Seismic signature of reservoir recovery processes

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Summary

Recovery processes are complex and usually oversimplified in geophysics. Time lapse seismic monitoring of these different processes will often be complicated and lead to conflicting interpretations. Pressure, temperature, or density changes can out weigh effects due to fluid replacement. Small concentrations of free gas can appear even during liquid or supercritical injection and will lower velocities unexpectedly. Fluid compositional and phase analysis can help predict the seismic response.

Introduction

Time lapse, or 4-D, seismic monitoring is becoming an increasingly important reservoir engineering tool. To be effective, we must understand the physical processes involved with different engineering techniques. These techniques should be modeled specifically for their seismic response since general engineering analysis may overlook important features, such as small concentrations of free gas.

In Table 1, the effect of various oil or gas production operations on reservoir conditions and seismic properties

PROCESS DESCRIPTION	EFFECT ON RESERVOIR CONDITIONS	EFFECT ON SEISMIC PROPERTIES
Primary Depletion with Weak Aquifer	Decrease pore pressure, increase effective pressure; Uniform increase in gas saturation when reservoir pressure falls below bubble point; Gas segregation upward if saturation exceeds critical value; Water saturation relatively constant	Initial velocity increase with increasing effective pressure, decrease in velocity and density as free gas phase forms
Primary Depletion with Strong Aquifer	Pore pressure and effective pressure relatively constant; If pressure remains above bubble point, no gas saturation; Increasing water saturation	Velocity and density increase as water saturation increases
Water Flood of Formation with Weak Aquifer	Increase pore pressure, decrease effective pressure; Decreasing gas saturation spreading from injectors; Increase water saturation	Increasing velocity and density with increased water saturation and loss of gas. Possible velocity decrease near injector.
Pressure Maintenance with Gas	Pore pressure and effective pressure relatively constant; increasing gas saturation spreading from injectors	Velocity and density decrease with expanding gas cap. Oil/water contact relatively constant.
CO_2 Flood	Increase pore pressure, decrease effective pressure; increase CO_2 saturation from injectors; May create a bank of methane ahead of CO_2; Asphaltenes may precipitate	Velocity and density decrease near injectors depending on pressure and temp., low velocity zone if gas phase in methane bank forms (Figure 4).
Enriched Hydrocarbon Gas Flood	Increase pore pressure, decrease effective pressure; Increase gas saturation spreading from injectors; Methane-rich bank may propagate ahead of oil bank; Asphaltenes may precipitate	Velocity and density decrease near injectors depending on pressure and temperature, Low velocity zone if gas phase in methane bank forms (Fig. 2)
Steam Flood	Increase pore pressure, decrease effective pressure; Increase formation temperature; Liquid water bank propagates ahead of steam	Velocity drops with temperature rise and steam saturation, slight velocity increase in water bank (Figure 5)

Table 1. General recovery processes and their effects. For oil production unless otherwise noted.

is briefly described The reservoir conditions that most strongly affect seismic properties are emphasized (pore pressure, effective pressure, and gas saturation). Most operations will alter the pore pressure and the effective pressure, and so alter the seismic properties. Some of the operations will lead to evolution of gas saturation or to increasing gas saturation, while others will decrease gas saturation. As demonstrated by the Gassmann equations, seismic velocities decrease rapidly with the first 10% or so of gas saturation. With miscible flooding for improving oil recovery, some unusual conditions can develop. Specifically, a methane-rich bank can propagate beyond the CO2 bank. It is likely impossible to distinguish from seismic response the methane-rich bank from a CO2 bank. With steam injection, reservoir temperature increases, and depending on reservoir pressure, gas will likely evolve from the oil phase.

Reservoir simulation is now sufficiently sophisticated to predict pore fluid saturations based on the reservoir models. Figure 1 shows the modeled distribution of an enriched gas during a miscible flood. The flow and pressures will be controlled by the permeability distributions assigned. This injectant will be in the supercritical phase region and can be expected to lower seismic velocities and densities.

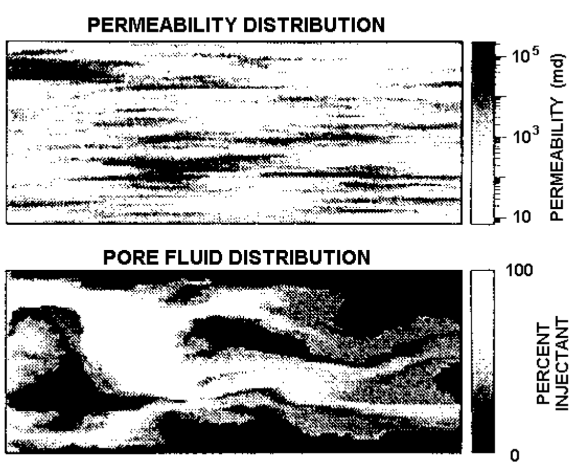

Figure 1. Permeability and pore fluid phase distribution for a modeled miscible gas injection (after Thiele et al., 1997).

In general seismic velocity in a formation will be sensitive to factors including fluid composition, density, effective pressure, and temperature. Figure 2 shows schematically a typical rock velocity behavior with pressure and saturation. During a water flood where brine replaces oil. Near the injection wells, pore pressure may increase enough to lower velocity (a). As the sweep proceeds, brine invasion further in the reservoir will increase velocity (b). Thus velocity changes will vary over the length of a flow profile. Such combinations of effects were first described by Nur (1989).

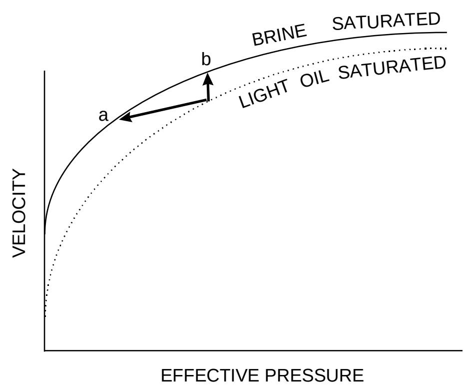

Figure 2. Generalized compressional velocity behavior during water injection. a: near injector, b: center reservoir

In thermal flooding, temperatures may increase sufficiently to lower velocities even before a change in fluid phase (figure 3). Rock matrix velocity decreases followed by a further drop as the pore fluid changes from liquid water to steam. Pressure variations will complicate this relation as free hydrocarbon gas can go in and out of solution depending on the pressure and temperature conditions (Eastwood et al., 1994; Jenkins et al., 1997).

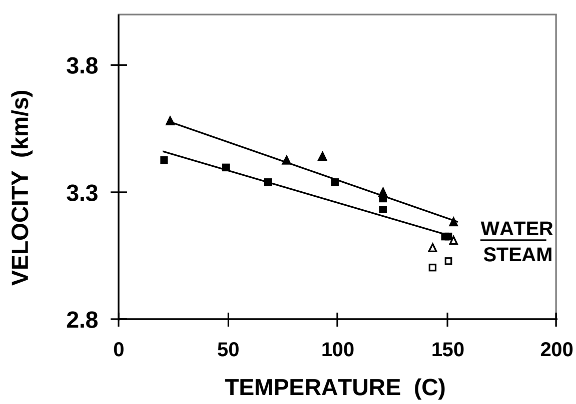

Figure 3. Temperature and saturation effects on Holt sand compressional velocity. Solid symbols: water saturated, Open symbols: steam saturated. (Graves et al., 1983)

Example process profiles

As mentioned, phase changes often occur in fluids associated with production or injection. These can include gas coming out of solution as a simple 'bubble point' phase boundry is crossed or liquids dropping out as the dew point line is crosssed. Under some conditions, gas can appear out of solution as the composition of the fluids in a reservoir mix and interact. As an example, figure 4 shows the expected pore fluid profile along a carbon dioxide flood. Carbon dioxide (CO_2) is injected and at, elevated temperatures and pressures, becomes miscible with oil. As the CO_2 is absorbed, oil swells and viscosity drops. The CO_2 velocity may be low , since it is generally supercritical.
As CO_2 penetrates and moves past the original oil, lighter hydrocarbon components may be preferentially absorbed in the moving phase. Because of this methane enrichment during sweep, a zone of high dissolved gas content builds following the initial front. Under some conditions, sufficient methane is stripped such that a separate gas phase evolves. Since small concentrations of gas make the fluid mixture much more compliant, seismic velocities will drop over this free gas zone as indicated schematically in figure 4 b.

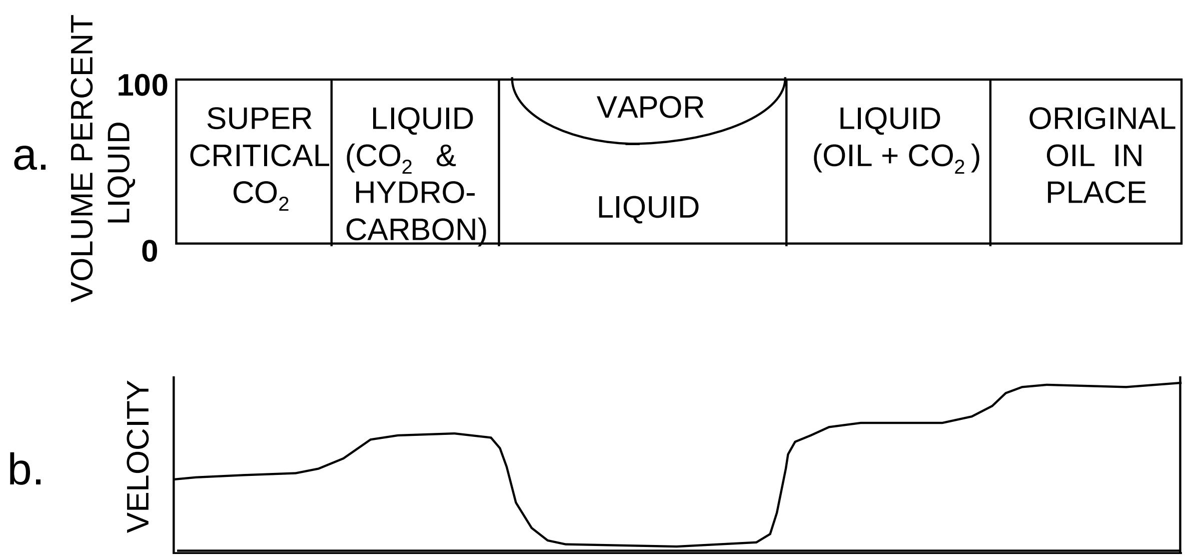

Figure 4. a) Fluid saturation profile during a CO_2 flood at about 8,000 kPa and 71 C. At other pressures and temperatures, a free gas phase may not occur (from Metcalf and Yarborough, 1979) b) Expected compressional velocity and density profile.

Another example is a steam flood. Here, high temperature steam is injected to mobilize the oil. Both the elevated temperatures and gas (steam) saturation result in low velocities near the injectors as was indicated in figure 2. A fire flood is a variation on this technique where air or oxygen is injected and combustion occurs in the formation. Combustion products are then included with the steam.

Figure 5 shows the expected pore fluid profile and velocity profile expected across a steam flood. The initial steam saturated zone may not be vary extensive. As heat is dissipated into the formation, hot water condenses and eventually a bank of high water saturation is built up in front of the flood front. A bank of mobilized oil precedes the hot water bank. Just from fluid saturation conditions, we would expect low velocities in the steam zone but higher velocities in the water and oil zones. These types of floods are usually conducted in shallow reservoirs with low pore and effective pressures. Rocks will be sensitive to injection pressures (figure 2). Small amounts of free gas may occur in extensive parts of the reservoir, and higher injection pressures may force this gas back into the solution (Jenkins et al., 1997).

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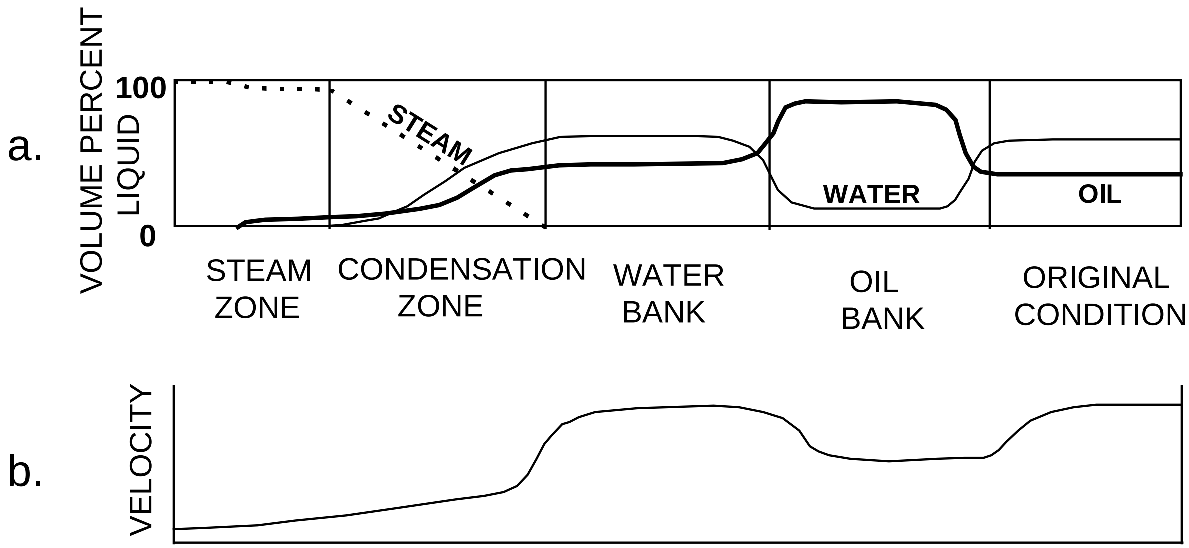

Figure 5. a) Schematic fluid saturation profile during a steam flood. (modified from Tadema, 1959)
b) Expected compressional velocity and density profile

Conclusions

The wide variety of recovery processes each can produce subtle and unexpected results during a seismic monitoring project. Time lapse seismic data needs to be analyzed within a context of realistic reservoir properties and conditions. Unexpected gas may appear. Pressures will vary between injectors and producers and can dominate the response. Reservoir simulations can predict important factors, but these simulations must be tuned to emphasize seismic responses.

References

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