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What Can Rock Physics Tell Us About Steam, Gas Migration, and Stress in SAGD Seismic Monitoring?

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ABSTRACT

Most heavy oil reservoirs, like those found in the Canadian oil sands, require enhanced recovery methods such as Steam-Assisted Gravity Drainage (SAGD) due to the extremely high viscosity of the oil. To monitor these operations, we rely on time-lapse seismic data to observe changes in the reservoir's elastic properties. Interpreting these changes meaningfully requires a deep understanding of the rock-fluid system, and this is where rock physics modelling plays an essential role.

One of the key challenges in modelling is the behavior of bitumen, particularly its shear modulus. Unlike true fluids, bitumen can transmit shear waves under certain conditions, especially at lower temperatures or higher frequencies. Throughout the life of the reservoir, bitumen transitions from solid-like to viscoelastic and eventually to fluid-like behavior, depending on its composition, temperature, and seismic frequency. In time-lapse seismic, these transitions help us identify zones where bitumen remains cold, becomes mobile, or is replaced by steam.

Our rock physics modelling focused on two main scenarios:

1) Initial reservoir conditions - the reservoir was modelled as an unconsolidated sandstone (Dvorkin and Nur, 1996), incorporating local geological constraints such as lithology, mineralogy, stress, pressure, temperature, and fluids. Bitumen shear modulus at reservoir temperature was calibrated using well data, fluid properties were modelled with the Baztle-Wang (1992) empirical model, and fluid effects on rock properties using a heavy-oil-specific approach (Ciz and Shapiro, 2007).
2) Steam injection conditions - facies-dependent changes were modelled to reflect increased pressure and temperature, and the replacement of bitumen with steam, hot water, or both. Steam injection significantly alters the reservoir's elastic properties, primarily by reducing the bitumen's shear strength, which was quantified using the Javanbakhti empirical model (2018).

Beyond these core scenarios, we examined two interesting 4D seismic observations:

- A strong amplitude anomaly outside the steam chamber, likely due to gas migration or exsolution. Both mechanisms predict similar P-impedance reductions, consistent with seismic data, but without supporting pressure observations, the cause remains uncertain.
- A time advance anomaly below the reservoir, mirroring the steam chamber. If a true physical response, it may result from stress reorientation at the chamber boundaries. Acting like a fluid zone, the chamber cannot support significant shear stresses and may redirect stress trajectories, increasing effective stress and seismic velocity in surrounding rock.

The steam injection modelling also highlighted the challenges in predicting temperature from 4D seismic data, resulting from ambiguities between the effects of temperature and fluid saturations.

This modelling can be further used to interpret the 4D seismic inversion results and generate volumes that illustrate the reservoir changes discussed. It also highlights the meaningful role that rock physics modelling plays in deepening our understanding of SAGD efficiency, especially considering the competing effects of increased pressure, temperature, and fluid replacement on the fluids and the rock frame.