Rock Physics of Heavy Oil Deposits

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Abstract

Heavy and bituminous oil production will be the main source of Canadian production in the not to distant future. Many of the methods employed are expensive in terms of capital investment and energy input during operation, and it is becoming more important to understand what actually occurs *in situ* during production. Geophysical time-lapse methods have a role to play in better understanding in situ processes. However, the greatest impediment to such understanding is the lack of knowledge of the in situ physical properties of heavy oil reservoirs and how these properties are influenced by reservoir conditions.

Introduction

The viscosity of many heavy and bituminous oils makes them difficult or impossible to produce using conventional methods. A variety of novel recovery techniques are now being employed, these range from cold production through viscosity-lowering fluid injection to in situ combustion. These methods are generally expensive and as such having some way to remotely monitor changes in the reservoir using geophysical techniques have long been considered. *In situ* 'extrinsic'[1] conditions of stress, pore fluid pressure, saturation, and temperature vary during production and all of these influence the 'intrinsic' physical properties of seismic velocities, density, and attenuation to varying degrees. The relationships between these extrinsic conditions and the intrinsic properties are qualitatively summarized in Figure 1. Changes in the physical properties of the rocks must be accompanied by a change in the geophysical response, and varying conditions can sometimes work against each other with little net gain to the overall properties. Here, some aspects of the physical properties of weakly consolidated heavy oil reservoirs are presented with a view to how changes in these properties will influence geophysical observations. Our knowledge of the behavior of such complex materials is still incomplete, however, and such lack of knowledge limits our abilities to both anticipate geophysical responses via forward modeling and to interpret observed responses.

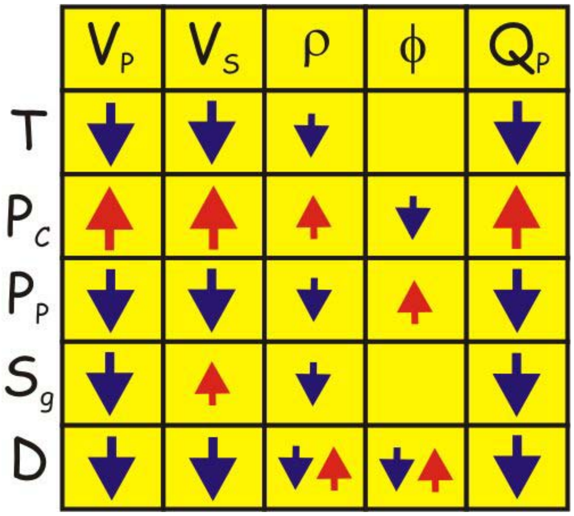

Figure 1. Influence table of the effects of an increase in the extrinsic conditions of T (temperature), P_c (confining pressure or stress), P_P (pore fluid pressure), S_g (Gas saturation), and D (reservoir damage) on the intrinsic properties V_P (P-wave velocity), V_S (S-wave velocity), r (mass density), f (porosity), and Q_P (P-wave quality factor or inverse attenuation). Blue downward and red upward arrows indicate that the value of the intrinsic property will decrease or increase, respectively, with an increase in the corresponding extrinsic condition. The size of the arrows qualitatively describes the magnitude of the relative change in the intrinsic property.

Fluids

Heavy oils are characterized primarily on the basis of their density (Figure 2). The density generally reflects the complexity of the hydrocarbons that make up the oil, with light oils consisting organic molecules with small numbers of carbon atoms, the heavier the oil the more long-chain or high carbon number molecules (e.g. asphaltenes) are

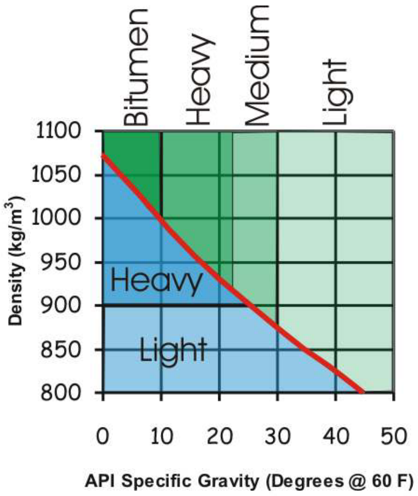

Figure 2. Characterization of oils in terms of density, shown as mass density (Canadian Government Designation) versus API Specific Gravity (API designations.)

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[1] Here, the terms 'extrinsic' and 'intrinsic' are used somewhat loosely with regards to their proper physical chemistry definitions. For example, the saturation is properly an intrinsic property in its own right. Here the terms refer to those 'extrinsic' time-dependent reservoir conditions that will influence the 'intrinsic' physical properties that will control the seismic response.

included. These higher carbon number molecules simply get in the way of one another and increase the fluid viscosity. The viscosity of the liquids increase with pressure but are highly temperature sensitive (Figure 3) changing by many orders of magnitude, such drastic changes in viscosity provide the motivation for many thermal production techniques, the most popular of which is Steam Assisted Gravity Drainage (SAGD). The physical properties of the liquid hydrocarbons are also dependent on both the pore pressure P_P and the temperature T. Batzle and Wang (1992) provide a series of empirical equations that attempt to estimate the velocities of heated oils, in general the velocity of these fluids decreases substantially with T and increase with P_P. Some of these effects as measured on a well known test fluid in our laboratory are shown in Figure 4.

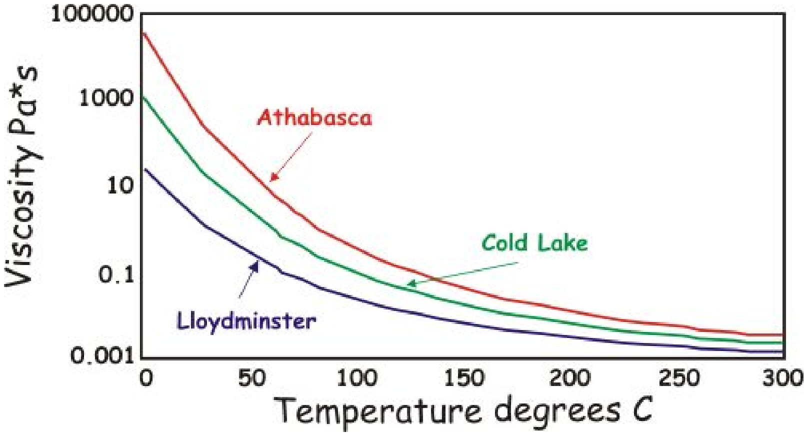

Figure 3. Typical viscosities of heavy oils as a function of temperature. The viscosity of pure water at 30°C is 0.001 Pa•s or 1 cPoise.

Reservoirs also contain gas phase fluids, however, primarily methane he case of SAGD, water vapor. The velocities of gases usually increase with T and P_P. It must be remembered that these gases are much more compressible than liquids (water or oil) and as is well known via Gassmann's relations, even a small gas saturation S_g of a few percent will influence the value of the effective bulk modulus K of the saturated rock. The degree to which K is changed will depend strongly on the drained frame modulus K_d. K is not changed substantially in stiff reservoir rocks (e.g. deeper Lloydminster reservoirs) by replacement of the liquid with a gas but in compressible formations (e.g. shallow Athabasca reservoirs) the variations are large (Schmitt, 1999). Such considerations should be taken into account when designing a time-lapse program (Theune and Schmitt, 2004).

Stress and Pore Pressure

During normal production, P_P is normally drawn down with time as fluid is removed from the reservoir. This has a number of effects, some that control the intrinsic fluid properties directly. However, the change in pore pressure also affects a number of mechanical properties. First, the frame bulk K_d and shear μ_d moduli of almost all rocks, and particularly poorly consolidated sediments, depend critically on the effective pressure (or more precisely stress) P_{eff} to which the material is subject:

$$P_{eff} = P_c - P_P$$

The dependence of effective pressure on the material properties is highlighted in Figure 5 modelled after Christensen and Wang's 1985 experimental results. The compressional wave (and also shear wave) velocity under conditions of $P_P = 0$ (red line) varies in a highly nonlinear fashion at low values of P_C. This nonlinearity is caused by continued consolidation of the material due with better grain-grain contacts and the closure of crack-like porosity within the material[2]. This means that as fluid is produced from the reservoir and P_P decreases, the seismic velocity of the rocks will generally increase; conversely, and increased pore fluid pressure results in a velocity decline. The other extreme occurs when both the pore and confining pressures are equal, in this case the velocity changes only very little with increased confining pressure (blue line). Figure 4 demonstrates that the seismic velocity can depend strongly on the competition between the confining and pore pressures. The degree of change depends on the structure of the pore space (i.e. vug-like to crack-like), the cementation of the mineral grains, and the porosity. While there are many theories that attempt to predict such properties on the basis of these pore factors, accurately

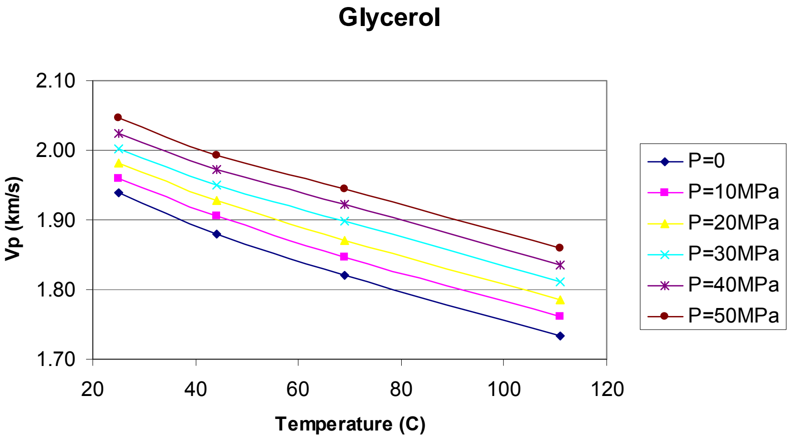

Figure 4. Compressional wave velocity in glycerol as a function of pressure and temperature.

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[2] See also He and Schmitt, Measurement of elastic frame properties on weakly consolidated sandstone in support of fluid substitution studies, this volume.

predicting such the pressure dependent behavior remains difficult and usually must rely on laboratory measurements to obtain some indication of the trends.

Fluid Substitution

The effect of fluid substitution is also critical to the overall seismic velocity and density, factors that influence the seismic reflectivity. Gassmann's relation depends on the effective pressure dependent K_d and K_{ef} (the fluid modulus) and on the more constant values of ϕ and K_s (the solid mineral grain bulk modulus). The effects of fluid versus gas substitution are highlighted in Figure 6 which is based on earlier laboratory experiments. There are two major observations. First, even a small amount of gas saturation has a large impact on the P-wave velocity. The reason for this is that as soon as the first bubbles appear in solution, the overall fluid compressibility nearly takes on that of the highly compressible gas but the density remains nearly that of the liquid. Both of these factor conspire to produce the large drop in velocity. Second, the shear wave velocity remains nearly constant with saturation increasing only a small amount with S_g because of slightly diminished density.

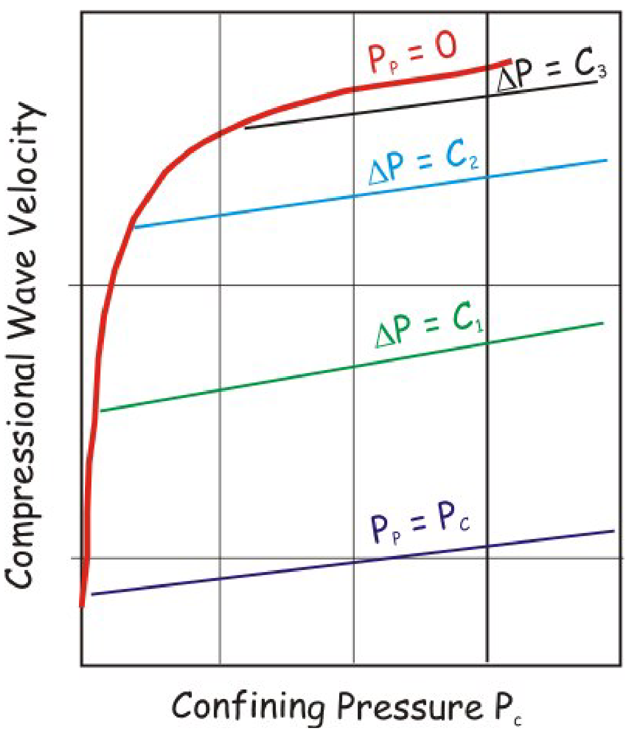

Figure 5. The effects of pore and confining pressure on seismic velocity. C_i refer to curves with a constant differential pressure P_c – P_P. After Christensen and Wang (1985).

The first factor is a critical point in time lapse studies. This means that the first appearance of gas will have a large influence on the overall velocity and hence the seismic reflectivity. The velocity does not change much with further increases in gas saturation; indeed, the slow change in velocity with increasing gas content indicates that the reflectivity itself cannot be used to predict gas content easily. Where this principle can be applied in seismic monitoring, however, is as a simple indicator of gas phase existence. This will occur in many reservoirs once the pore fluid pressure drops below the bubble point at which point gas comes out of solution. This may be problematic in many reservoirs but could be a sensitive gauge of in situ fluid pressures in cases such as cold production where fluid pressures in the reservoir drop below the bubble point regularly.

Structure of the Heavy Oil Reservoirs

Despite years of study, the pore scale structure of the heavy oil reservoirs is still problematic. The working assumption has always been that the quartz grains in the weakly consolidated sands are water wet with the result that a micron-scale layer of water surrounds the grains. This has important implications for grain-grain contacts and hence the overall compressibility of the medium. The source of this information remains obscure, but we have recently found microscopic evidence that the agent bonding the grains together is not water but heavy hydrocarbons. SEM images of an oil sand from the East Senlac, Saskatchewan reservoir suggest that some heavy oil components entirely coat the mineral grains and fill in the zones of grain contacts (Figure 7). This observation may have implications to the change in the bonding of the oil sands with temperature, if the hydrocarbons material is the cementing agent then the bonding strength, and hence elastic properties, are expected to decrease at higher temperatures.

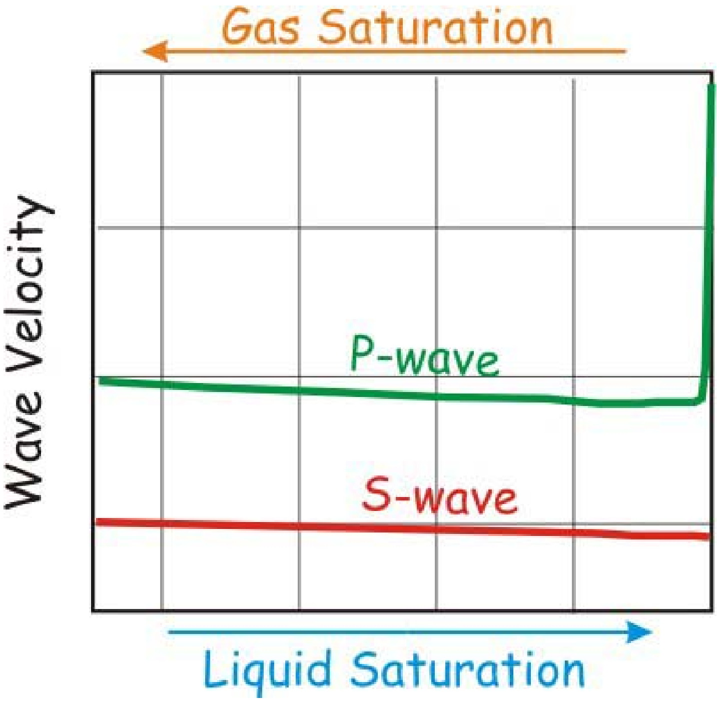

Figure 6. The effects of gas saturation on wave velocities.

Other Considerations

We have only touched on some of the more important rock physics considerations in the above material. However, what are often ignored are geotechnical effects on the materials. That is, what will be the effects of disruption of the rock matrix by the stresses induced by the flow of both heat and fluid through the rock. Such effects are intimately tied to pore pressures. In situ failure of the material can have two consequences. Either the material can dilate (expands) as it nears failure such that the porosity will be increased or under sufficient stress the material will be further consolidated with the crushing of the pore space. Either change will impact the elastic properties of the material.

Attenuation has not been discussed here in detail either. Anecdotal evidence and recent measurements (Solano and Schmitt, 2004) suggest that that attenuation of compressional seismic waves through the heavy oils can be substantial with Q values between 9 and 20. The mechanism of such attenuation is not known. The high values at seismic band frequencies are not supportive of a Biot bulk fluid motion mechanism and may be more in line with squirt-flow concepts. However, whether the correct crack-like porosity exists in oil sand deposits for the squirt-flow mechanisms to operate is debatable.

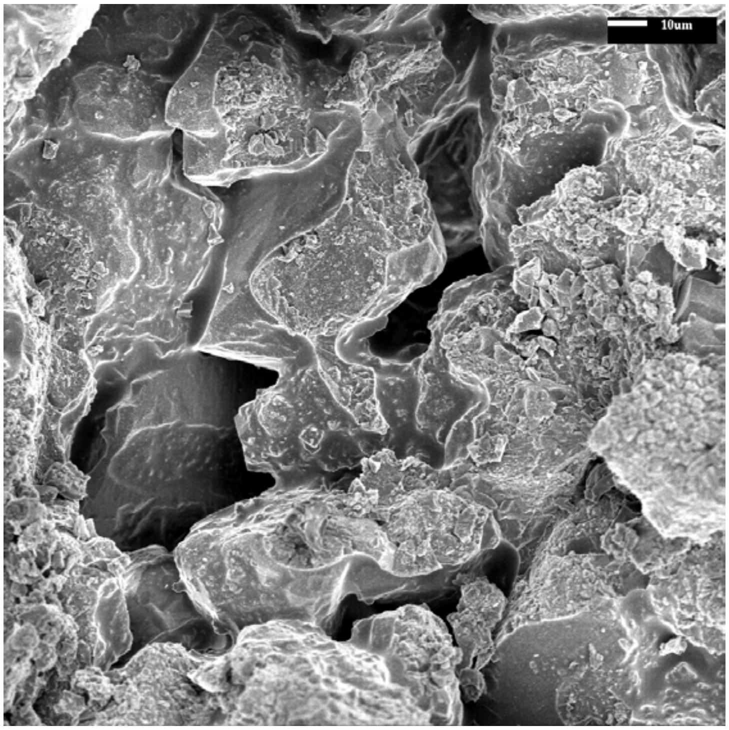

Figure 7. SEM of heavy oil core. Note that the mineral grains appear to be coated by a glassy material that is heavy hydrocarbons.

Conclusion

There are a large number of different extrinsic factors that influence the seismically-relevant intrinsic properties. While the behaviors are generally understood, the details for a given specific case remain difficult to obtain. Currently, laboratory measurements remain the only way to provide trends. However, this information is critical to the interpretation of time-lapse seismic results and is currently the weak link in trying to incorporate engineering, geological, and geophysical results. Work in our laboratory will continue in the better delineation of the physical properties of the fluids and frame moduli of heavy oil bearing rock.

Acknowledgement

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