Effects of pore structure on 4D seismic signals in carbonate reservoirs

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Summary
Carbonate reservoir rocks of different pore structure have quite distinct and detectable 4D seismic signatures. Using three defined pore structure types (PST), these seismic signatures are correlated with the permeability patterns of carbonate rocks. In both the high-permeability PST3 and intermediate-permeability PST2 regions, gas injection is preferred than water injection for effective 4D seismic monitoring. In the low-permeability PST1 region where lies most of the bypassed oil, both gas and water injection options result in similar 4D seismic signal magnitude. Fluid saturation changes under in-situ reservoir conditions can be better detected by offset domain 4D seismic analysis.

Introduction
4D or time lapse seismic has proven to be a successful method for siliciclastic reservoirs (e.g., Anderson et al., 1996; Mehdizadeh et al., 2005). It has been used to monitor reservoir fluid saturation and pressure changes due to production. Khazanehdari et al. (2005) reported that impedance change as low as 2% can be detected and related to saturation and pressure variation using high-resolution 4D seismic surveys. Efforts have also been made to separate the effect of saturation on seismic signals from that due to pressure change. Recently a successful 4D seismic pilot study has been reported for a carbonate field (Soroka et al., 2005). The report by Soroka et al. is indeed encouraging amid debates over the applicability of 4D seismic to carbonate reservoirs. Carbonate rocks hold about 60% of world hydrocarbon reserves. It is thus important to develop accurate geophysical methods such as 4D seismic to optimize field production of carbonate reservoirs, including short-term and long-term design of injection and production strategy.

Different from siliciclastic rocks, carbonate rocks have inherent internal structures, due to their sensitivity to chemical reactions and their history of diverse depositional environments, evolution and diagenesis. Many methods of seismic inversion and 4D rock physics modeling have been developed for sandstone reservoirs. Caution should be therefore exercised when applying these methods to carbonate reservoir rocks. One parameter porosity-velocity model that is used to average sonic log data should be avoided. For it is the “scatters” that represent the different acoustic signatures of water pathways and bypassed oil zones that 4D seismic is to resolve. In this report, we illustrate that pore structure can be one of the major factors affecting elastic wave velocities and 4D seismic signals in carbonate reservoir rocks.

Effects of pore structure on elastic wave velocities in carbonates
There are many factors that contribute to the observed seismic signals, including source and receiver parameters. Seismic attenuation in onshore weathering zones or offshore unconsolidated marine sediments cannot be neglected. Physical coupling of source and receiver to subsurface rock is an important factor to improve the signal quality. Assuming an excellent repeatability of seismic acquisition and processing parameters, differential seismic signals of elapsed surveys can then be attributed to reservoir property changes. An accurate and quantitative interpretation of 4D seismic signals, however, needs a rock physics model that is valid for the reservoir rocks.

Many rock physics models including Biot-Gassmann model and its extensions can be used for relatively homogeneous sandstone reservoir rocks. They nevertheless may need modifications in order to be applicable to carbonate rocks. This is due to the internal pore structures unique in carbonate rocks that are far more complicated than in siliciclastic rocks. For many carbonate reservoirs that are now in production, porosity usually ranges from 15% to more than 30%. They however exhibit amazing complexity of pore structures where pore shape, pore size, pore and matrix connectivity strongly affect the elasticity of the rock and the hydrodynamics of reservoir fluids. Although there are only a few theoretical models that explicitly consider these internal structures of carbonate rocks, models such as Biot-Gassmann model combined with Kuster-Toksoz model or Berryman model can be practically adjusted, to certain extent, as an approximation. In short, the effects of pore structures on elastic moduli and attenuation should be considered either explicitly or effectively in any rock physics model used for 4D seismic analysis.

For a given reservoir porosity (~20-25%), permeability can span more than four orders of magnitude. Due to difference in depositional environment and diagenesis, zones of different permeability in a carbonate field usually have a good spatial separation (Soroka et al., 2005). Recent studies in carbonate rock physics indicate that carbonate pore structures do have detectable acoustic signatures on core, log and seismic scales (e.g., Anselmetti and Eberli, 1993; Sun et al., 2002; Tsuneyama et al., 2003). For two rocks of the same mineralogy, porosity and saturation, acoustic
Carbonate pore structure and 4D seismic

wave velocity can differ by more than 2 km/s only as a result of differences in pore structure and pore size (Figure 1; see also Eberli et al., 2003). Sun (2004) defined three elastic pore structure types (PST 1, 2, and 3) corresponding to three regimes of low, intermediate, and high permeability, respectively as indicated in Figure 1. It is concluded that AVO interpretation aimed at fluid detection can be complicated where the presence of large pore structure variations on seismic scale is expected, because the effects of pore structure on wave propagation in carbonate rocks can be much stronger than the fluid saturation factor. Bracco Gartner et al. (2005) recently reported a successful field test of an innovative seismic inversion method of assessing permeability from seismic data, considering explicitly the effect of pore structure and pore connectivity on elastic wave velocities.

In this report, we use a simple model applicable to carbonate rocks to study the 4D seismic response of fluid changes in a reservoir of constant porosity but different pore structure and different permeability (Sun et al., 2002; Sun, 2004). As indicated in Figures 1, the \( \gamma \) factor in this model is a parameter used to characterize the effect of pore shape and pore size, grain coupling and pore and matrix connectivity on the elasticity of a porous carbonate rock. The \( \gamma \) factor is inversely related to pore aspect ratio and pore size. It can also be expressed by using other models through solving appropriate constitutive equations.

Using this model and the ultrasonic laboratory data on elastic wave velocities under various pressure and saturation conditions, wave velocities at seismic frequency can be approximated. Table 1 lists the reservoir rock parameters used in this 4D study that have been corrected for in-situ reservoir conditions. The shale layer has a density of 2.06 g/cc, P-wave velocity of 2.73 km/s and S-wave velocity of 1.39 km/s.

**AVO and 4D seismic modeling**

For simplicity, we use a two-layer model consisting of a shale layer overlying an oil limestone reservoir with a porosity of 26%. We further consider three separate regions of the reservoir that have three pore structure types PST1, PST2, and PST3, respectively. In each region, we investigate both gas and water injection options. We thus have 9 model cases as given in Table 1.

This hypothetical model could have a possible field application where a carbonate field has high-permeability region near the crest (PST3), a relatively low-permeability flank (PST1) and an intermediate-permeability zone in between (PST2). For each of the 9 model cases, we calculate the seismic reflection coefficients (RC) versus incident angle by solving the full Zoeppritz equation. Figure 2 shows the computed RC versus the incident angles for these 9 scenarios. Regardless of the injection options or fluid saturation, the AVO signatures of PST3 and PST2 have a nice separation in the occurrence of their critical angles. The high permeable layer (PST3) has a critical angle ranging from 35° to 40°, whereas the intermediate permeability region has a critical angle ranging from 40° to 50°. For the low permeability region (PST1) where the bypassed hydrocarbon lies, critical reflection occurs where incident angle is greater than 50° and less than 60°. If the bypassed hydrocarbon is completely swept out of the PST1 region by brine, the critical seismic reflection could occur at a smaller incident angle of about 46°. These results are similar to those given by Sun (2004) for a carbonate field of a younger depositional age. The latter shows a much larger separation in the AVO “spectrum” between the three permeability zones.

We further convolve the RC in each of the 9 model cases with a Ricker wavelet of a dominant frequency of 25 Hz, to obtain synthetic seismic offset data as shown in Figure 3. For example, in the case of PST3 and Gas Injection scenario, the offset data for the oil reservoir are obtained from the shale/O3 model and the data for the fluid replacement (gas in this case) are from the shale/G3 model, assuming 100% fluid replacement of oil by gas for simplicity. The data shown as “4D difference” are a simple difference between the two data sets (fluid replacement model – oil reservoir model). Consistent with the quantitative estimates given in Table 1, these offset domain data show that the fluid saturation changes in carbonate reservoirs under in-situ conditions do produce 4D seismic signatures detectable using present 4D seismic acquisition and processing technology. In both the high-permeability PST3 and intermediate-permeability PST2 regions, gas injection option could be preferred than water injection. In the low-permeability PST1 region that holds most of the bypassed oil, both gas and water injection produce similar 4D seismic signal magnitude but opposite polarity.

**Concluding remarks**

Unlike siliciclastic rocks, carbonate rocks have complicated internal pore structures that cannot be neglected in any rock physics model to be used for 4D seismic analysis. Carbonate reservoir rocks of different pore structure produce quite distinct and detectable 4D seismic signatures. These seismic signatures are correlated with the permeability patterns of carbonate rocks. Offset domain 3D seismic analysis should be conducted to determine the permeability structures of a carbonate field first. Different injection options can be used in different permeability regions for effective 4D seismic monitoring. High-permeability region near the crest of a field prefers gas injection whereas both gas and water injection options are seismically effective in low-permeability areas of the field.
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High-resolution offset domain 4D seismic analysis can then be used to detect the sweep efficiency and to locate the bypassed hydrocarbon in a carbonate field.

References


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Table 1. Input physical parameters for offset 4D seismic modeling of limestone reservoirs

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<th>Reservoir layer</th>
<th>PST</th>
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<th>ρ g/cc</th>
<th>Vp km/s</th>
<th>Vs km/s</th>
<th>Al 10^6 kg/sm²</th>
<th>SI 10^6 kg/sm²</th>
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Figure 3. AVO and 4D seismic modeling showing relative intensity of differential 4D signals from limestone oil reservoirs of constant porosity but different pore structure (PST1, 2, and 3), underlying a shale layer, in different injection scenarios.