High Resolution Seismic Modeling and Monitoring of the SAGD process at the Athabasca tar sands: Underground Test Facility (UTF)

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Introduction

The Underground Test Facility (UTF) site is located approximately 60km northwest of Fort McMurray, Alberta and was initiated in 1984 by the Alberta Oil Sands Technology and Research Authority (AOSTRA). The purpose of this facility is to validate the Steam Assisted Gravity Drainage (SAGD) method, commercial viability and ancillary operations. The UTF consists of two vertical shafts 3.3m in diameter penetrating 140m of overburden, 20m of oil sands and 15m of limestone. Within the limestone formation, a horseshoe-shaped horizontal tunnel 5m wide and 4m high was excavated. From these tunnel walls, horizontal wells were drilled upward through the limestone sequence then horizontal through the lower pay zone of the oil sands (figure 1).

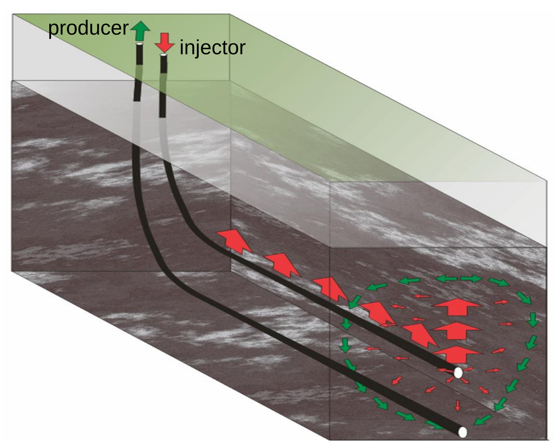


Figure 2: Schematic representation of the SAGD method

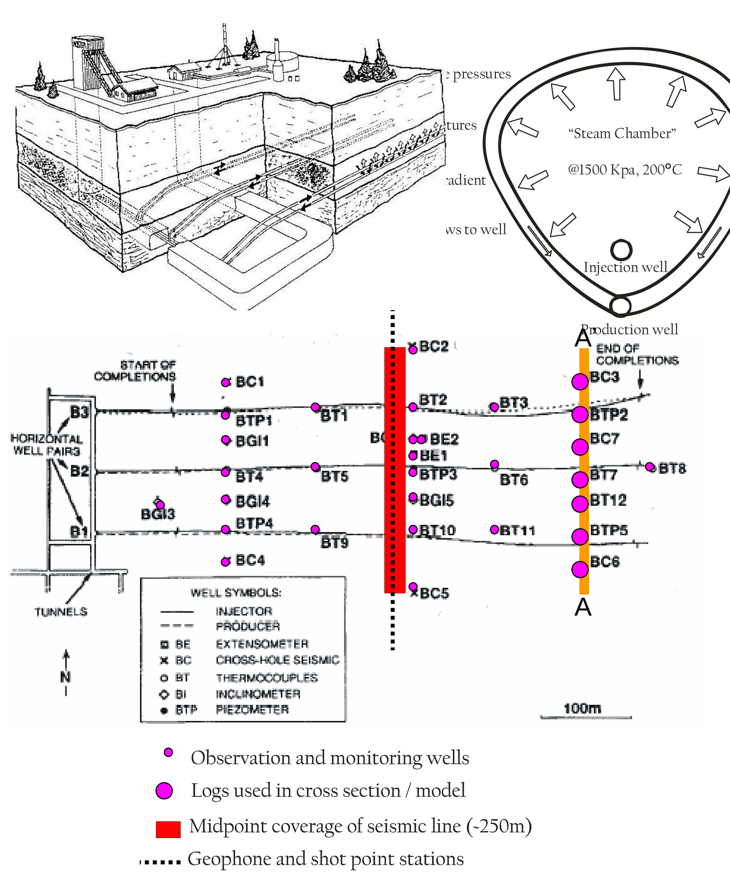


Figure 1: Shaft and tunnel access concept (top), and map view of UTF site, seismic survey and observation well locations (bottom)

11 repeated lines of 2-D seismic data, acquired by the University of Alberta from 1995-2000, provide major insights into the timing and potency of seismic attributes that can delineate the SAGD physical process.

The goal of this research is to,

1) integrate all available well data and reservoir data into a detailed rock physics model of the fluid substitution and production related processes in order to extract suitable seismic attributes indicative of SAGD evolution,

2) examine the data reproducibility conditions required to perform reservoir surveillance,

3) use repeated seismic profiles to create an image of the steam chamber and depleted reservoir zone.

For small scale seismic reflection surveys, often conventional processing techniques do not produce desired results. To bypass significant near surface static and surface wave problems, the shift stack processing procedure was employed [Schmitt, 1999]. This procedure takes a minimalist approach to processing, and due to its simplistic nature, lends itself more agreeably to time-lapse analyses of multiple data sets. Application of this method yields a favored image of the reservoir over conventional processing (i.e. standard velocity analysis NMO-correction, and stack).

Geological database and cross-section

It has been recognized that the geological setting and reservoir heterogeneity impacts significantly on the recovery process. Barriers to vertical steam / bitumen flow are apparent in core analysis [Strobl et al.,1997], but is not easily distinguishable on well logs and seismic data.

The high density coverage of well logs over this site (~every 40m) allows for the accurate construction of a high resolution 2D velocity model for seismic waveform modeling, analysis, and processing applications.

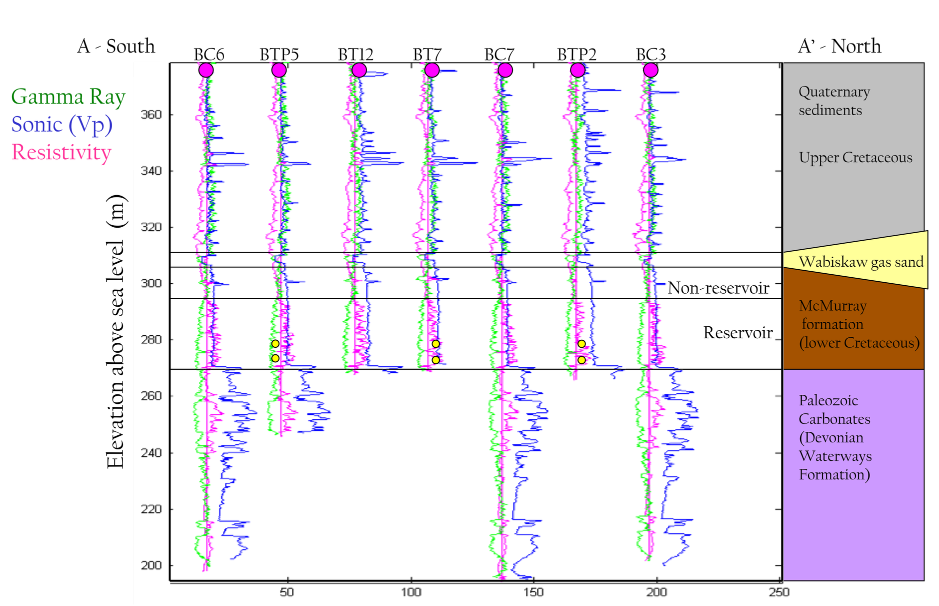


Figure 3: Simplified geologic cross section A-A' (see Figure 1). The approximate positions of the well pairs are denoted by the yellow dots. Notice how distinctly flat and laterally homogeneous the log response is across the survey area.

Due to the pronounced horizontal continuity of the well log response across the study area, the velocity model was constructed to contain as much of the well log signal as possible. The velocity model shown in Figure 4 is interpolated from the well logs and has the same vertical resolution (i.e. 10 cm by 10 cm cell size). This model was created with intentions to study the complex wavefield interactions not only within the reservoir zone, but also above and below the reservoir.

The steam chamber is represented in this velocity model by a simple ellipse shape indicating a rising chamber. The velocity in the heated zone is modeled with a constant 10% decrease in velocity simulating a mixture of steam, hot water, and residual hydrocarbons in the pore space. In reality, there is likely to be greater complexity within the multi-phase system (oil, water, steam, gas, and residual hydrocarbons), and consequently high uncertainty in the true velocity anomaly. The size and shape of the anomaly is affected further by more complex interactions such as conductive heating, steam condensation, gas exsolution, etc. Modeling of all these effects on the rock properties is going to require tighter integration with reservoir engineering data.

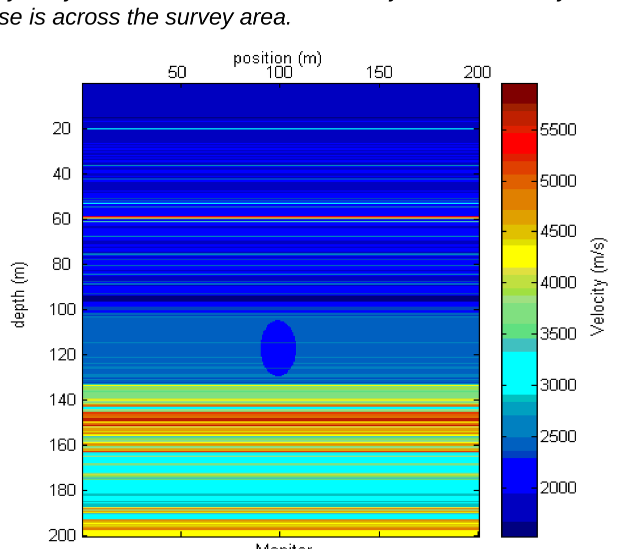


Figure 4: High resolution acoustic velocity model derived from sonic logs shown in figure 3.

Wave propagation

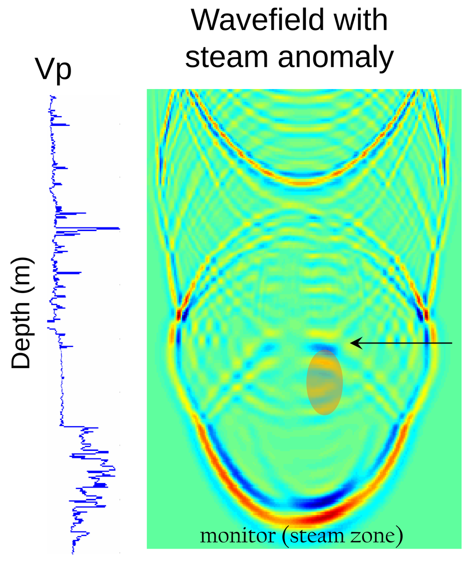


Figure 7: Wavefield simulation of the SAGD process

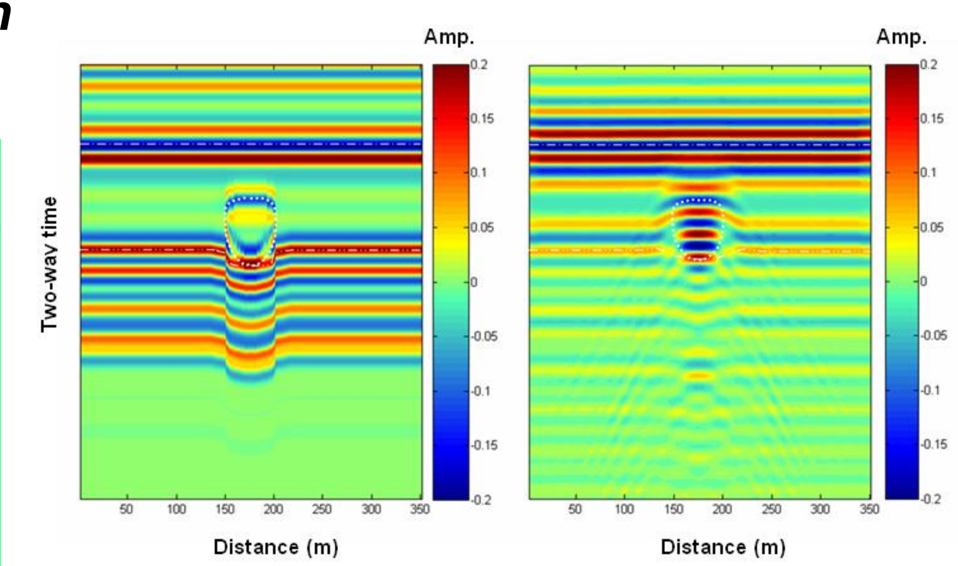


Figure 8: Wavefield simulation at surface, shot gathers

To explain the propagation of seismic energy through the subsurface, a finite-difference algorithm was employed to calculate the wavefield generated through the acoustic velocity model shown in Figure 4. Figure 7 shows a snapshot in the wavefield before (left) and after (right) steam is injected into the reservoir. The anomaly produced by the steam zone yields an increase in amplitude and large time delay as anticipated, but this example also shows that the fluid substitution exhibits scattering symptoms; portraying diffraction hyperbolae, complicated reverberations and multiple reflections from within the steam zone (Figure 8). The perturbation in the wavefield is very localized about the steam zone and there are subtle seismic attributes contained in the gather that might be lost after stacking processes are performed.

A key step in survey planning?

The results from this analysis suggest that the feasibility of seismic monitoring does not only depend on the thermal and mechanical related changes associated with the fluid substitution, but also on the scale of the steam anomaly itself. Thorough rock physics modeling can aid in the long term survey design for monitoring reservoir depletion. Parameters such as spatial sampling, optimal fold, repeat time intervals, source type, etc., can all be evaluated prior to first steam.

With the exception of surface waves (a), near surface refractions (b), airwave noise (c), and static problems, the numerical simulation is successful at reproducing the field data set (Figure 9).

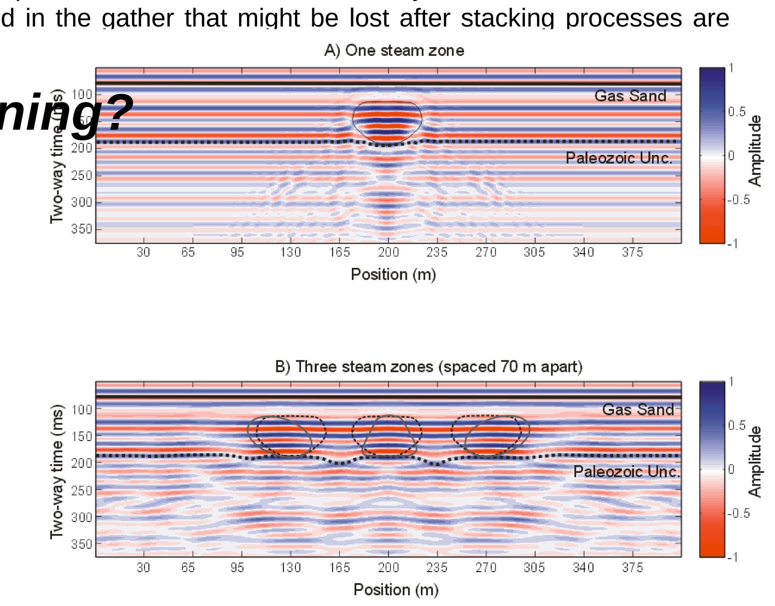


Figure 9: Comparison between field data and synthetic data

Single channel repeatability: constant-offset gathers

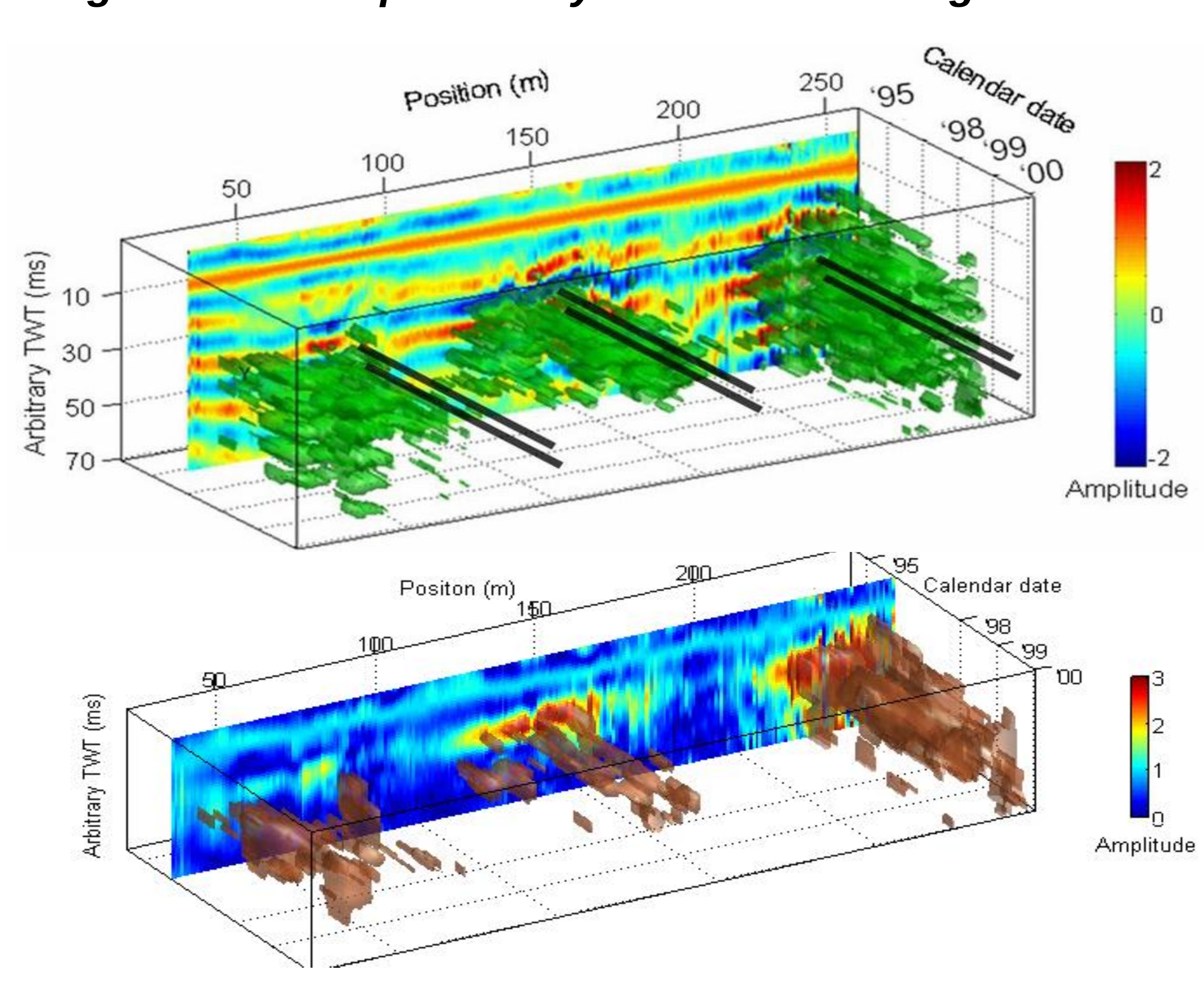
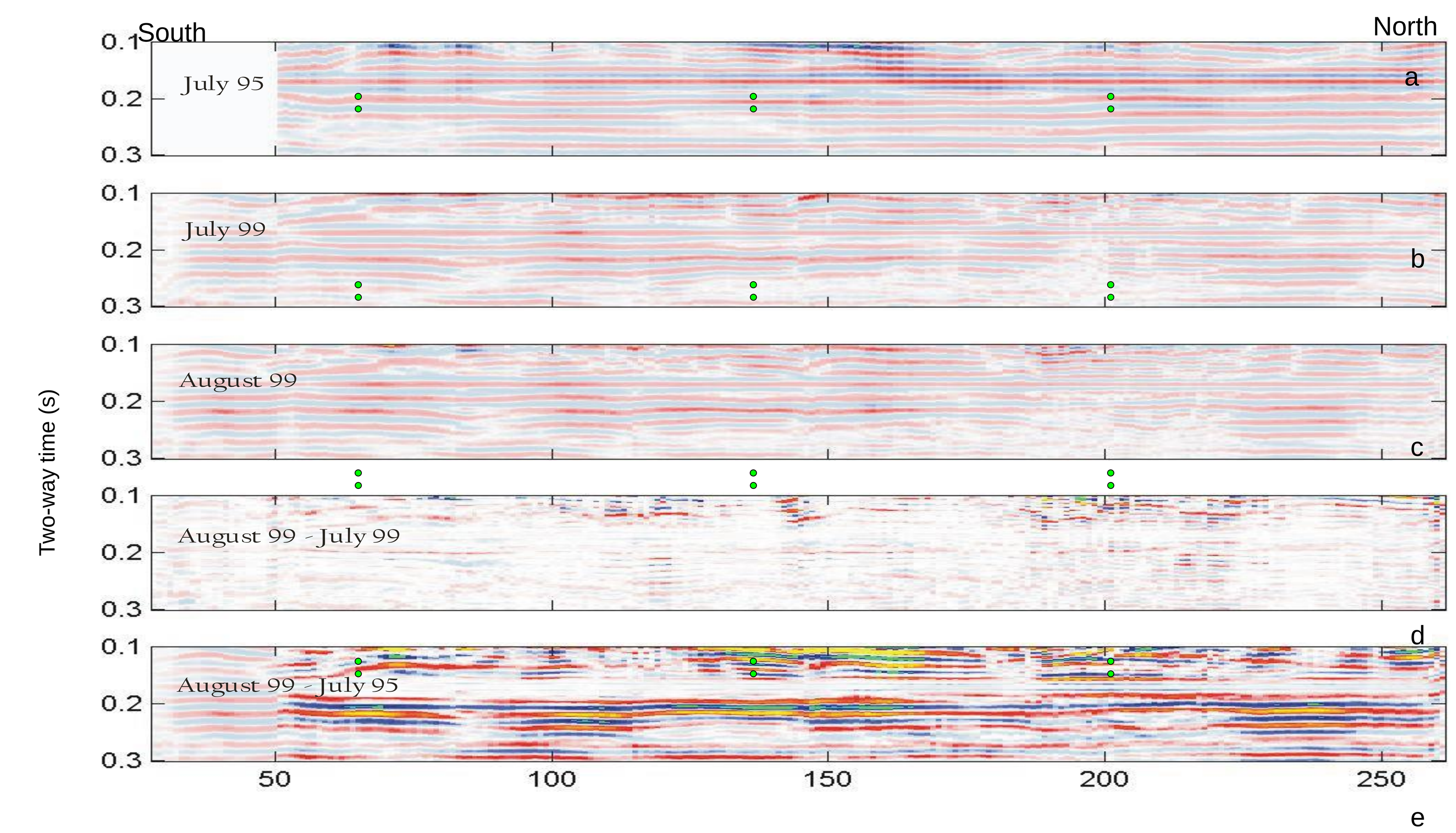


Figure 10: 3D representation of 11 seismic profiles as a function of time. a) A semi-transparent volume rendering of the highest amplitude values coincide with the locations of the well bores. Notably, the left chamber presents asymmetric growth indicating a steam baffle or permeability heterogeneity to the right. a) A Hilbert-transform of the seismic traces consolidates the amplitude energy and demonstrates amplitude weakening upon steam chamber cooling

High resolution seismic data and time-lapse imaging



- A truck-mounted weight drop source was used to collect these data. The source was reliable and repeatable, however is narrower in bandwidth and lacks higher frequencies compared to dynamite or vibroseis sources.
- Repeated, high density seismic reflection lines were collected as an experiment to test repeatability conditions, and to try to image the steam zones and heated regions of the reservoir (Panels a, b and c). Data was processed to maintain consistent amplitudes from one survey to the next.
- Over a one month period, there is little change between profiles, but there are large problems repeating data in the near surface.
- Significant time-lapse signals can be generated by "differencing" two profiles. The anomalies in the reservoir region are highlighted by time-delay and amplitude changes between two surveys. The effects of poor near surface conditions are also amplified.
- The seismic data suggests that the evolution of the steam chamber and corresponding depletion of the reservoir is not symmetric about the well pairs as proposed by many engineering models (i.e. Figure 6). Panel e is likely exhibiting the cumulative effects of a variety of heated regions, thermal and mechanical effects, and irregular patterns of operation shut downs throughout the course of the program.
- "A reservoir can only be produced once, and it is difficult and costly to correct mistakes in the approach, once the project has been initiated" Chow and Butler, 1996.

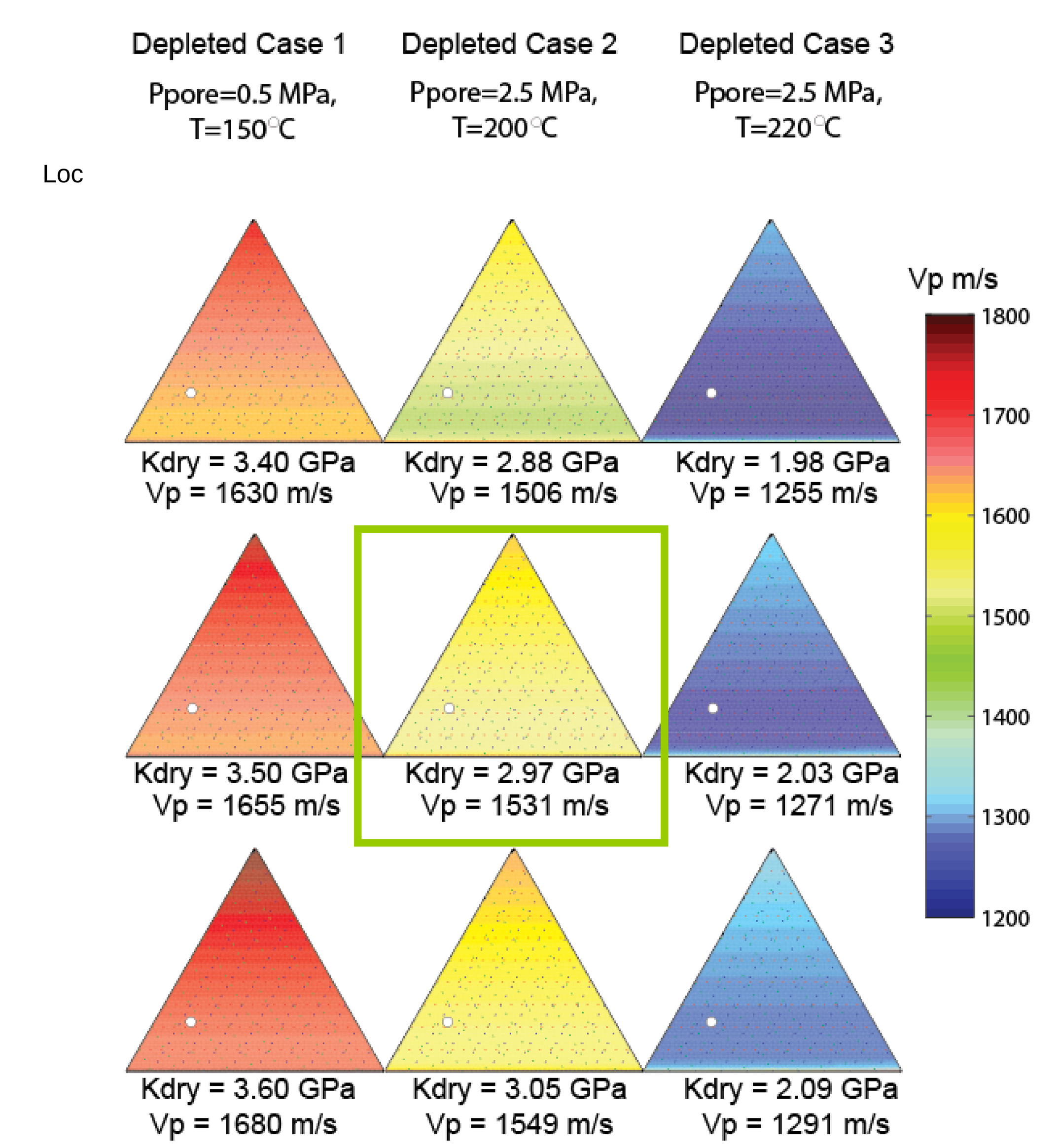


Figure 11: Ternary diagrams to express the P-velocity variation as a function of a 3-phase fluid (oil, water, steam) pore system. Injected steam increases pore pressure which dramatically affects the rock frame modulus .

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