Rock physics of the unconventional

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The resource industry faces old and new problems that stem from the vagaries of rock and fluid properties. As exploration and monitoring techniques improve, the results must become more directly related to the material properties in situ. At the same time, the materials and their characteristics become more complex or "unconventional." Today's challenges include viscous heavy oils, clays and shales, gas hydrates, tight gas sands, organic-rich shales, coals and coal-bed methane, salt, and many nonsedimentary rocks. Note that not all of the materials we must examine directly involve extractable resources: shale deformation due to stress changes is important around boreholes or compacting reservoirs; and carbon dioxide injection not only produces fluid displacements and phase changes, but also involves chemical interaction with the host matrix. In addition, to understand the important characteristics of rocks, we must employ "unconventional" measurement techniques such as polymer and surface chemistry, nuclear magnetic resonance, high-resolution X-ray imaging, molecular simulation, nano-indentation, atomic-force microscopy and scanning-acoustic microscopy, and broadband elastic measurements. In this paper, we cannot cover the complete spectrum of materials and measurements. Rather, we will describe some of the important unconventional rock properties and examine some of the techniques applied to their characterization. We hope to stimulate discussions on where technology is headed and what resources will be required in the near future to make innovations successful and the tools adequately calibrated.

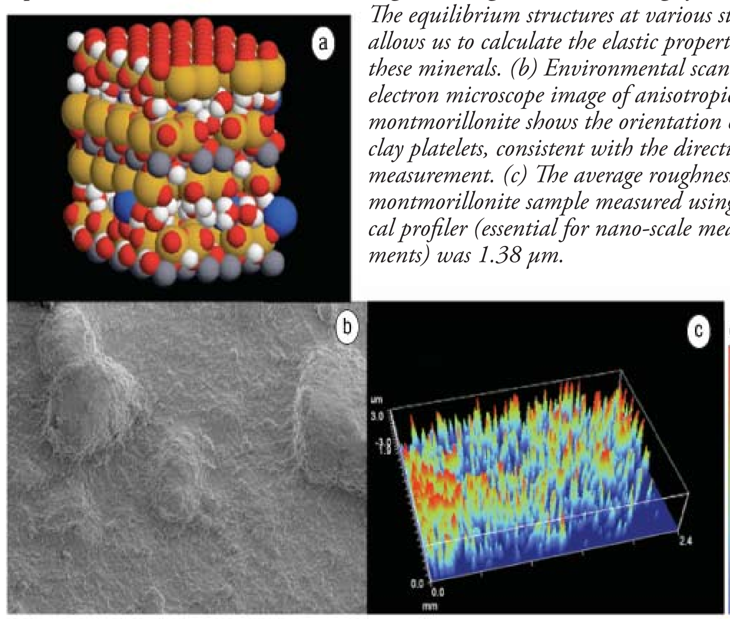

Figure 1. *(a) Equilibrium structure from molecular simulation for a uniaxial stress of 1 GPa, normal to the two clay layers, with four unit cells in the X direction and two unit cells in the Y direction, for two layers of water in the interlayer. Gold represents Si atoms; white = H; red = O; green = Mg; blue = Na; and grey = Al. The equilibrium structures at various stresses allows us to calculate the elastic properties of these minerals. (b) Environmental scanning electron microscope image of anisotropic montmorillonite shows the orientation of clay platelets, consistent with the direction of measurement. (c) The average roughness of montmorillonite sample measured using optical profiler (essential for nano-scale measurements) was 1.38 µm.*

Heavy oil and tar sands

Worldwide, heavy oils rival the more conventional light oils in terms of quantity and energy content. Heavy oils are defined as having API gravities below 22, and super heavy oils have gravities of 10 and below. These heavy oils are the primary production in Canada, and huge amounts exist in Venezuela, Alaska, Russia, China, and elsewhere. However, production from heavy oil (tar) sands or heavy oil saturated carbonates is difficult and expensive. Thermal stimulation is common in many production processes. Seismic monitoring, therefore, requires knowledge of the rock and fluid properties to interpret the extent of stimulation.

One of the important aspects of very heavy oils is that they act like solids under certain conditions. Several examples of heavy oils with substantial shear modului were shown in Han et al. (2008). At lower temperatures, fluid viscosities and shear moduli are high. The shear modulus also increases with frequency. One result of this dispersive behavior is that velocities measured in the seismic frequency band will not equal sonic logging values or ultrasonic laboratory values. This behavior renders Gassmann's equations inapplicable. This shear behavior is strongly dependent on the chemical makeup of the particular heavy oil. Heavy oils are made up of complex mixtures of saturates, aromatics, resins, and asphaltenes. Unlike lighter oils, there is little relationship between the density of the oil, or the API gravity, and its shear properties. However, the shear modulus does show a strong dependence on the combined resin and asphaltene content (see, for example, Hinkle, et al., 2008). Thus, when modeling tar-sand behavior or interpreting production monitoring data, the composition and behavior of each specific oil will need to be considered.

Shales

Since shales are the most abundant sedimentary rock on Earth, and clays are present in abundance in shales, the elastic properties of clays are of utmost importance in soil science and geophysics. Polymer, paper, ceramic, medicine, automobile, and other industries also use clays in various ways. Our current knowledge of clay and shale properties is rather limited, considering their abundance and importance.

The major challenges in measuring elastic properties of clay minerals are due to their small grain size, ease of reactions with polar molecules, and low permeability. The large variations reported in Young's moduli for clays (0.15 GPa to 400 GPa) may be due to various kinds of clays being considered, different external environments leading to varied amounts of cations and bound water in the interlayers, or

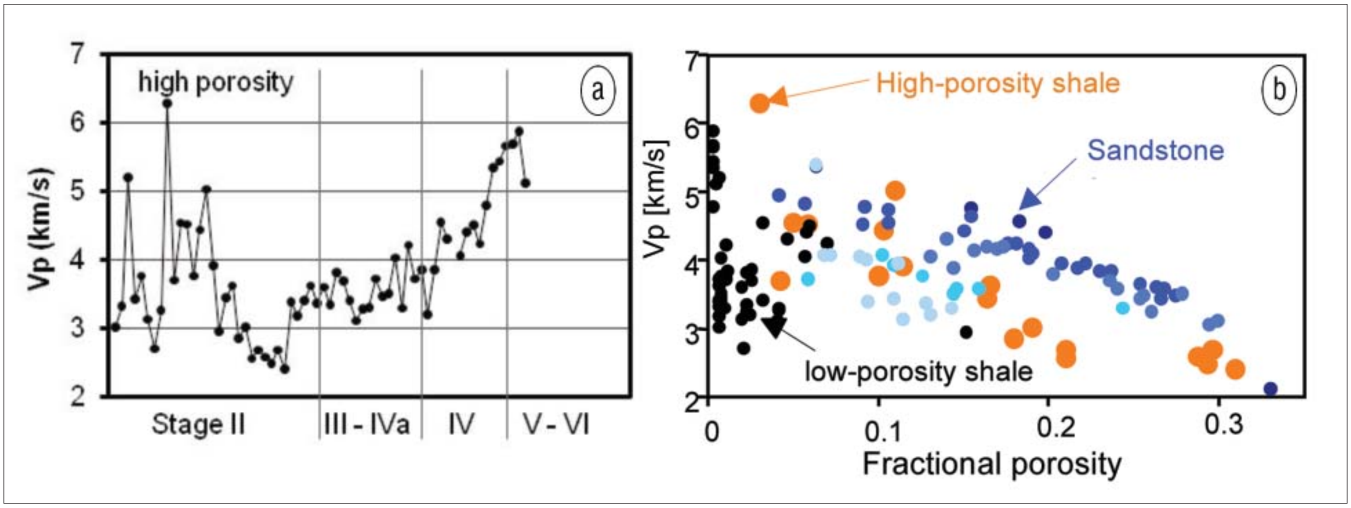

Figure 2. *(a) Correlation between V_p and maturity stage increasing from immature (stage II) to mature (stage VI) and (b) porosity. V_p increases with increasing maturity. This corresponds to the overall increase in acoustic impedance on a micron scale observed in acoustic microscopy. V_p in ORS is inversely correlated with porosity (solid red symbols). In low-porosity ORS (solid black symbols), there is no correlation. Shaly sandstone data (blue symbols) are shown for comparison (Han et al., 1996). From Prasad et al. (2002).*

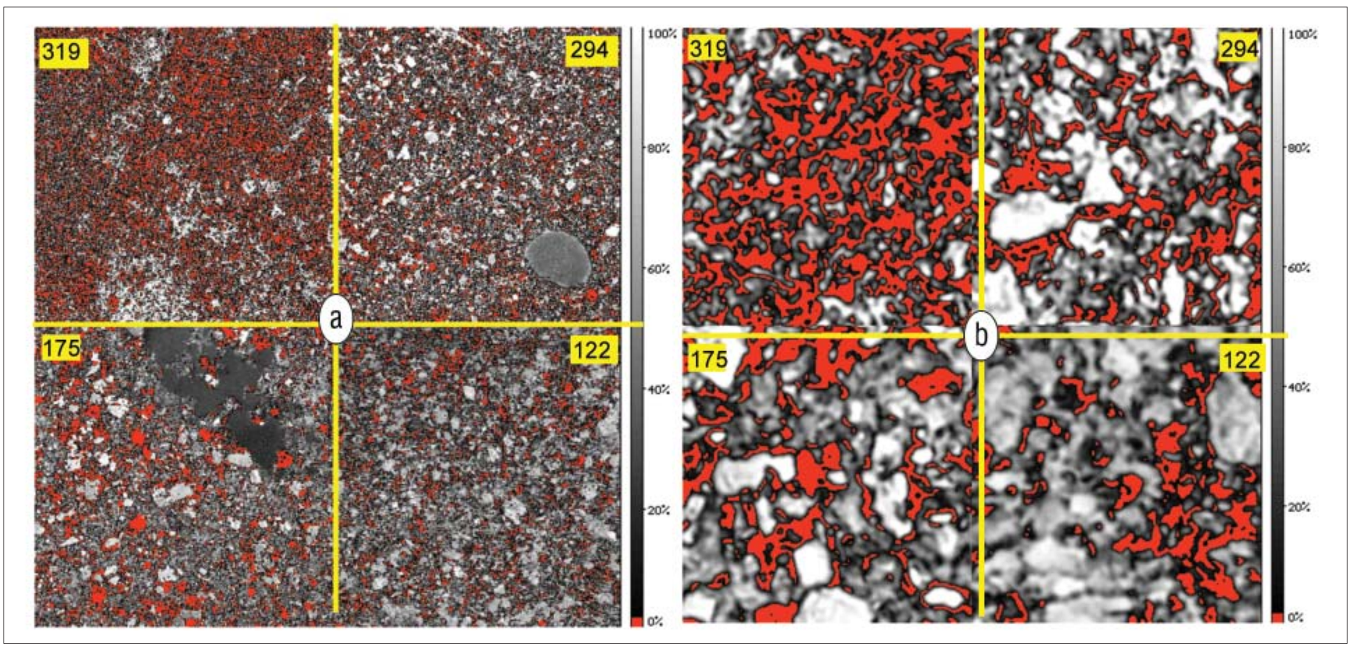

Figure 3. *Impedance microstructure in the Bakken Formation. The numbers show the Hydrogen Index HI (upper right corner) in each shale sample. A decreasing HI number denotes increasing maturity. The color code (0–100% grey shade) varies from high (100% = 50 km/s*g/cm^3) to low (0% = < 7 km/s*g/cm^3) impedance. The lowest impedance is red. Note change in texture (decrease in red color) from immature (HI = 319) to mature shales (HI = 122). The images scale in (a) is 1x1mm^2 and the image scale in (b) is 62 x 62 μm^2. From Prasad et al. (2002).*

anisotropy resulting from the layered structure of clays. An example of the complexity of the clay minerals is given in Figure 1, where we present different views of the same montmorillonite using different techniques at different scales. It is important to understand the clays by combining all observations from atomistic scale to the bulk scale.

The combination of physical measurement and computational techniques allows us to understand and predict in-situ shale properties, which is essential for the interpretation and modeling of their seismic response.

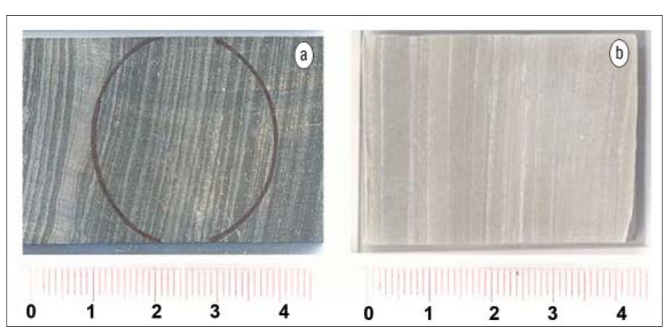

Figure 4. *Sections of organic-rich (a) and lean (b) oil shales. The dark kerogen is immature and imparts strong anisotropy to the material.*

Organic-rich shales (ORS) and oil shales (OS)

Organic-rich shales (ORS, often given the misnomer of "oil shales;" OS) have been studied in detail to understand the provenance and the generation of oil from source rocks. In recent years, ORS have become interesting as important hydrocarbon resources. Proven and recoverable oil reserves from ORS and OS account for about 33 trillion tons of shale and 68 billion tons of oil, respectively. Of these, the U.S. alone has 3.3 trillion tons of shale (10% of proven reserves from oil shales) and 60 billion tons of oil (90% of total recoverable oil from shales) with the estimated U.S. OS and ORS reserves totaling 1.5 trillion barrels of oil (Hepbasli, 2004).

Organic-rich shales. Successful exploration and production programs for ORS depends on reliable identification of the kerogen content and its maturity through indirect seismic methods. The seismic properties of kerogen remain poorly understood so that predictions of the seismic response of a rock-kerogen system and the kerogen maturity remains a big challenge. Kerogen maturity changes shale texture; for example, it leads to microcracks and fractures in the matrix. Assessment of maturity from indirect measurements can be greatly enhanced by exploiting any existing correlations between physical properties, microstructure, and kerogen content.

One way of looking at ORS is through acoustic analysis: kerogen content, and with it maturity, can be related to V_P at low-porosity. V_P increases with increasing maturity, except in high-porosity shales (Figure 2a). In these high-porosity (low maturity) shales, V_P is better correlated with porosity (Figure 2b). The correlation between V_P and HI is reasonable when we constrain the data by formation. Within a single formation, the scatter in the correlation between V_P and HI is greatly reduced (Figure 2b).

In low-porosity ORS (solid black symbols) there is no correlation. Shaly sandstone data (blue symbols) are shown for comparison (Han et al., 1996).

A second way of examining ORS is through impedance microstructure imaging with acoustic microscopy (AM). AM allows us to compare the textural impedance variations with maturity. Acoustic micrographs obtained at 1 GHz of the Bakken shale series samples show a significant difference in texture with maturity (Figure 3 of two mature and two immature shales from the Bakken formations). Impedance properties of kerogen are not well known, but we expect it to have the lowest value among all other constituents. And so, by mapping the lowest impedance, all red-colored areas have impedance less than 7.5 km/s*g/cm^3; we expect to map the relative location of the kerogen in the shales. Figure 3 shows that kerogen is load bearing and forms a connected network in immature shales. In the mature shales, the grains are load bearing, and the kerogen appears dispersed in the matrix. This characteristic has important consequences for the velocity and the pressure dependence of the velocity in the different shales. In Figure 2, velocity decreased with maturity and with increasing kerogen content.

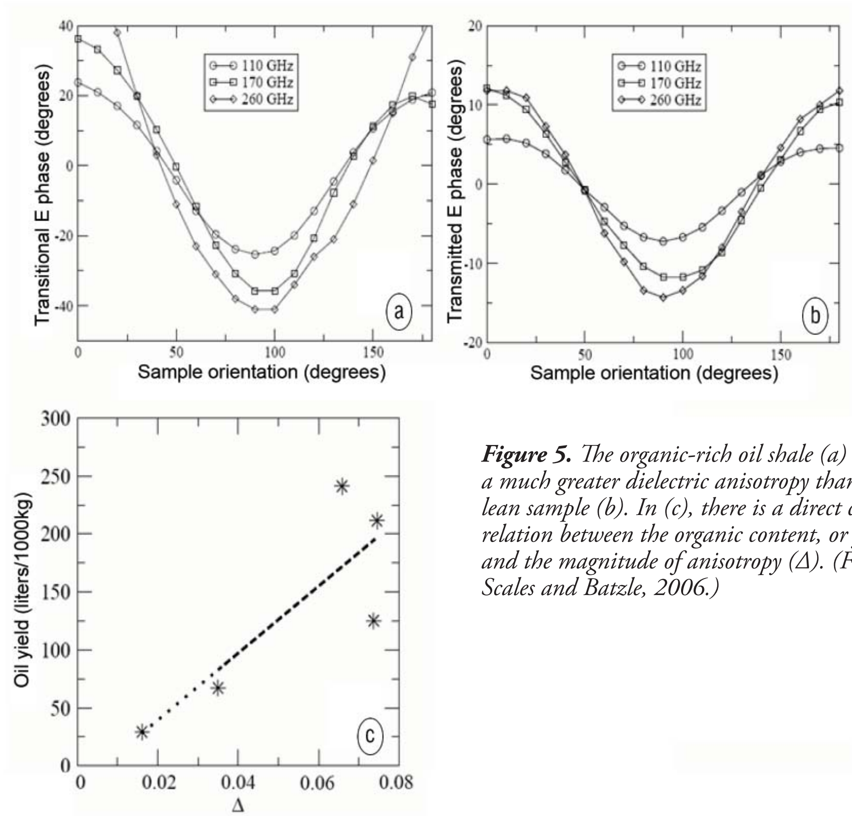

Figure 5. The organic-rich oil shale (a) has a much greater dielectric anisotropy than the lean sample (b). In (c), there is a direct correlation between the organic content, or yield, and the magnitude of anisotropy (Δ). (From Scales and Batzle, 2006.)

Oil shales. Another resource with enormous potential but confronted with severe technical challenges is oil shales. Hydrocarbons have been extracted from these materials around the globe for numerous decades. Extensive production has occurred in places such as Estonia, the United Kingdom, and China. Most of these operations have been relatively small and economically marginal. However, the current economic environment and recent technological advances have made oils shales an inviting target. The oil shales of western Colorado, Utah, and Wyoming are estimated to contain between 500 billion and 1 trillion barrels of economically recoverable oil. Some regions may yield more than 1 million barrels per acre. However, numerous technical and environmental challenges exist. Proposed in-situ recovery processes use heat to crack the kerogen and produce light oils and gases.

The oil shales themselves are fine grained and strongly layered, particularly as organic content increases. This results in strong anisotropy not only for compressional and shear waves, but also for other properties such as dielectric constant. This

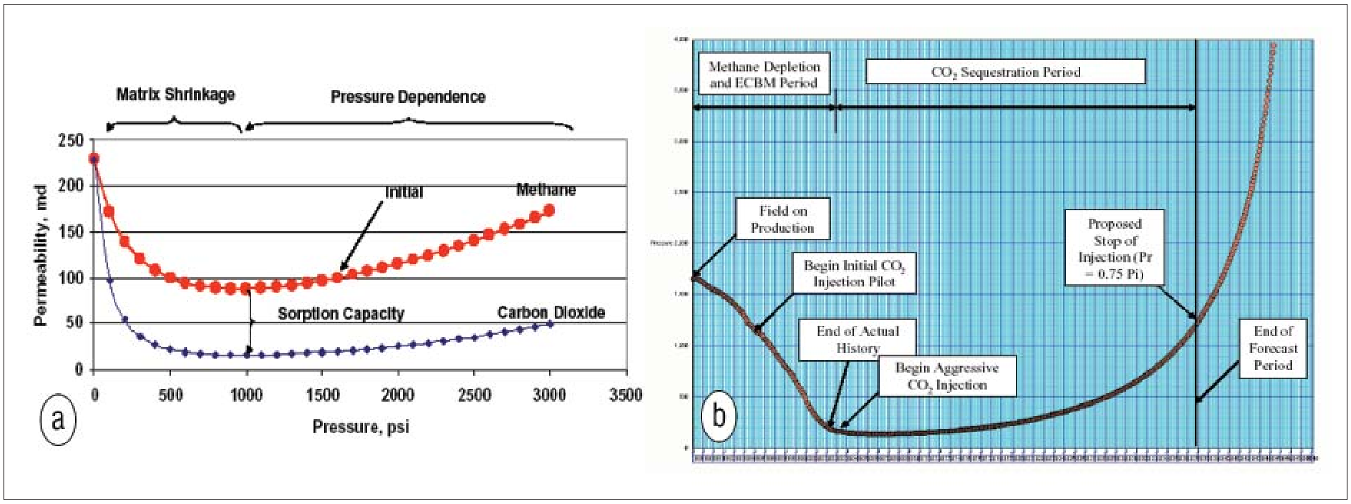

Figure 6. *(a) Projected permeability changes with pressure (and gas concentration), for both CH_4 and CO_2, assuming a differential swelling factor of 1.0, an initial permeability of 100 md, an initial pressure of 1600 psi, and a porosity of 0.25%. (b) Reservoir pressure history for the CO_2 sequestration cost (from Reeves et al., 2002).*

anisotropy persists even at high pressures. In Figure 4, two slices from different depths of the Green River formation are seen. The darker sample (a) is much more organic rich than the light sample (b). This contrast in kerogen content is obvious in the anisotropic behavior of the dielectric constant (Figure 5).

Geophysical techniques, such as dielectric anisotropy, have great potential for monitoring several aspects of the recovery processes. However, the behavior of rock properties at the high temperatures (>350°C) and moderate pressures of these processes are not known.

Coal

Coal beds are among the prime targets for geologic sequestration of CO_2. Since coal beds are extensive throughout the U.S., they hold a special importance for the U.S. carbon sequestration program. Table 1 shows the worldwide capacity of potential CO_2 storage reservoirs (Herzog, 2001).

Sequestration option	Worldwide capacity [a]
Ocean	**1000s GtC**
Deep saline formations	**100s–1000s GtC**
Depleted oil and gas reservoirs	**100s GtC**
Coal seams	**10s–100s GtC**
Terrestrial	**10s GtC**
Utilization	**<1 GtC/yr**

Table 1. *Worldwide capacity of potential CO_2 storage reservoirs (from Herzog, 2001).Note: Worldwide total anthropogenic carbon emissions are ~7 GtC per year (1 GtC = 1 billion metric tons of carbon equivalent).*

As the importance of coal seams for carbon sequestration in the subsurface increases, demand for more reliable monitoring, verification, and risk assessment of the sequestration process also increases. Thus, we need geologically realistic, quantitative, and low-risk coal-bed models from remote seismic measurements. In order for seismic measurements to attain a beneficial role in carbon sequestration, we need systematic studies to develop relations between seismic properties and physical properties. There are two problems in monitoring and verification of carbon sequestration in coal seams:

1) Very few data exist on the seismic and elastic properties of coals.
2) Relations between seismic and physical properties are known for major reservoir rock types, but there is a paucity of such information for coals.

CO_2 sorption in coal is a strong function of coal properties, such as coal swelling associated with carbon dioxide sorption, carbon dioxide sorption capacity, Langmuir volume and pressure, ash content, maceral composition, partial pressure of carbon dioxide (critical pressure), and the equilibrium between bicarbonate concentration in formation water and the coal surface. Reeves et al. find a significant reduction in coal permeability due to CO_2 sorption in the Allison Unit CO_2-ECBM Pilot (Figure 6). Thus, we need reliable, economical, and effective means for monitoring and verification of CO_2 stored in coal beds.

Gas hydrates

Gas hydrates are ice-like, crystalline solids that form from water and gas molecules under conditions of low temperatures and high pressures. Vast amounts of natural gas could be stored in natural gas hydrates, which occur in a variety of settings such as shallow sediments of marine and permafrost environments. Because of the enormous amount of naturally occurring gas hydrates and their wide geographical distribution and high energy density, clathrate hydrates are considered an alternative energy resource capable of partially satisfying the world's increasing demand for energy. Actual volume estimates of the amount of contained gas, however, are highly speculative because detection and quantification algorithms for gas hydrate deposits are based on imprecise empirical observations and assumptions. We use millimeter wave spectroscopy to determine the relationship between the dielectric properties of the hydrate-bearing sediment samples and their gas hydrate content.

Millimeter wave spectroscopy (MWS) is a novel experimental technique to measure the dielectric properties of materials. Electromagnetic waves are generated by a millimeter wave vector network analyzer in a "frequency sweep," radiated into free space via a scalar horn antenna, and focused onto the sample with a polyethylene lens (Figure 7).

Phase and/or amplitude of the transmitted and/or reflected wave fields are recorded as a function of the excitation frequency. If there is no dispersion over the frequency range of interest, the frequency response shows a very distinct contour within the sample, which can be fit with an analytic model that depends on the thickness of the sample and the dielectric permittivity ε only. As the thickness of the sample is generally known, the overall ε of the whole sample system can be easily determined from the data fit.

As an example, MWS is also used to observe gas hydrate dissociation time. For this, synthetic gas hydrates samples have been formed from tetrahydrofuran and deionized water in consolidated Berea sandstones. Figure 8 shows how the amplitude of the transmitted field changes over time while the gas hydrate present is dissociating in the pore space of the sediment. As can be seen, the amplitude of the signal decreases as the gas hydrate is decomposed into liquid water and gaseous THF.

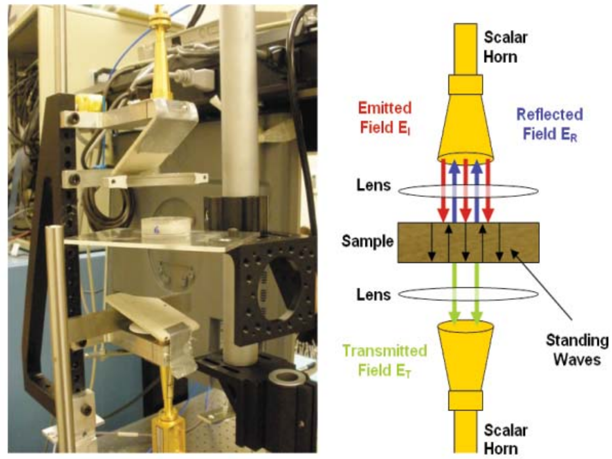

Figure 7. Experimental setup and basic measurement principle for the millimeter wave spectroscopy.

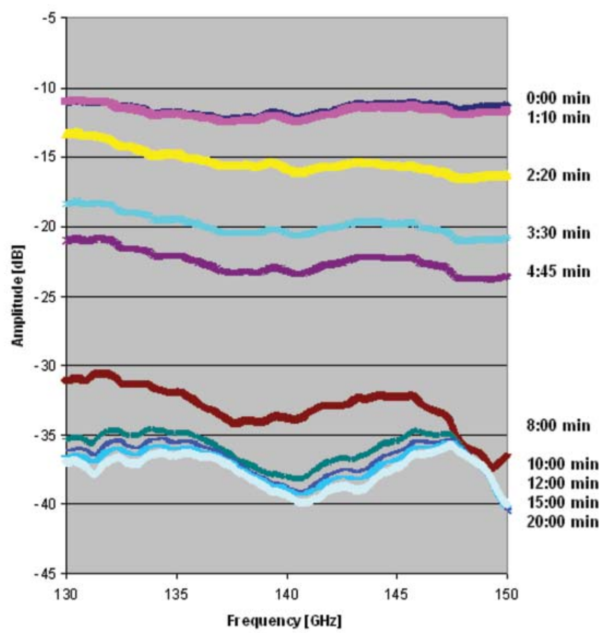

Figure 8. Amplitude of transmitted EM field over time for THF-saturated sandstone.

Conclusion

The variety of materials, properties, and measurement techniques is vast. As our data improve and the problems become more complicated, we need to extend our analysis techniques to include information usually not associated with "rock physics." In the future we will be expected to provide calibration for a host of mechanical, chemical, transport, as well as wave propagation phenomena and must broaden our approaches accordingly.

Suggested reading. "Seismic properties of heavy oils—measured data" by Han et al. (*TLE*, 2008). "Oil shale as an alternative energy source" by Hepbasli (*Energy Sources*, 2004). "Correlating the chemical and physical properties of a set of heavy oils from around the world" by Hinkle et al. (*Fuel*, 2008). "Determination of the elastic constants of orthorhombic and transversely isotropic materials: Experimental application to a kerogen-rich rock" by Mah (PhD thesis, University of Alberta, 2005). "The effect of kerogen content on ultrasonic wave velocities in oil shales" by Parker (master's thesis, University of Texas, 1968). "Quantitative acoustic microscopy: Applications to petrophysical studies of reservoir rocks" by Prasad et al. (in Acoustical Imaging 25, Kluwer, 2002). "The Allison Unit CO_2—ECBM Pilot: A Reservoir Modeling Study: Topical Report for 2001–2002" by Reeves et al. (U.S. Department of Energy Award Number DE-FC26-0NT40924, 2002). "Millimeter wave characterization of rocks and fluids" by Scales and Batzle (Joint International Conference on Millimeter Waves, 2006). "The influence of confining pressure and water saturation on dynamic elastic properties of some Permian coals" by Yu et al. (Geophysics, 1993)"What future for carbon capture and sequestration?" by Herzog, (*Environmental Science and Technology*, 2001). TLE

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