is essential for reliable calibration. Access to, understanding, and incorporation of the downhole data will provide the spatially continuous attribute set required to describe the reservoir and drive the simulation model at the appropriate stage(s) in the production cycle. This integration must come hand in hand with closer interdisciplinary communication if the geophysicist is to address directly the problems currently facing the engineer. The geophysicist must clearly understand the requirements of the production department and provide input as a set of meaningful physical parameters.

## Conclusion

The 3-D seismic method has emerged as a potentially valuable tool in improving the information available to the petroleum engineer. Its application in both structural and stratigraphic contexts was presented for different stages in the production cycle. 3-D seismic alone provides not only accurate information on reservoir geometry but also offers estimates of spatial changes in rock properties and content when used in conjunction with advanced wavelet processing and inversion techniques. The ability of 3-D seismic to portray reservoir heterogeneity is its most valuable asset. The 3-D method will not, however, achieve full utilization as an integral component of the production process unless advances in resolution are matched by better integration of all available geophysical and geologic data as well as closer communication with the petroleum engineer.

# Seismic Monitoring of Thermal Enhanced Oil Recovery Processes RS6

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Studies made at elevated temperatures, overburden pressures, and pore pressures revealed that heating of heavy oil or tar sands has large effects on measured $P$ and $S$-velocities and amplitudes. Furthermore, shear wave attenuation and velocities in sandstones containing viscous pore fluid as well as in the fluids themselves change greatly as function of temperature from $-100°C$ to $100°C$. Several attenuation peaks are observed in the liquid bearing rocks and the liquids themselves. These peaks appear to originate from relaxation mechanisms in the pure fluids and are related to fluid viscosity. The loss peaks in the saturated rocks are sensitive to the nature of the rock as well as the degree of the saturation in the pores. We found also, that velocity and attenuation in rocks with high brine-to-oil ratios are sensitive to the presence of steam or gas. In sands with low brine-to-oil ratios are sensitive to the presence of steam detected but velocities and attenuation are highly sensitive to the temperature of heated oil.

The results imply that seismic properties may be highly useful as a thermometer, providing a powerful tool for the mapping of temperature and consequently fluid viscosity distribution within heated reservoirs. This suggests that judicious use of seismic wave transmission and reflection should be highly successful in locating the position of thermal enhanced oil recovery (EOR) fronts and in monitoring the distribution of heated tar and heavy oil in-situ.

## Introduction

A systematic laboratory study was undertaken to evaluate the potential for using seismic imaging to map thermal EOR fronts in sandstones and in unconsolidated sand reservoirs. The study was prompted in part by known effects of steam or gas on wave propagation in consolidated and unconsolidated rocks, in part by Conoco's successful use of seismic reflection to image the steam flood at the Street Ranch pilot project (Britton et al., 1982) and in part by anticipated, but unverified, seismically detectable changes in oil viscosity, compressibility, and rigidity upon heating of reservoir sands. This paper summarizes results of a series of experiments dealing with the effect of elevated overburden pressure, pore pressure, temperature, and oil/brine ratio on sonic resonance and ultrasonic pulse-transmission data. Reservoir samples studies include heavy-oil and tar sands from Kern River, California; Maracaibo, Venezuela; and Athabasca, Alberta; and samples of Boise and Berea sandstones. Fluids used include natural hydrocarbons, brine, glycerol, and refined oil.

## Ultrasonic studies

Short plugs were prepared by compacting the unconsolidated samples into cylindrical cores subject to in-situ differential pressure. Each plug was then placed between $P$ and $S$ ultrasonic wave transducer assemblies which were jacketed to isolate the pores and pore pressure from the confining pressure.

The samples from Venezuela were used to study the effect of oil-to-brine ratio on rock properties. Three types of cores were prepared: (1) with 100 percent dead crude of API gravity 12, (2) 50 percent oil/50 percent brine, and (3) 100 percent brine. $P$ and $S$-wave traveltimes and first-arrival amplitude measurements were made as a function of temperature, pore pressure, and confining pressure. After temperature was increased to its highest value of 150°C to 200°C, it was lowered to ambient to check for reversibility. When equilibrated at the maximum test temperature, each sample was held at constant temperature and confining pressure while pore pressure was varied through the water/steam-transition and wave properties measured.

Figures 1 and 2 show the main ultrasonic results, indicating that in fully oil-saturated sands velocities are extremely sensitive to temperature, while only weakly dependent on stress. For example, a 40 percent decline in compressional velocity between 25°C to 150°C at constant differential pressures is found in the Venezuelan samples.

The pressure and temperature effects are strikingly reversed when oil is replaced by brine. With warm brine occupying the pore space, the velocities are strongly dependent on differential pressure, but show little dependence on temperature. Consequently, the strong temperature dependence of velocity in the oil-saturated rock is evidently due to the presence of oil. Velocities in the sample with oil/brine mixture show intermediate pressure and temperature effects. Much like the velocities, large decreases in the $P$-wave amplitudes with increasing temperature were found in the samples containing oil (Figure 2). Specifically, the amplitude losses in samples with 100 percent brine, brine/oil mix, and 100 percent oil over the range from 25°C to 150°C are 15, 45, and 60 percent, respectively.

The changes of velocity and amplitudes with temperature

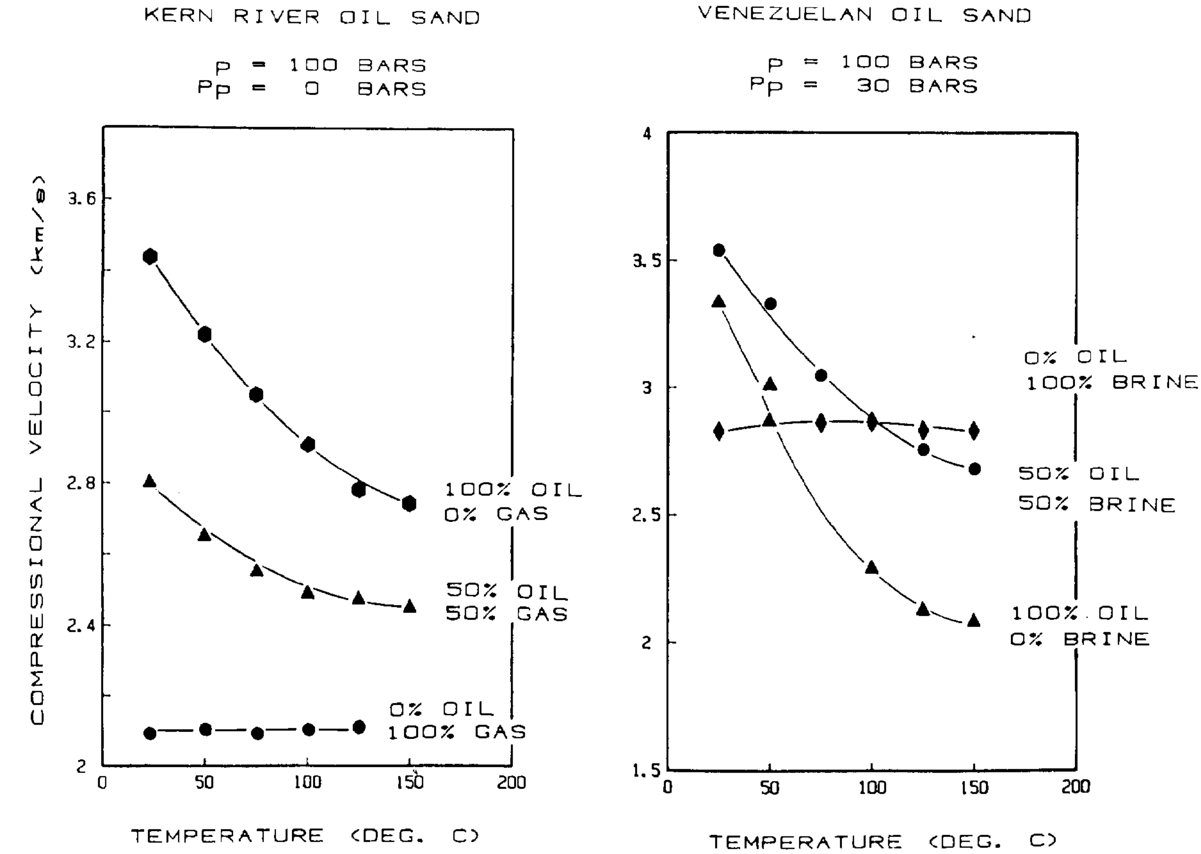


FIG. 1. Dependence of compressional velocity on temperature and oil/brine ratio in oil sands from Kern River, California and Maracaibo, Venezuela, subject to simulated in-situ.

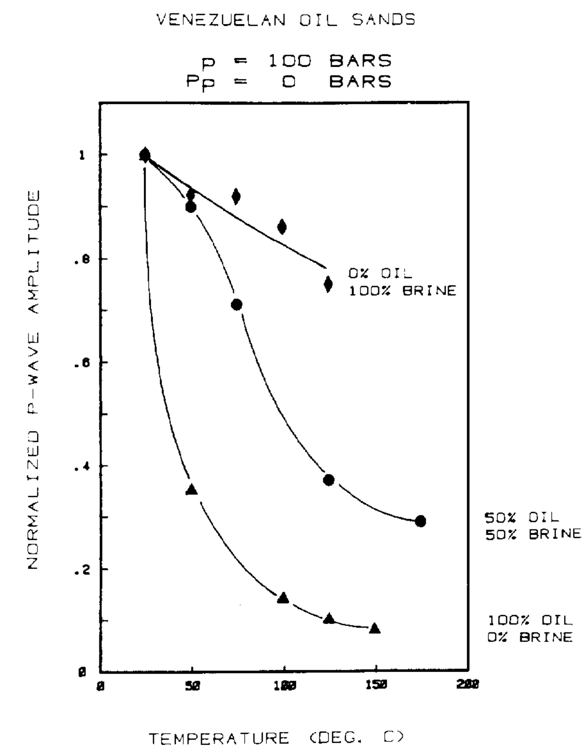


FIG. 2. Dependence of compressional wave amplitude on temperature and oil/brine content in heavy oil sands, subject to simulated in-situ.

in the Kern River sand are about half the Venezuelan values whereas in the oil-saturated Athabasca tar sand the effects are twice as large. We found that these are also approximately the ratios of oil content by volume of these samples. Velocity and amplitude data for the steam-transition test in the 100 percent brine-saturated sample showed a drop of 17 percent in compressional velocity and a 75 percent drop in $P$-wave amplitude. In contrast, no measurable changes in velocity or amplitude through the steam transition were detected in either the fully oil-saturated sample or the 50 percent oil/50 percent brine saturated sample. These results suggest that the presence of steam in a reservoir may be detectable only in regions of low oil content, such as areas of the reservoir that have been swept and left with a high residual water saturation.

### Resonant bar sonic studies

To understand the effects of viscous fluids better we investigated attenuation and velocities in porous sandstones containing temperature-sensitive viscous fluids, as well as the fluids themselves. Shear resonance measurements were made using the resonant bar technique (e.g., Winkler, 1979; Jones, 1983) on jacketed rock samples with pore fluid, and on pore fluids held in a copper tubing.

We obtained $Q^{-1}$ and $V_s$ data on Berea and Boise sandstones, as a functions of temperature (Figure 3), with (1) full glycerol saturation $S_g = 1.00$; (2) mix of glycerol and air $S_g$ = .60 – .68; (3) mix of glycerol and water $S_g$ = .50; and (4) a-

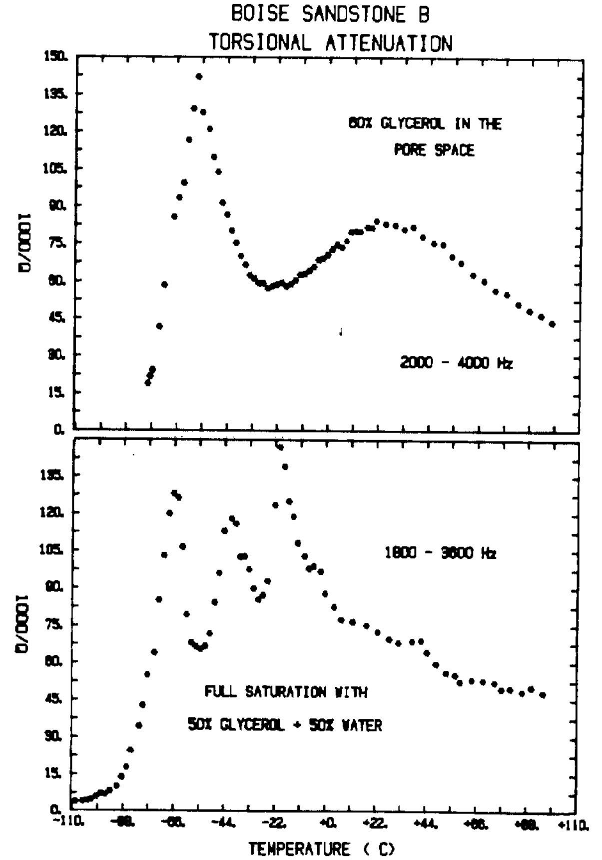


FIG. 3. Dependence of $Q^{-1}$ on temperature in Boise sandstone containing mixtures of glycerol/air and glycerol/water.

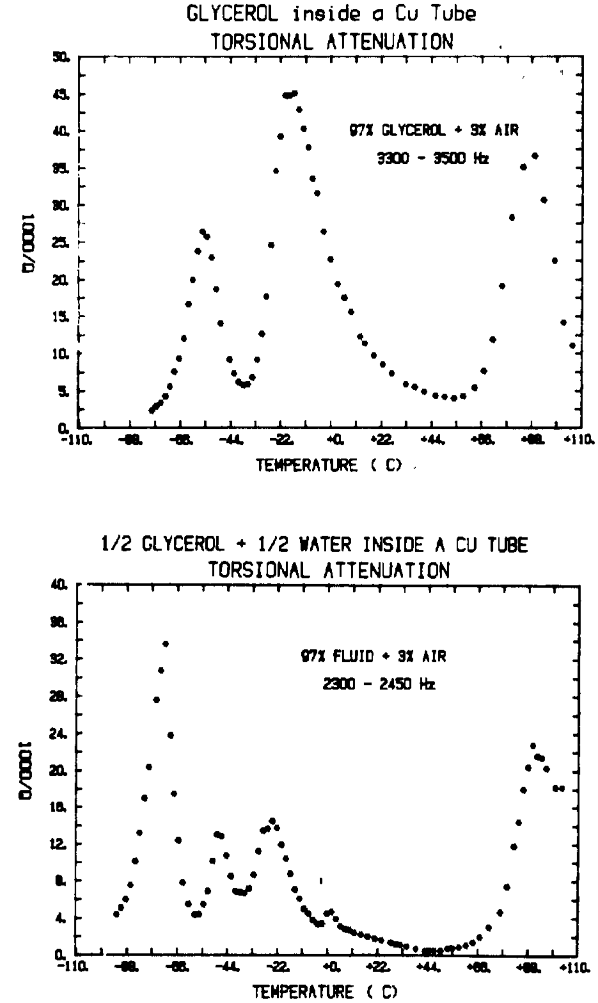


FIG. 4. Dependence of $Q^{-1}$ on temperature in glycerol and a mix of glycerol/water.

only. Because of the surprising complexity of the results, as discussed below, we also measured $Q^{-1}$ and $V$ of copper tubes filled with (1) glycerol, and (2) a 50/50 mix of glycerol and water (Figure 4). We also used a refined oil (Drakeol 35), a Silicone oil, and a heavy oil extracted from Monterey shales. The results are summarized in Table 1 for the rocks with pore fluids, and in Table 2 for just the fluids and their mixtures.

In both the rocks with fluids and the alone, we found sharp $Q^{-1}$ peaks. For the glycerol air mix (Figures 3 and 4), the peaks occur at −57°C and 22°C in Boise sandstone, and at −43°C and 28°C in Berea sandstone. For $S_g$ = 1.00, peaks are found at −56°C and 60°C in Boise sandstone, and −37°C and 40°C in Berea sandstone. In comparison, $Q^{-1}$ peaks in the water/glycerol mix are found at −71°C, −24°C, and 90°C, and in pure glycerol, $Q^{-1}$ peaks at −56°C, −16°C, and 90°C.

The results indicate that the loss peaks in rock with viscous fluids are due largely to losses in the fluids themselves, although the pore space environment tends to increase the temperature at which these loss peaks occur, and also tends to increase the magnitude of the loss. For example, in pure glycerol at −56°C, $Q^{-1} = 2.7 \times 10^{-2}$, whereas the corresponding peaks are $1.3 \times 10^{-1}$ and $1.25 \times 10^{-1}$, respectively, in the fully saturated Boise and Berea. In Boise and Berea with $S_g = .6 - .7$, $Q^{-1}$ values at low temperature are $1.4 \times 10^{-2}$ and $1.7 + 10^{-2}$, respectively.

The number of loss peaks in the fluids, over the temperature range investigated, ranges from 1 in brine, to 3 in glycerol, and 4 in the glycerol/water mix and the heavy Monterey oil. The number of loss peaks in the rocks with the fluids range from 2 in partially glycerol saturation, to 3 in glycerol to 4 in Boise with the water/glycerol mix.

Torsional wave velocities were also measured in these experiments (Figure 5). The presence of glycerol or heavy oil in the pore space causes a large dependence of velocity on temperature, relative to the behavior in dry rock, as shown for Boise sandstone in Figure 5. Besides a general pattern of decreasing velocities with increasing temperatures, inflection points and minima or maxima in velocity versus temperature were found. For example, a 6 percent velocity minimum was observed in both glycerol saturated Boise sandstone at −25°C and in glycerol itself at −38°C and 70°C. Minima were found in the Monterey heavy oils at −30°C, 2°C, 40°C, and 65°C. These minima, which correspond only in part to the $Q^{-1}$ peaks, imply that a number of interactive processes are caused in the organic liquids and mixes by the passage of strain waves. The nature of these processes (e.g., phase transformation, structural transformations, sluggish chemical reactions, etc.) remains to be investigated further. However, the results indicate that waves in laboratory samples and in-situ can yield much more information than recognized to date.

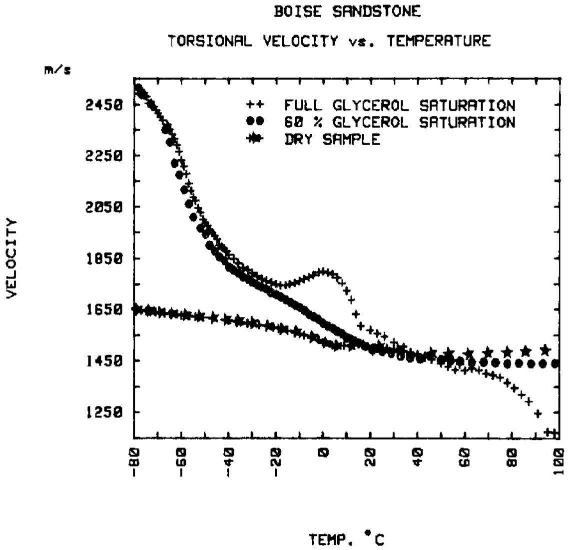


FIG. 5. Wave velocities in Boise sandstone samples containing air, air/glycerol, and glycerol in the pores.

## Conclusions

The experimental results are as yet insufficient to resolve the detailed mechanisms responsible for the complex dependence of velocities and $Q^{-1}$ on temperature in viscous liquids and liquid saturated rock. However, our data show that the fluid rheology strongly affects both wave velocity and attenuation in viscous liquids as well as rocks saturated with these liquids. The results of the sonic experiments suggest that (1) the attenuation peaks in liquid saturated rock are associated with relaxation processes in the liquid itself; (2) these peaks occur at higher temperature in the rock than in the fluid itself; (3) amplitude of the $Q^{-1}$ peaks is greater in the rock than in the fluid itself; and (4) velocity in saturated rock decreases with decreasing pore fluid viscosity much more than in the fluid itself.

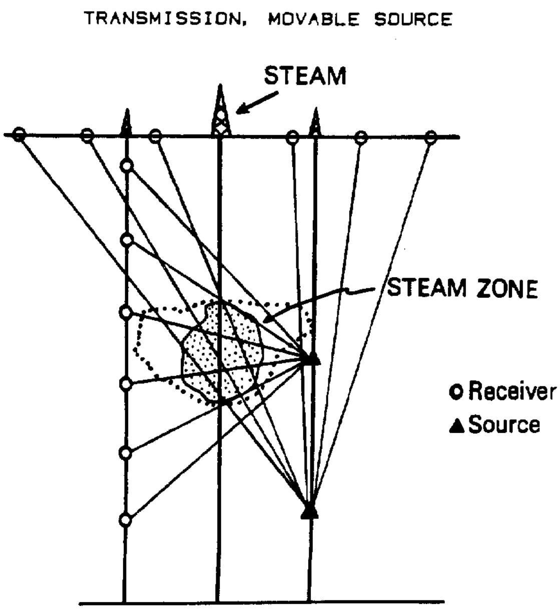


FIG. 6. Possible applications of the results to the monitoring of thermal EOR via seismic imaging.

Furthermore, ultrasonic studies show the following. (1) Tar and heavy–oil sands containing a percentage of oil in the pores have strongly temperature-dependent seismic velocities and amplitudes. Neither brine nor gas-saturated samples display this behavior. (2) The magnitudes of the dependence of compressional velocities and amplitudes on temperature are proportional to the oil content of the sample. (3) Large changes in compressional velocities and amplitudes were measured when steam was generated in the pore space of a brine-saturated sand. Sands that were saturated with oil or with a mixture of half brine and half oil showed no detectable changes in seismic properties through the steam transition.

The very large magnitudes of the effects of temperature and steam on the measured seismic properties of laboratory samples strongly suggest that efforts to monitor thermal EOR fronts, including hot water and steam floods (Nur, 1982), should be highly successful if seismic signal strength and spatial resolution can be made adequate (Figure 6). In addition, the velocity and amplitude measurements in reservoir sands such as reported here indicate that seismic properties can be used as a thermometer to map the spatial distribution of heated oil within reservoirs.

## Acknowledgments

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## Low-Frequency Electromagnetic Logging RS7

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Controlled-source electromagnetic sounding (CSEM) is becoming a valuable tool for resolving certain geologic features in problem areas where seismic reflection methods are unsatisfactory. The detection of electrically conductive sediments beneath overthrust sections of older rock or beneath volcanic flows are examples of such situations. Another type of sounding can be made if a drill hole is available in the area. In this case, the transmitter is located on the surface and the receiver is lowered down the hole. The advantage of surface-to-borehole sounding is that the method is inherently more sensitive to subsurface layering or inhomogeneities than surface-only measurements. A surface-to-downhole EM technique for petroleum exploration would also have inherent advantages over conventional well logs for determining subsurface conditions away from or below the well. In particular, it may also be possible to determine these conductivities in the presence of the casing.

A preliminary analysis shows that there is no surface dat