

Simultaneous inversion for velocity and passive microseismic event locations: a particle swarm optimization approach

Sary Zantout^{1,2}, Ted Urbancic¹, and Peter McGillivray³

¹Engineering Seismology Group, Kingston, Canada,

²sary.zantout@esg.ca

³Shell Canada Limited, Calgary, Canada

Summary

Passive microseismic monitoring of cyclically steamed production wells has been gaining popularity as a potential tool for optimizing drilling by delineating lateral and vertical steam migration within the reservoir. The initial challenge with passive monitoring was to create robust systems capable of permanently recording data with semi-automated triggering thresholds and remote data transfer capabilities for further data processing. While these technical challenges have been overcome in the past few years, the present challenge with long-term monitoring is in accounting for the dynamic processes taking place within the reservoir as steam is introduced. The introduction of fluid and varying temperatures during cyclical steaming cycles have direct influence on the pre-existing physical properties of the rock and as a result, the velocity model in use needs to be calibrated accordingly. Since passive source waveforms are influenced by the dynamic nature of the reservoir properties it is sufficient to say that their associated event locations need to account for these changes. To this end, we employ a Particle Swarm Optimization (PSO) approach to invert for both the velocity model and the spatial locations of the events. Based on this approach, we observed *P*-wave velocity reductions up to 16% at the reservoir level for any given cycle. The re-located microseismic events appear ‘well behaved’ in the context of reservoir processes, and the location uncertainty of the re-located events dropped by approximately 21%. The approach further opens opportunities to examine the anisotropic conditions in the reservoir and assist in re-defining velocity derived lithologic boundaries.

Introduction

Shell Canada's Peace River *in situ* heavy oil production operation in northwestern Alberta consists of 9 pads of multi-lateral and single lateral horizontal wells set out to steam the bitumen-saturated sand reservoir, while using the same wells for production. While the Peace River bitumen production operation has been in place since 1986, little is known about the reservoir processes, thus making it difficult to optimize drilling. Specifically, the lateral steam movement away from the wells and how the steam distributes itself vertically can be ambiguous (McGillivray, 2005). As such, continuous microseismic monitoring systems were installed at several pads since 2002 in an attempt to better understand these processes.

The initial challenge in passive microseismic monitoring of permanent production reservoirs is in creating and maintaining a robust monitoring system. These challenges have been overcome by the development of 24-bit semi-automated systems, with permanently installed downhole geophones, capable of providing near real-time feedback on dynamic reservoir behaviour (Urbancic, 2005). The present challenge of permanent monitoring is to account for the dynamic processes taking place within the reservoir while locating microseismic events.

During cyclical steam stimulations, some physical properties affecting seismic wave velocities in rock may change. These include changes in the elastic constants of the rock, porosity, pore fluid characteristics, consolidation, pore geometry, hydrocarbon saturation and effective pressure. More importantly, changes in pressure and pore fluid compressibility appear to have the most effect; high pore fluid pressures generated by thermal volume expansion of heavy oils were found experimentally to affect *P*-wave velocities, but not to the same degree as for *S*-wave velocities (Wang and Nur, 1988). Several laboratory measurements (Nur et al., 1984 and Nur, 1987) of seismic velocities in heavy oil-saturated rock sample show that, in general, *P*-wave velocities decrease with increasing temperature. The amount of velocity reduction, however, is unique for each site depending on the composition and viscosity of the hydrocarbons and the nature of the host rock.

Several time-lapse three-dimensional and multi-component seismic reflection experiments (for example Isaac, 1996) have shown *P*-wave velocity reductions and decreased V_p/V_s ratios during steaming cycles. At Peace River (Pad 40), based on time-lapse studies over multiple steaming cycles, a 17% *P*-wave velocity reduction was observed at the reservoir level (McGillivray, 2005).

To perform reliable seismic velocity inversions, it is usually assumed that the shot locations are known to a relatively high precision. However, in passive microseismic monitoring, the objective is to locate events, and therefore the locations inherently contain errors. To avoid some caveats of conventional methods of seismic velocity inversion, we exploit a method based on Particle Swarm Optimization (PSO; Kennedy and Eberhart, 1995), whereby both the velocity model and source locations are simultaneously inverted to find the best fit solution for the event locations and the change in velocity model.

In this paper, we examine microseismicity recorded over multiple steam cycles at Pad 30. Initial processing assumptions assumed that the changes due to steaming in the reservoir would have minimal affect on the raypaths, which, for the most part traveled in the zone situated above the reservoir. The observed events, under this assumption, were found to locate upwards to 150 m from the injector wells, and in one case, in an event distribution that paralleled the well configuration (Northwest quadrant, Figure 1). By utilizing the PSO approach, we examine the validity of the above assumption and assess how changes in velocity resulting from steaming affect the calculated event locations.

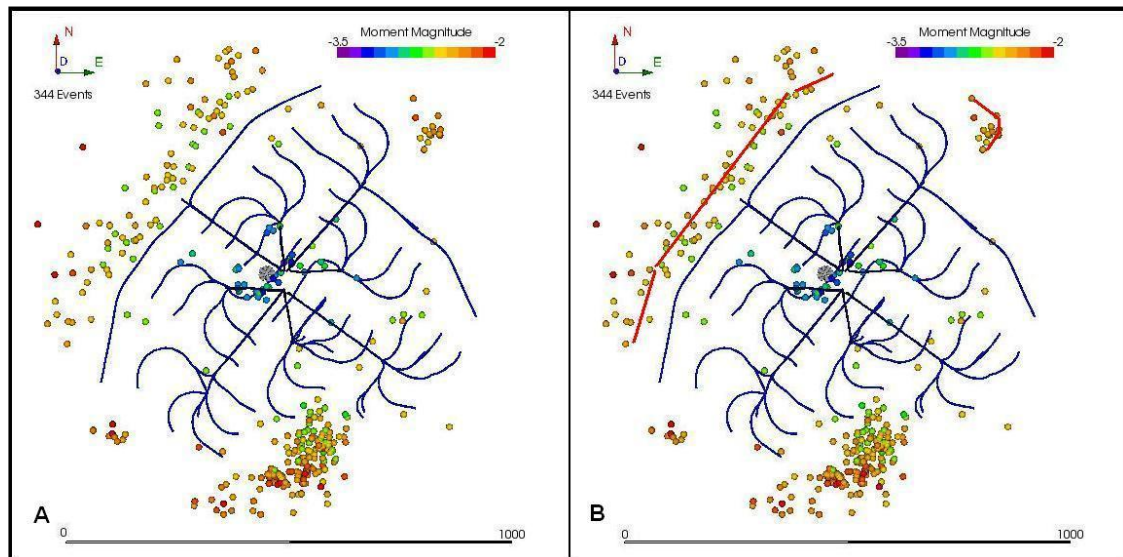


Figure 1: (A) Microseismic events in plan view recorded during the 4th steaming cycle located using original velocity model. (B) A trendline (red) over the northwest and northeast clusters.

Microseismic Data Acquisition and Processing

Passive monitoring of acoustic emissions, or small magnitude microearthquakes (microseismicity), associated with stress changes within the reservoir can be used to image reservoir dynamics. As the rock mass reacts to stresses and strains associated with pressure and temperature changes during steaming cycles, microseismic events are generated from these movements (either along preexisting weak structures or creating new fractures). The microseismicity can be used to localize fracturing or to deduce geomechanical details of the deformation.

At Shell Canada's Peace River production site, Pad-based microseismic monitoring began in 2002. Currently, there are four passive microseismic monitoring arrays are operational. At Pad 30, microseismicity associated with steam cycles 3 and 4 have been detected. In total, 680 microseismic events were recorded for the last two steaming cycles.

As previously shown in Figure 1, the processed microseismic events of the 4th steaming cycle at Pad 30 appear to be systematically offset by approximately 150 m from the wells. Also, two clusters of events recorded during the 3rd cycle appear to locate north and south of the pad by about 100 and 150 m, respectively (Figure 2). The southern cluster of events in Figure 3 appear to lie in the buffer zone between Pad 30 and Pad 31 to the south.

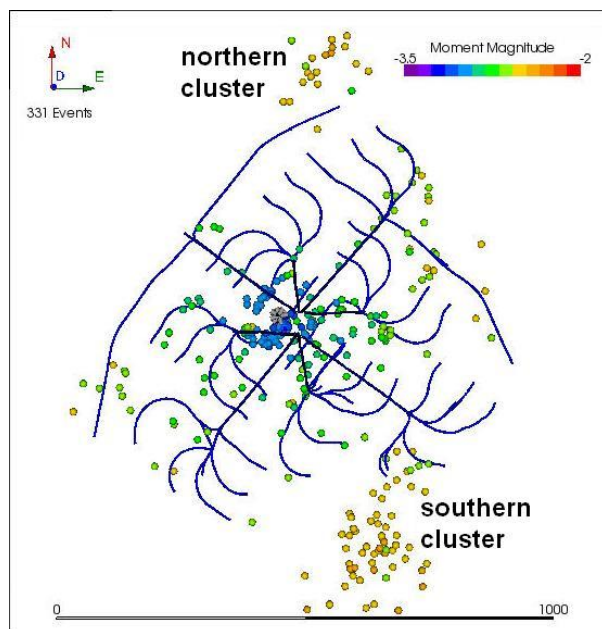


Figure 2: Plan view of cycle 3 microseismic events at Pad 30 located using original velocity model. The southern cluster of events lie in the buffer zone between Pads 30 and 31.

Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a population-based stochastic optimization technique developed by Eberhart and Kennedy in 1995, motivated by flocking birds and fish schooling. Each particle represents a set of specified

parameters of interest. In our case, these are the spatial coordinates of a subset of the microseismic events generated from each steaming cycle and the P - and S -wave velocities for each of the predefined stratigraphic layers.

The particles change their positions in a multidimensional search space. Each particle, while in motion, keeps track of its coordinates as it adjusts its position according to its own experience or best solution (fitness) it has achieved. The best fitness value of its neighboring particles is also stored (known as the local best), along with the best value of the entire population (known as the global best). At each time step, the velocity (or jump) of each particle changes according to each particle's best location and the local best solution.

PSO Results and Reprocessed Events

A subset of about three dozen located events from each steaming cycle were selected for the inversion. Most events lie within the reservoir layer at depth 590 m. There are no PSO velocities for the first two layers because there are no raypaths from the events in these layers. The cycle 3 inversion results show little P -wave velocity variations for the four layers (Table 1). The S -wave velocities seem to exhibit the most variation, especially for the 510 and 590 layers. For the cycle 4 inversion (Table 2), again we see a large S -wave velocity variation for the 510 layer. However, for layers 570 and 590 (where most events lie), we see a drop in S -wave velocities and a 16% decrease in the P -wave velocity at the 590 velocity layer. Table 3 shows the PSO results in comparison for cycles 3 and 4.

The reprocessed events using the two new velocity models brought the events closer to the pad and wells (Figure 3). The southern cluster of events that appeared to locate in the buffer zone is now closer to the southern wells at Pad 30, however, they still occur off-Pad, suggesting that the buffer zone between pads may be susceptible to being breached in the future. The events that were relocated closer to the pad (and the receiver array) are lower in moment magnitude. The average residual location errors for the reprocessed events using the new velocity model is lower by 21% than was previously calculated.

Depth (m)	Original Velocities (m/s)		CYCLE 3 PSO		Variance		V_p/V_s	
	V_p	V_s	V_p	V_s	V_p	V_s	Org.	Est.
300	2200	800	-	-	-	-	-	-
360	2400	1000	-	-	-	-	-	-
510	2300	1100	2322	1290	1.0%	17.3%	2.09	1.80
570	2500	1400	2556	1501	2.2%	7.2%	1.79	1.70
590	3000	1500	2977	1639	0.8%	9.3%	2.00	1.82
---	3800	1800	3607	1900	5.1%	5.6%	2.11	1.90

Table 1: Cycle 3 PSO results. The largest variations are exhibited by the S -wave velocities, especially for layers 510 and 590. The V_p/V_s ratios show a significant drop for each layer after the PSO inversion.

Depth (m)	Original Velocities (m/s)		CYCLE 4 PSO		Variance		V_p/V_s	
	V_p	V_s	V_p	V_s	V_p	V_s	Org.	Est.
300	2200	800	-	-	-	-	-	-
360	2400	1000	-	-	-	-	-	-
510	2300	1100	2398	1336	4.3%	21.5%	2.09	1.79
570	2500	1400	2575	1428	3.0%	2.0%	1.79	1.80
590	3000	1500	2500	1457	16.7%	2.9%	2.00	1.72
---	3800	1800	3005	1548	20.9%	14.0%	2.11	1.94

Table 2: Cycle 4 PSO results. Layer 3 shows a significant drop in S -wave velocities. At the reservoir level at 590 m, the S -wave velocity variation is relatively small compared to the 16.7% P -wave velocity reduction. The V_p/V_s ratios show a significant drop for each layer after the PSO inversion.

Depth (m)	CYCLE 3 PSO		CYCLE 4 PSO		Variance	
	V_p	V_s	V_p	V_s	V_p	V_s
300	-	-	-	-	-	-
360	-	-	-	-	-	-
510	2322	1290	2398	1336	3.3%	3.6%
570	2556	1501	2575	1428	0.7%	4.9%
590	2977	1639	2500	1457	16.0%	11.1%
---	3607	1900	3005	1548	16.7%	18.5%

Table 3: Cycles 3 and 4 PSO comparison results. At the reservoir layer at 590 m, there is a 16% and 11% velocity drop for the P - and S -wave velocities, respectively.

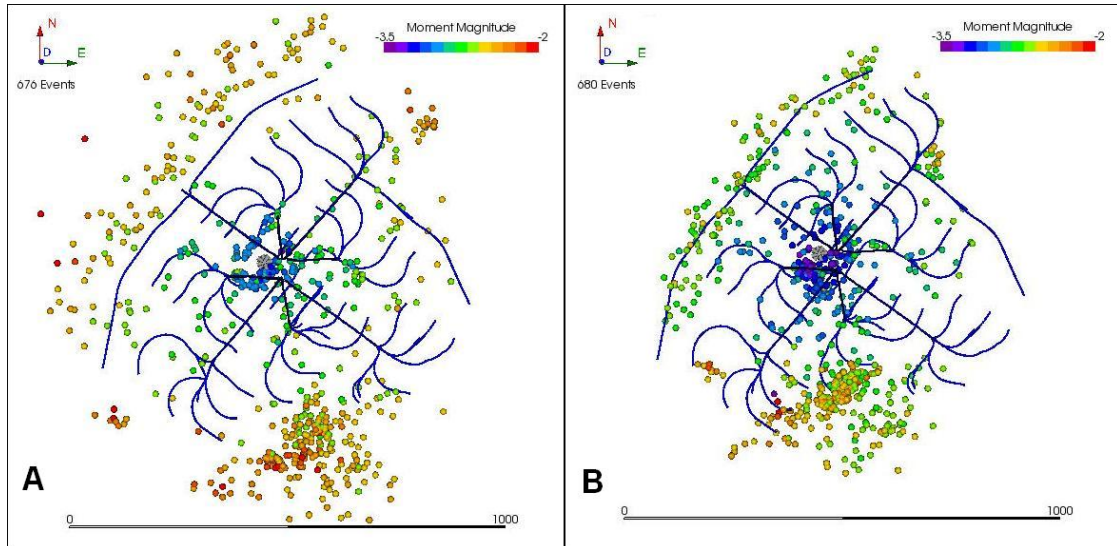


Figure 3: (A) Cycles 3 and 4 events shown in plan view located using original velocity model. (B) events located using PSO velocity model.

Conclusions

Simultaneous inversion for microseismic event locations and velocity model, as shown for Pad 30, provides locations that are in agreement with microseismic activity expected from a conventional point of view; events locate mostly at well locations within the reservoir depths, reducing the impact of possible steam seepage between adjacent pads. The inversion velocity estimates, based on PSO, show that a significant (up to 16%) *P*-wave velocity reduction could occur as a result of persistent steaming at the reservoir. The results obtained suggest that PSO is an approach that can be utilized to effectively account for velocity changes resulting in the reservoir as a result of steaming.

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