Time-Lapse Monitoring of Steam Assisted Gravity Drainage (SAGD) of Heavy Oil using Multi-Transient Electro-Magnetics (MTEM)

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Introduction

Currently, the most important process for in situ recovery of heavy oil is SAGD (Steam Assisted Gravity Drainage). This process has opened up the heavy oil sands in Alberta to economically successful exploitation, allowing Canada to increase their recoverable reserves to the second largest in the world after Saudi Arabia.

The total amount of recoverable oil in the Alberta oil sands using current technologies is estimated to be at least 175 billion barrels. Approximately 10 % of the area can be exploited by excavating the oil sand, but the remaining deposits have to be produced in situ.

Seismic monitoring is an established technology to optimize reservoir drainage in new and existing fields. However its applicability is limited to high porosity reservoirs and light, low bulk modulus hydrocarbon fluids. Hence, seismic cannot accurately characterize the heavy oil saturation in situ, but can easily detect the reservoir quality rock volumes occupied by live steam. Seismic can then show the volume occupied by live steam but not the residual saturation, nor where the remaining oil is located. Multi-transient electro-magnetic (MTEM) is a new technology that shows promise to characterize in situ reserves followed by monitoring steam saturation, temperature and residual oil saturation during SAGD production.

The SAGD Process

The SAGD process is based on the emplacement of parallel horizontal well pairs located at the bottom of the oil sand maintaining a vertical separation of approximately 5 m over a distance of 600 – 1,000 m length.

Initially, steam is injected along both well tracks in a steam soaking process. This is intended to mobilize the oil in the volume surrounding the wells facilitating free flow of fluids.

The lower well is then converted to a production well while the upper well continues as a steam injection well. The two well tracks are located at the bottom of the oil saturated formation and some distance above the occasional water aquifer.

When steam is injected into the reservoir rock through the upper well track, the heated oil is mobilized and flows down towards the producing well where pressure is maintained slightly below the in situ reservoir pressure. The heated oil releases hydrocarbon gas that improves the recovery by displacing mobilized oil faster.

There is a need to monitor the SAGD process making sure the steam reaches the entire oil charged volume located in the immediate vicinity above the horizontal injection/producer wells, and also making sure the steam does not break through the regional seal and migrate to the surface creating a catastrophic blowout.

To take full advantage of the superior 3-D imaging capability of seismic, very large offsets are required to provide the necessary migration aperture. Hence, it takes a very large surface spread of geophone arrays to image a small target and the acquisition and processing cost are substantial. In addition the steam injection generates white noise requiring high fold to improve S/N.

The MTEM Method

MTEM (Wright et al., 2002) is a time-domain method where current is injected into the ground between two source electrodes and the resulting potential field is measured between pairs of receiver electrodes. All electrodes are in a straight line. The distance between source and receiver is referred to as the offset and the common mid-point (CMP) is where the data is posted. The source signal is a Pseudo Random Binary Sequence (PRBS) providing a white spectrum. The source bandwidth is optimized to the offset, typically in four steps, taking into account that only the lower frequencies will reach the far offsets.

Processing, including source signature and system response deconvolution, results in the earth's impulse response function for each source – receiver pair. The impulse response function rises to a peak value and then decays to zero. The entire shape of the impulse response depends on the resistivity depth profile which is recovered in the subsequent inversion of the processed data. The amplitude of the peak and the timing of the peak can be evaluated as trace attributes providing real time information regarding the subsurface resistivity.

SAGD Resistivity Effects

By rearranging Archie's equation (Asquith et al., 2004) we can express the resistivity of the rock as: $R_t = \dfrac{a \cdot R_w}{\phi^m \cdot S_w{}^n}$; where $a =$ tortuosity, $R_w =$ water resistivity, $\phi =$ porosity, $m =$ cementation exponent, $S_w =$ water saturation and $n =$ saturation exponent.

Live steam is free from dissolved salts and exhibits very high resistivity. In this sense it is similar to a hydrocarbon fluid.

As steam propagates through the rock the resistivity is affected in three different ways:

- Temperature rise: exposure to steam increases the temperature, hence lowers the resistivity of the pore fluid and the resistivity of the rock.
- Steam condensation: Accumulation of condensated steam in the pore-space increases the water saturation, hence lowering the resistivity of the rock.
- The condensated water dilutes salinity, and where the accumalating water is also constantly drained away, the dissolved salts are depleted and the resistivity of the rock increases.

Temperature affects the resistivity of the pore water according to the following expression (Desai et al., 1969):

$R2 = R1 \cdot \left[\frac{(T1 + 21.5)}{(T2 + 21.5)} \right]$; If the resistivity R1 is known at the temperature T1 (C), then the resistivity R2 can be calculated at the temperature T2 (C).

The steam effect is quite dramatic since these rocks are at a low in situ temperature. Assuming the rock is initially at approximately 10 C, we find that at 42 C the resistivity ($Rt \,\&\, Rw$) has decreased to half and at 105 C it is down to only ¼ of the in situ resistivity.

Condensation water from the steam is free from dissolved salts and this will reduce the salinity of accumulating pore water by mixing with the in situ pore water. The net effect is a decrease in resistivity except close to the injection site where water is constantly condensing due to the pressure drop upon entering the reservoir. The long term effect is that accumulating water is also constantly drained away thus depleting the dissolved salts over time. This results in a dramatic rise in the resistivity in the vicinity of the steam entry point creating a high resistivity halo along the injection well track over time.

Cross-Section of a Mature SAGD Chamber

There are reservoir simulators available specifically designed to model the SAGD process and by tracking the temperature and saturation, we can map the resistivity changes. However, it is also possible to deduce the sequence of events in a mature steam chamber with the main physical processes highlighted to create an understanding of the process and how it is expressed in changing resistivity. In Figure 1 below we can examine the cross-section in the reverse direction from the thermal front on the right towards the injector to the left. At the thermal front the resistivity dips quickly from the nominal in situ oil-charged reservoir resistivity of 175 ohm-m.

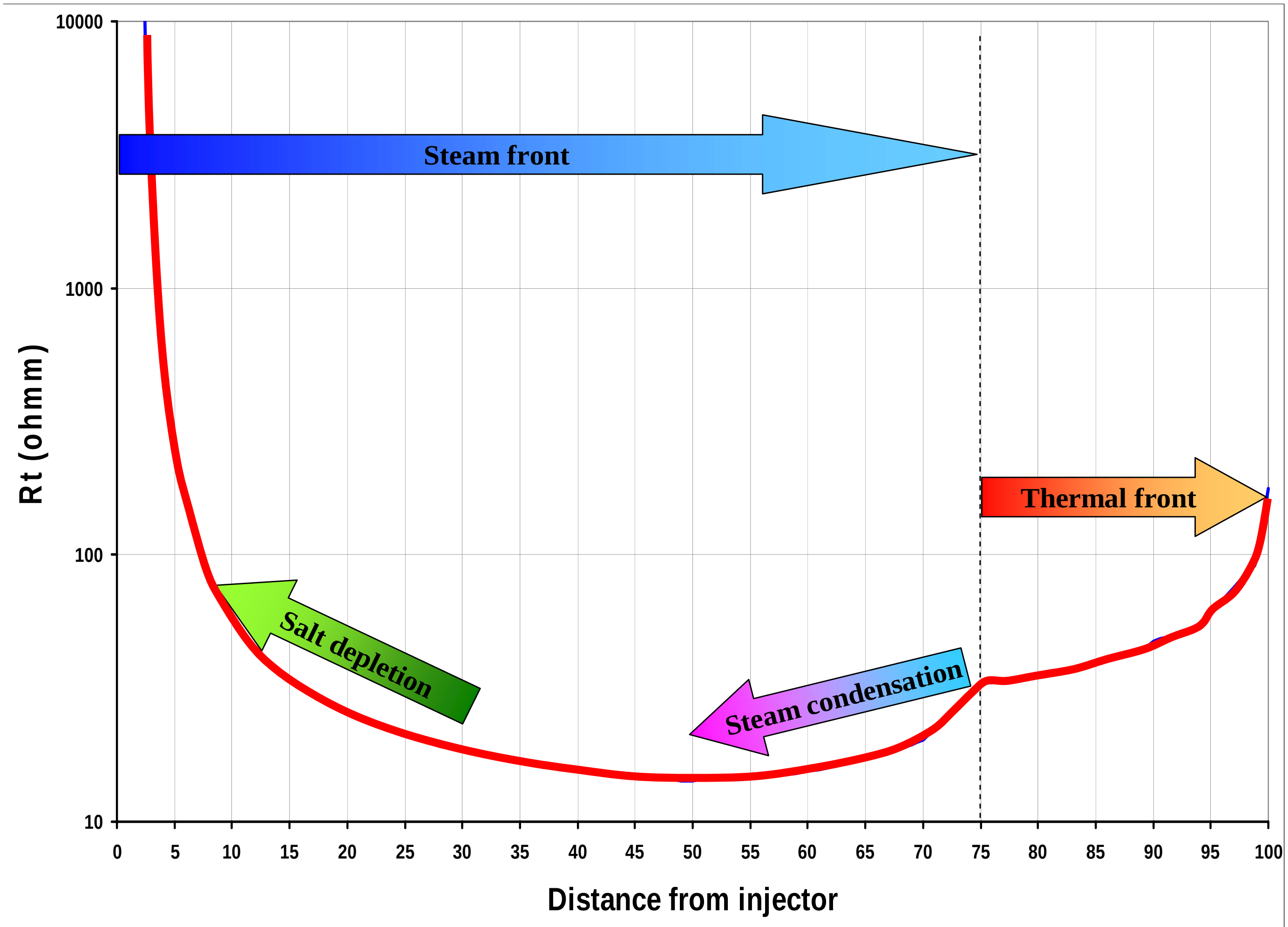

Figure 1. Cross-plot of a cross-section through a mature steam chamber with the injector to the left and the thermal front to the right. The oil-charged in situ resistivity is 175 ohm-m. The "Distance from injector" scale have unit-less reference numbers. A mature steam chamber expands very slowly whereas the thermal front expands at a constant rate, hence will at some point create a thermal shell that grows in thickness over time. Looking at the profile from the edge of the thermal shell towards the injector we observe the resistivity trend dropping quickly at the thermal front and experience a second sharp dip at the steam front where condensation water increases the Sw. A minimum resistivity is reached at reference distance 50 where the accumalated condensation water has removed sufficient amounts of dissolved salts to reverse the decreasing resistivity trend. At approximately reference distance 5, the resistivity has returned back to the in situ value but increases dramatically towards the injector.

There is then a second sharp dip at the steam front, reference distance 75, where the water saturation starts to increase in the pore space. Half-way through the profile there is a minimum in resistivity at which point the salt depletion reverses the resistivity trend. At approximately reference distance 5 the resistivity is back to in situ level but continues to rise dramatically towards the injector due to the extreme salt depletion.

Conclusions

Time-lapse seismic is an established technology where the steam chamber evolution can be tracked through the changes in eleastic properties; mainly the bulk modulus. The steam injection can also be monitored by MTEM by tracking the changes in resistivity. The strengths and weaknesses between seismic and MTEM monitoring are shown in Table 1 below:

Table 1. A comparison of strengths between MTEM and seismic time-lapse monitoring of the SAGD process

Characterization aspect	MTEM strength	Seismic strength
Early steam entry into oil sand	Yes	Yes
Spatial resolution	No (laterally yes)	Yes
Ability to image complex shapes	No	Yes
In situ oil saturation	Yes	No
Steam saturation in oil reservoir	Yes	No
Temperature in oil Reservoir	Yes	No
Early steam entry into brine reservoir	Yes	Yes
Signal/Noise	Yes	No
Repeatability	Yes	No
Acquisition & Processing cost	Yes	No

References

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