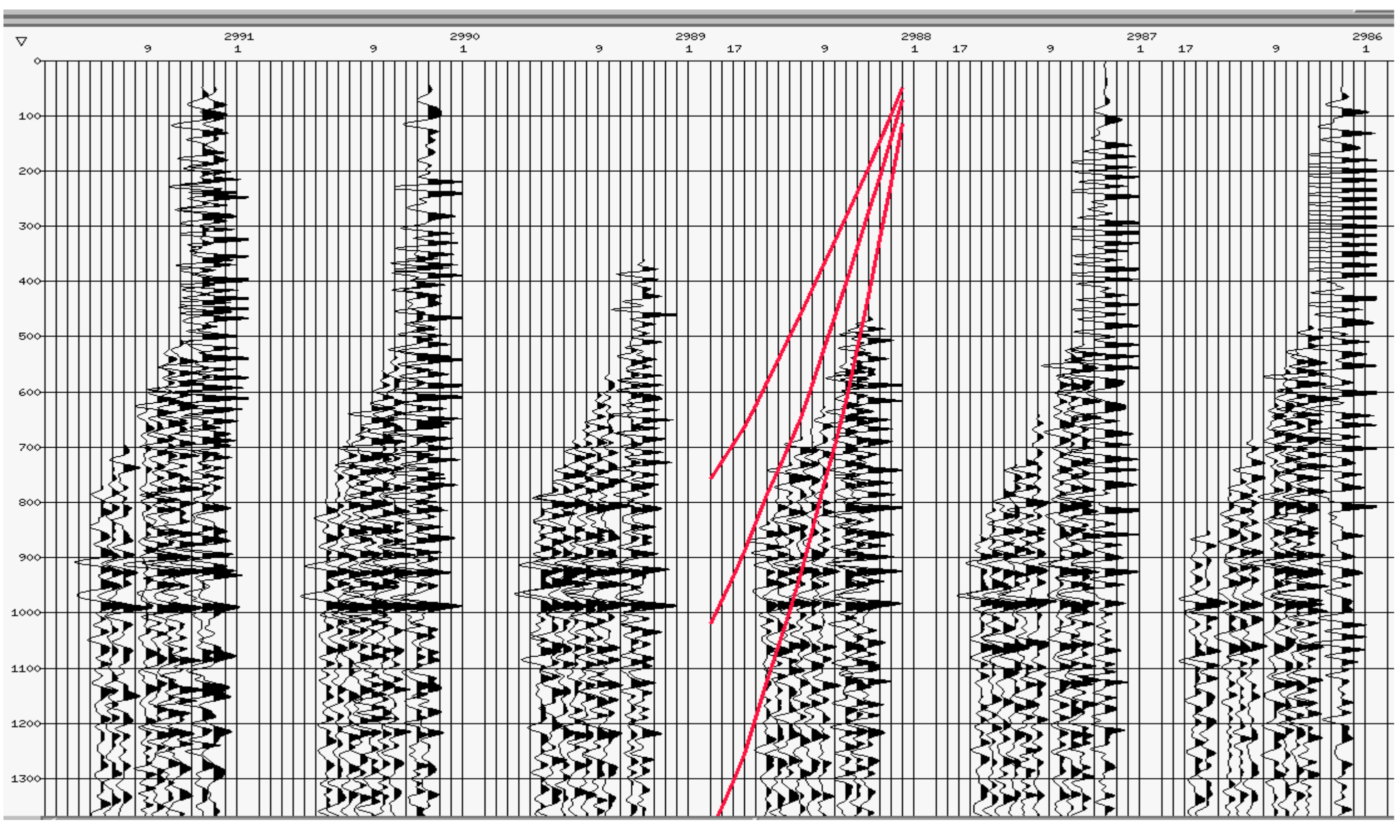

Figure 3: The pre-stack seismic data used in the AVO analysis to generate the reflectivity of compressibility shown in Figure 1. The top of the Devonian Reef is at 1180 ms and its base at 1210 ms.

Discussion

Compressibility is a value that is useful in engineering applications, for example, volumetric estimation in black oil reservoirs (Cronquist, 2001). The method described in this paper shows how it can be determined using seismic data via a slight variation of the commonly used techniques of AVO and amplitude inversion. The compressibility so generated is "total compressibility" and as such represents the combined compressibility of the rock-fluid system. This result is still largely limited by the narrow bandwidth of the seismic data and the post-stack amplitude inversion and so is best done in the seismic time domain in order to ensure stability of the seismic wavelet. However, these limitations can be overcome. Subsequent depth conversion moves the compressibility volume into the depth domain. Stochastic methods, such as sequential Gaussian simulation, using the seismically-derived compressibility volume as a soft constraint, can generate realizations of compressibility of sufficient vertical resolution for use in a reservoir simulator (Gutteridge, 2004).

Conclusions

The Devonian Reef example shows that compressibility can be derived from seismic data using a slight modification of common seismic techniques: AVO and inversion. This method produces compressibility throughout the section. It is calculated in the reservoir, in the overburden and below the reservoir. This ability to estimate compressibility from seismic data throughout the section has important ramifications in better describing reservoir models between well locations, which should allow for improved estimates of the volume of oil in reservoirs.

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