PRINCIPALS AND OBSERVATIONS TO EFFECTIVE MICROSEISMIC MAPPING AND DERIVED STUDIES. AN EXAMPLE ON VACA MUERTA FORMATION, NEUQUINA BASIN

Scott Taylor[1], Ana Curcio[2]

1: SIGMA[3]. s.taylor@sigmacubed.com

2: Pan American Energy L.L.C. acurcio@pan-energy.com

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RESUMEN

Principios y observaciones para un eficaz mapeo microsísmico y estudios derivados. Ejemplo en la Formación Vaca Muerta, Cuenca Neuquina

El mapeo confiable y la interpretación de microsismos inducidos por operaciones de fractura hidráulica contribuyen al conocimiento geológico de sistemas de fallas, fracturas naturales, posible conectividad entre ellos y estudios de geomecánica. También permite una evaluación ingenieril para la completación y ubicación de pozos.

Es importante seguir un flujo de trabajo con el objetivo de tener un dato de alta calidad en cada uno de los puntos: 1. Estudio de factibilidad 2. Diseño de campo y sistema de adquisición 3. Procesamiento de datos 4. Ubicación de microsismos y 5. Análisis, interpretación e integración geo-ingenieril.

A través del estudio de dos adquisiciones con pozos verticales en la Cuenca Neuquina, se muestran importantes lecciones en cada etapa del flujo de trabajo. Se concluye que es crítico entender las ventajas y limitaciones de cada una de las metodologías de adquisición y procesamiento. En la etapa de diseño, se debe comprender las ventajas de operar con arreglos de geófonos largos y el costo de adquirir con solo un pozo monitor. En la etapa de procesamiento y ubicación del microsismo, se debe entender las limitaciones en la metodología de picados de ondas P y S. También se debe considerar las ventajas de 1. Considerar anisotropía 2. Combinar ondas directas e indirectas 3. Considerar el frente refractado y 4. Evaluar el riesgo de ubicar la ristra de geófonos sin considerar contrastes de velocidades desfavorables. Las lecciones y consideraciones contribuyeron a entender las mejores tecnologías y definirán los diseños más adecuados para las próximas operaciones.

INTRODUCTION

The importance of the Microseismic studies is their contribution is in the geological understanding of the faults systems, natural fractures, possible connectivity between wells, and geo-mechanical studies. It also allows the effectiveness of the completion and well placement strategy.

As there are different methodologies on acquisition, processing, SRV calculations and others, it is very useful to understand the advantages and disadvantages of each one. Focusing only on acquisition on vertical wells, we propose to follow a workflow that encompasses each of the following points: Pre-survey 3D full wave field modeling; effective data acquisition and array geometry design, enhanced signal processing and wave mode discrimination; reliable and confident event location position; quantitative quality control statistics for valid localizations; and integrated geo-engineering analysis and interpretation. Under this workflow, the objective is to have a high quality output on each of this points.

Pan American Energy reprocessed the microseismic event data generated during the hydraulic fracture stimulation of the vertical sections of the LA.x-A (~2,700 m TVD) and the LA.x-B (~2,800 m TVD) wells, Neuquén Province, Argentina on 2012. The aim of this reprocess was to cross-check the results and to investigate another methodology.

WORKFLOW

In order to acquire, process and interpret a reliable microseismic dataset a phased and holistic approach was considered. The workflow is shown in the following (Figure 1):

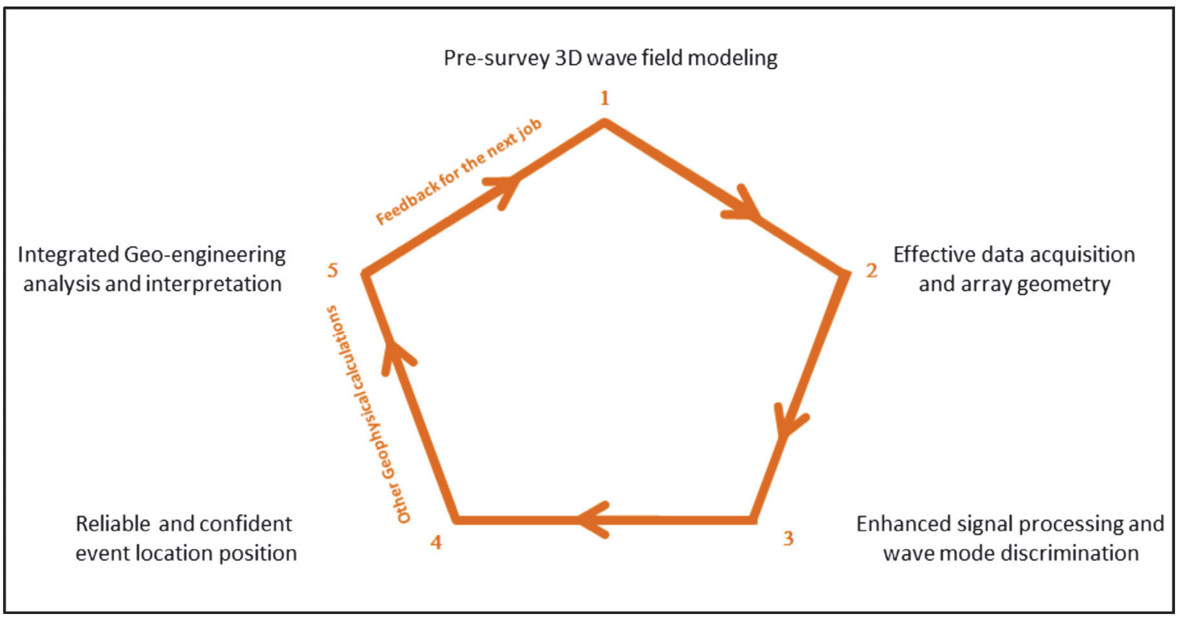


Figure 1. Microseismic Planning, Acquisition, Processing, & Interpretation workflow-

1. PRE-SURVEY 3D WAVE FIELD MODELING

The first step in the process is to take an inventory of all relevant and available project data. The purpose of this exercise is to create an initial 3D earth model. The amount and quality of available data influences the level of sophistication of the starting model. Once the model is built and assured for quality and accuracy, the engineering objectives specific to the project must be defined and further embed the completion design within the starting model. The final step is to work through logistical constraints. This step is very important because the results of the modeling are quite useful in predicting the optimal location of seismic receivers for an array and maximizing the probability of success for the survey.

Seismic wave field modeling, such as the finite difference method, allows simulation of the interaction between the velocity field and the seismic wave field generated by fracture events. Seismic modeling results can provide an objective means by which to design seismic receiver placement, vertical receiver aperture, and receiver density in observation wells. The goal of modeling is to design receiver placement such that seismic receivers will always record a useful part of the seismic wave field for all likely locations of seismic events. Further, modeling provides a means of predicting which seismic receivers should not be used for locating events from specific regions relative to observation wells because they may have recorded waveforms that cannot contribute to a unique event location and may actually provide incorrect results.

There are several degrees of sophistication that increases the accuracy of a solution. For example, the modeling may be 1D, 2D, or 3D isotropic or up to orthorhombic anisotropy depending upon input data. Pre-survey modeling is performed to:

- Estimate wave field complexity
- Estimate ray-path coverage
- Improve the quality of logs through petrophysical editing
- Provide a recommended acquisition design

The role of modeling is to address the fundamental requirements for a successful survey to:

- Assure correct placement of the observation wells for optimal survey aperture and geometry
- Assure optimal placement in depth of the sensor arrays in each observation well
- Assure the correct number of sensors in each monitor well
- Assure that the observation well can effectively monitor the entire lateral/pad
- Determine limitations on use of surface sensors based on actual geophysical constraints from seismic and well data.

Data requirements for effective modeling

Historically, microseismic monitoring has been done without the proper pre-survey design and modeling work, and without the proper input data that can assure a robust analysis of the earth model before data collection begins. With the advent of modern sophisticated earth modeling tools and acoustic and elastic modeling technology, it is possible to predict the performance of the survey. With the proper input data (1) including sonic, lithology and density logs, (2) seismic gathers, velocities and stacked data, and (3) all interpreted horizons and faults, it is possible now to build a high-resolution 3D earth model that can serve as the basis for both the pre-survey modeling, and also for the travel-time computation for perforation shot and microseismic event location analysis. When integrated with available production, stimulation and completion data from offset wells, the chance of success for a new microseismic survey is dramatically higher.

The following outline is presented for the benefit of all interested parties (Figure 2).

Deployment, Treatment, & Formation Questions	YES	NO
1. Are you confident that each observation location is close enough to the treatment(s) to record microseisms?	☐	☐
2. IF [1=NO] – would you like a pre-survey / pre-bid design with ray tracing and finite-difference elastic wave field modeling?	☐	☐
3. IF [1=YES] – would you like a 1D model ☐ 2D model ☐ 3D model	☐	☐
4. Will each observation well allow a geophone array to pass through to depth? *How has this been determined* ____________________	☐	☐
5. Is the temperature in each observation well less than 125°C?	☐	☐
6. Is/are each observation well free of corrosive and/or dangerous chemicals, e.g., H_2S?	☐	☐
7. Is/are each observation well free of noise sources (e.g., production; open perfs, casing leaks, open hole, etc.)?	☐	☐
8. Is each observation well clear or clear-able of obstructions that restrict a geophone array from locking against the well casing?	☐	☐
9. Is the casing cement over the observation range(s) in each observation well good quality?	☐	☐
10. Is there fluid in the observation well? (see below)	☐	☐
11. If [10=YES], can fluid level be lowered to >1,500 ft below surface?	☐	☐
12. Is/are all targeted formation(s) rigid, competent rock types?	☐	☐
The receiver well should be filled so that after deploying the array the fluid level is ~500ft below the surface flange (~3bbls array volume) with non-corrosive fluid, ideally fresh water (or less than 2% KCL). Concentrations greater than 2% KCL can cause significant damage to the equipment.		

Figure 2. Outine of important considerations during the job planning

2. EFFECTIVE DATA ACQUISITION AND ARRAY GEOMETRY

Seismic data acquisition planning is as important for microseismic applications as it is for surface seismic and for the same reasons. The data acquisition plan must anticipate how the seismic wave field will interact with the seismic velocity field. Seismic receivers must be placed such they that will capture a useful part of the wave field at all locations from which microseismic events are likely to originate. Seismic modeling provides ways to evaluate optimal data acquisition plans.

The examples shown in following sections of this paper are based on the Vaca Muerta formation where there is a high vertical velocity gradient near the depth range of the treatment formation. The lessons are equally important for many other shale plays globally which present similar challenges.

3. ENHANCED SIGNAL PROCESSING AND WAVE MODE DISCRIMINATION

Seismic wave field phenomena such as critical head wave refraction, converted waves, trapped modes, and seismic anisotropy have been understood both mathematically and observationally by physicists and seismologists for many decades. Additionally, each of these phenomena has been observed to affect the recorded seismic wave field in microseismic surveys in ways that, if ignored, can lead to incorrect determination of seismic event locations and significant economic repercussions.

Many important unconventional shale assets are hosted within regions where geological formations near the target layer create multiple paths through which the energy from a single microseismic event can reach an array of geophones positioned near target depth. These indirect arrivals, which include reflections and head waves, have traditionally been viewed as a nuisance in microseismic analysis, potentially causing additional false-positive event detections and erroneous localizations into the layers which generate them. In particular, the effects and potential use of head waves in microseismic analysis have been studied recently (Fuller *et al.*, 2010; Zimmer).

Coffin *et al.* (2012), published a paper on the analysis of a data set using conventional earthquake localization methods and migration approach. The conventional approach had produced event localizations spanning a depth range of 400 meters, with a large number of events being localized within the geological interval below the shale target (Figure 3). The accuracy of these (orange) localizations was questioned because the geological layer below the shale horizon was expected to limit fracture growth and has an upper portion that is porous and water- bearing, implying that induced connectivity between it and the wells would be expected to cause water production which was not observed following the fracture stimulations. In this case, the use of both arrival types in a migration localization yielded an approximate decrease in depth errors to about 1/10 their previous values.

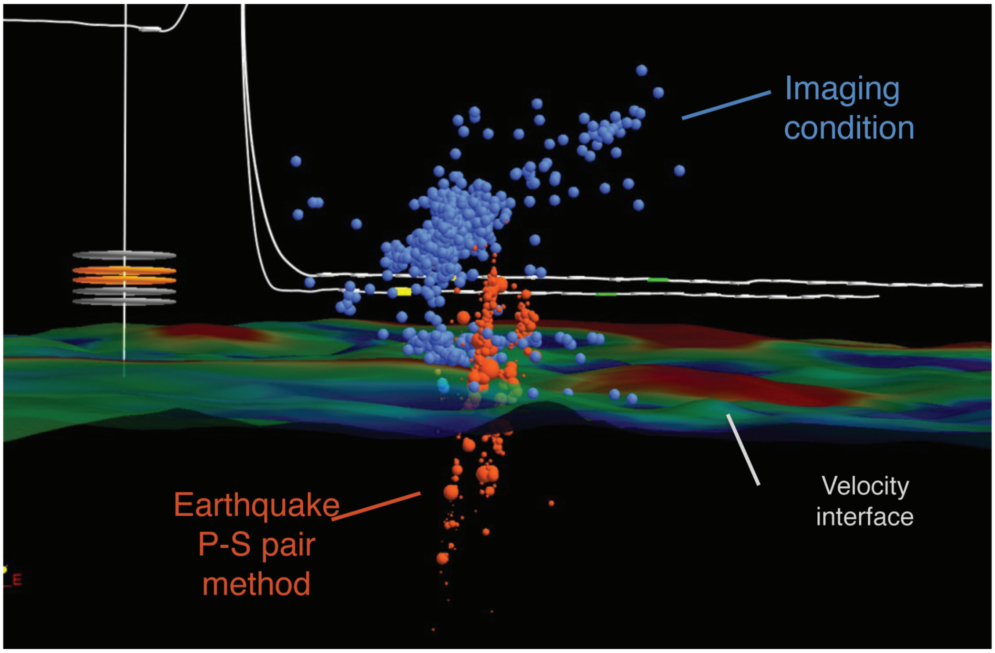


Figure 3. Analysis of data set using conventional earthquake and migration methods (Coffin, 2012).

RELIABLE AND CONFIDENT EVENT LOCATION POSITION AND CONTROL

In general there are two methodologies for downhole microseismic monitoring and processing: earthquake based P-wave/S-wave picking, and migration.

The first approach is to acquire data with short arrays typically straddling the formation of interest with between 8 and 12 geophones. The localization of the microseism is performed using the so called earthquake location method which consists on picking both the direct arrivals of both the P-mode and S-mode(s). The event location is placed in the travel time grid which minimizes the cost function between the measured and modeled time of arrival differences between the direct P-wave and direct Shear wave. The disadvantage of this method is that sometimes it is very difficult to pick the legitimate Shear first arrival, and calculating the theoretical first arrival of the Shear-mode in highly anisotropic medium, can lead to incorrect results.

Regarding the second approach, a fast Kirchhoff-like migration algorithm for accurately locating microseismic events from hydraulic fracture stimulations has been developed on 2006 and used for reprocessing. Once the events have been detected and visually confirmed, this method uses a diffraction stacking technique, similar to Kirchhoff pre-stack depth migration, to focus the P- and/ or S-wave recorded by the geophone array or arrays back to its source location. The algorithm uses a velocity model that includes anisotropy, determined from logs, surface seismic, VSP, perforation shots, etc.

The algorithm's first step extracts the treatment-induced events from the continuously-recorded data stream; then, for each event, the 3-component data are combined, strengthening the P- or S-wave signal-to-noise ratio; and finally the event is migrated to its source location within a very dense grid of the velocity model. In comparison, conventional earthquake location methods must identify both a P- and an S-wave for an event to be located. This approach needs both P- and S-wave velocity models and, frequently, an S-wave velocity model may only be assumed from the P-wave model. Also, both wave types may not be identifiable for the same event. This results in events that cannot be included in the final solution or are located with considerable inaccuracy, even though these events are treatment-induced and should contribute to the final image.

The algorithm works with either P-waves or S-waves, data interpretation and editing is minimal allowing for expedient turnaround (*e.g.*, real-time, on-site images in less than a minute!) and leading to faster on- and off-site decisions. Migration or locating a microseismic event consists of determining the best location from a group of candidate locations within a grid. The migration consists of removing the moveout or "flattening" the P-wave arrivals across a geophone array or arrays (Figure 4).

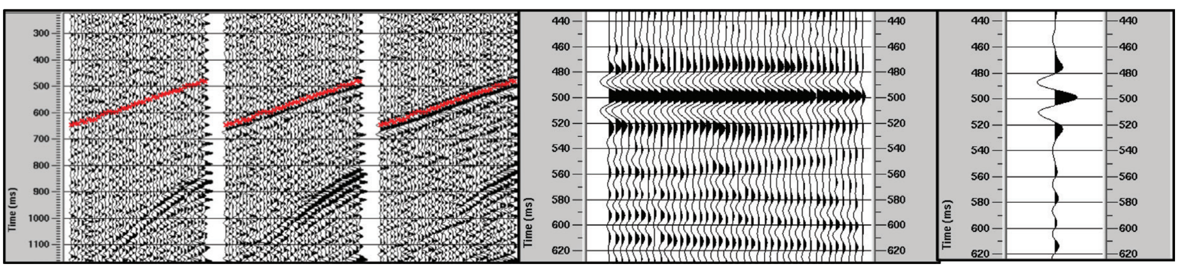


Figure 4. The three images above reinforce this workflow: [from left to right]: (1) an event is auto-picked by an algorithm; (2) the vertical, north, & east components are rotated to the source and flattened; and (3) the ensemble is stacked and then migrated to the appropriate image node within the velocity field.

To determine the moveout, travel times of the P-waves are computed from each geophone in the array or arrays to every grid node. The travel times are calculated using a gridded velocity model that can include velocity anisotropy. The following figures each show an example of the wave front for a 135-ms P-wave travel time from a geophone to grid locations near the wellbore. Dotted line on right border of figure is the geophone array (Figure 5).

Figure 6 shows the wave front corresponding to 135-ms (left figure) and 160-ms (right figure) travel times for an "upper geophone" in the geophone array. The geophone arrays is the dotted line along right boundary in each figure.

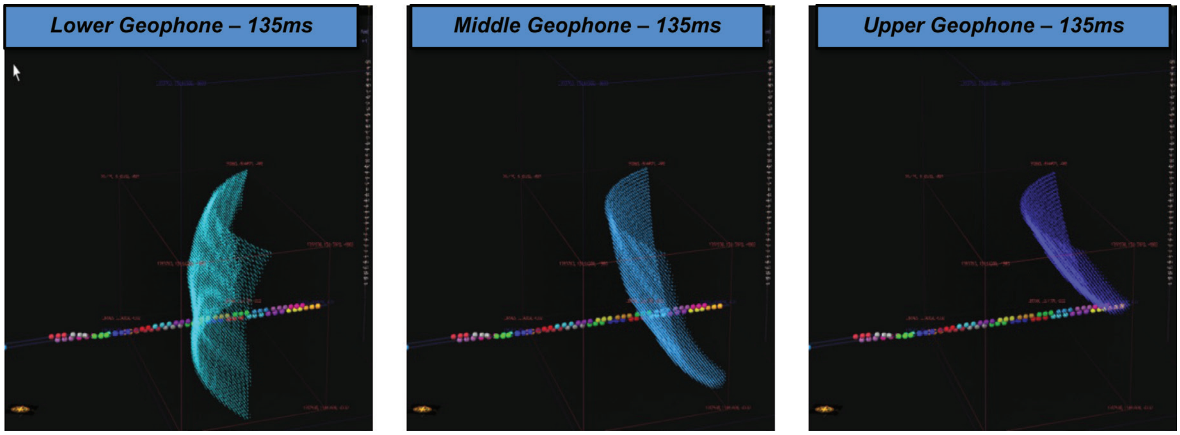


Figure 5. Moveout computation across 3 geophones in an array.

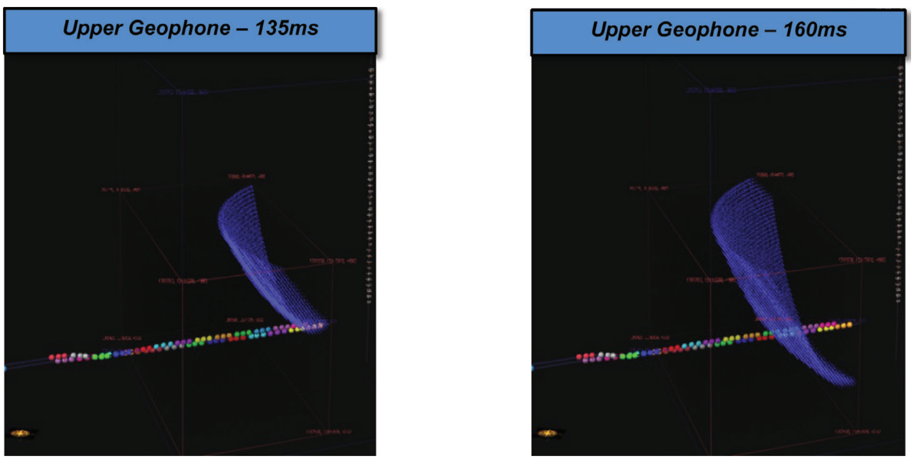


Figure 6. Computation of different travel times at the same geophone.

INTEGRATED GEO-ENGINEERING ANALYSIS AND INTERPRETATION

It is imperative to make all efforts to correlate and corroborate a microseismic dataset with any and all available engineering, geologic, or geophysical measurements, or controls. The following is a typical list of good analyses:

Detailed and Comprehensive Treatment Evaluation.

These reports detail, assess, and integrate all relevant data in conjunction with the microseismic response(s) detailed here. These reports can include a single well/stimulation, multi-well stimulations, and regional/reservoir assessments.

Adaptive Fracture Management.

The microseismic complexity generated by a hydraulic fracture stimulation is dictated, in part, by the characteristic stress regime (ratio of minimum/maximum stresses) and geomechanical properties of the formation. For example, greater fracture length and, potentially, a greater degree of fracture complexity may be achieved using larger volume treatments, fracture diversion techniques, proppant slugs, Immediate Re-Fracturing strategy, etc. These and other options can be part of an Adaptive Fracture Management strategy.

Pressure History Matching.

Qualified engineering analysis through modeling software can provide net pressure history matching to detail and interpret each injection stage.

Production Testing.

Based on the microseismic response, a production log may provide valuable insights and correlations to the microseismic behavior. Production data can also be used to develop and calibrate a production model. With the result coupled with additional microseismic monitoring studies, a reservoir model can be constructed that can be used to predict well production.

Microseismicity and Surface Seismic Attributes.

If surface reflection or VSP data are available, valuable insight into the microseismic response frequently will surface from correlation with the seismic attributes. If these data are available and can be provided, we recommend integration within a reservoir model reflection or VSP data are not available, we recommend recording these types of data and combining them with the microseismics and other data to better image the reservoir and its heterogeneities.

Reservoir Modeling.

Interpretation of microseismic data within a reservoir model provides valuable insights. The geologic and geophysical controls may be used to help constrain and permit a more meaningful interpretation

Real-Time Hydraulic Fracture Stimulation Monitoring (Engineering or Microseismic).

Specialists can provide both real-time, on-site engineering support/supervision and/or real-time, on-site microseismic event imaging. With regard to the microseismic imaging, the data can be broadcast within minutes to any and all customer-requested internet-capable devices (*e.g.*, computers, smart phones, etc.).

CASE STUDY: LA.X-A & LA.X-B WELLS.

Two vertical wells were stimulated in Neuquén province Argentina, the well LA.x-A (~2,700 m TVD) and the well B (~2,800 m TVD) , and the targeted formation was Vaca Muerta shale.

Location

In the following, it is shown the area and location of the two wells (Figure 7.a and Figure 7.b):

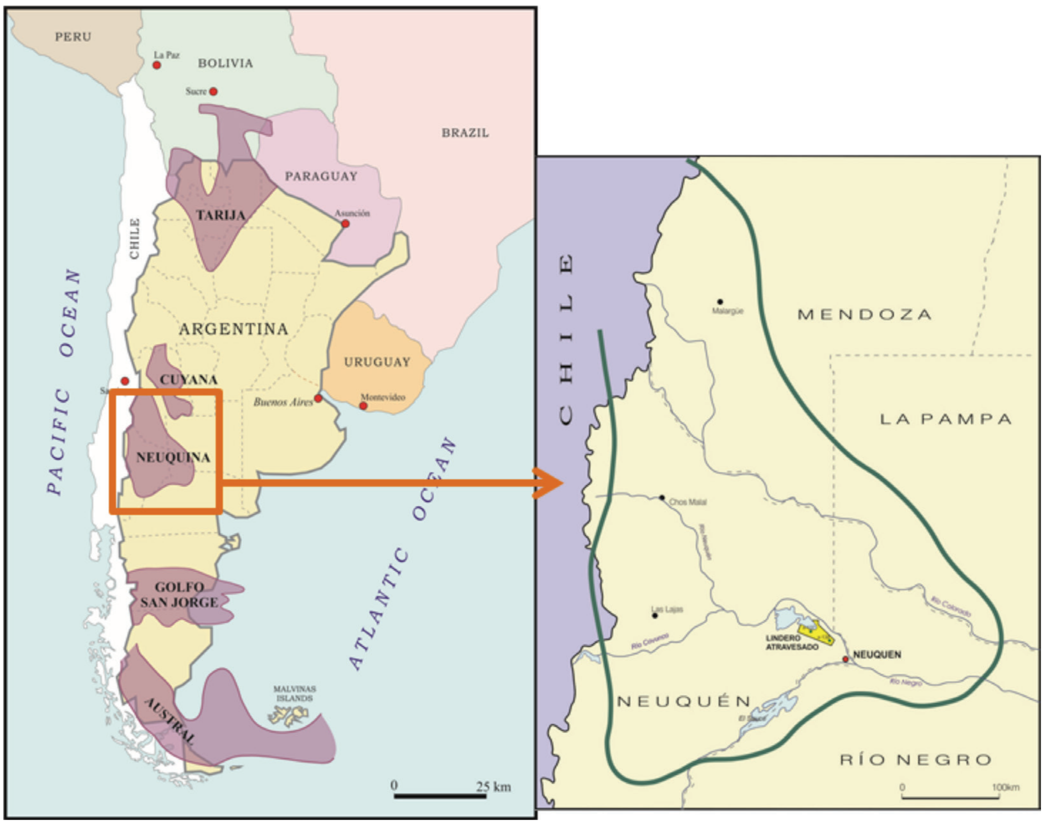


Figure 7.a. Study location map from Neuquén province, Argentina.

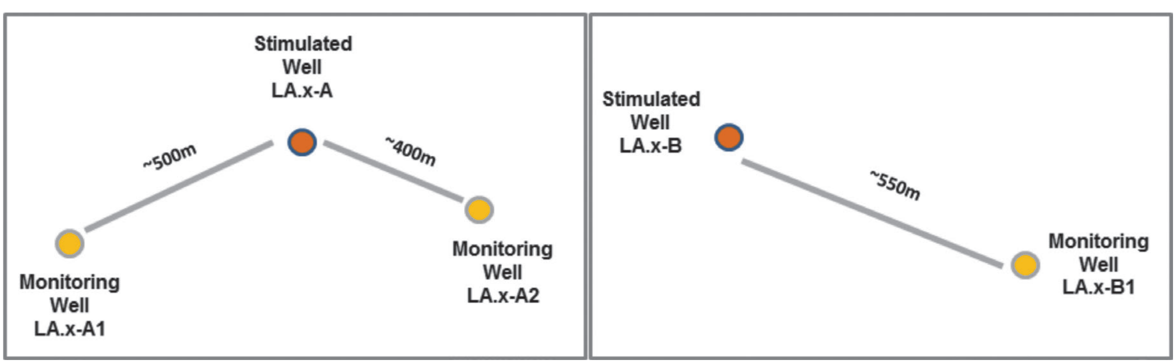


Figure 7.b. Scheme of the stimulated wells LA.x-A & LB.x-B and monitoring wells LA.x-A1, LA.x-A2, LB.x-B1

Key Basin Comparisons

In the following figure (Figure 8), it is shown a quick comparisons of some unconventional plays

Shale Play	Barnett	Marcellus	Fayetteville	Haynesville	Woodford	Lewis	Eagle Ford	Vaca Muerta
Age	320	410	330	150	370	85	95	140
Sq. Km	13,000	250,000	23,000	23,000	28,900	26,000	5,000	30,000
Depth (km.)	2.0-2,6	1.2-2.6	0.3-2.1	3.2-4.2	1.8-3.4	0.9-1.8	1.2-4.2	2.0-3.5
Pressure Gradient (psi/ft)	0.43-0.44	0.15-0.40		>0.9		0.2-0.25	0.6	0.6-1.1
Porosity %	4.5-5.0	10.0-11.0	2.0-8.0	8.0-9.0	3.0-9.0	3.0-6.0	4.0-15	4.0-12.0
Gross Thickness (m)	60-90	30-120	30-210	60-90	90-300	150-580	20-150	30-550
Net Thickness (m)	15-60	15-60	15-60	61	35-67	61-92	25-100	50-350
Kerogen type	II	II-III	II-III	III	II	II-III	II	II
Termal Maturity (%Ro)	0.5-1.5	0.5-2.0	1.0-3.0	0.94-2.62	0.5-3.0	1.7-1.9	0.5-2.2	0.5-2.6
COT(%)	3.0-6.0	3.0-12	4.0-9.8	4.0-10	0.6-1.0	0.45-2.5	4.5-5.5	2.0-12.0

Figure 8. Quick comparison of some unconventional plays (Source: Askenazi *et al.*, Revista Contacto SPE N°43).

Stimulation Design

The LA.x-A and LA.x-B stimulations utilized pump-down, plug-and-perforation guns with flow-through bridge plugs for stage isolation ("plug-n-perf"). Each stage began with a 15% HCl acid spearhead followed by a slickwater pad. After the pad, the stimulation used slickwater to carry 50/150-mesh Sinterlite (stepped from 0.2 to 1.0 ppg), linear gel to carry 40/80-mesh Sinterlite (stepped from 1.0 to 2.0 ppg), and cross-linked fluid to carry 30/60-mesh Sinterlite (stepped from 2.2 to 3.2 ppg). Intermediate sweeps were pumped through the proppant stepping.

PRE-SURVEY 3D WAVE FIELD MODELING

A Finite Difference Seismic Modeling was prepared to Optimize Microseismic Data Acquisition parameters on 2012. Elastic finite difference seismic models were computed to predict the expected wave field behavior from microseismic sources during fracture stimulation operations. The models simulate the wave field that would be recorded by receivers in the depth range between 2100 m and 3000 m at a receiver depth interval of 15 m. The source is modeled at the three distinct anticipated perforation depths of 2750 m, 2810 m, and 2878 m in a well that is 520 m from the observation well.

Preview of modeling results and conclusions.

The modeling results (Figure 9 and 10) indicate the proposed large vertical velocity contrasts within the treatment zone causes wave field distortion in horizontally-traveling wave fronts. Distorted wave fronts preclude accurate location of microseismic events because high-confidence determination of arrival times is not likely.

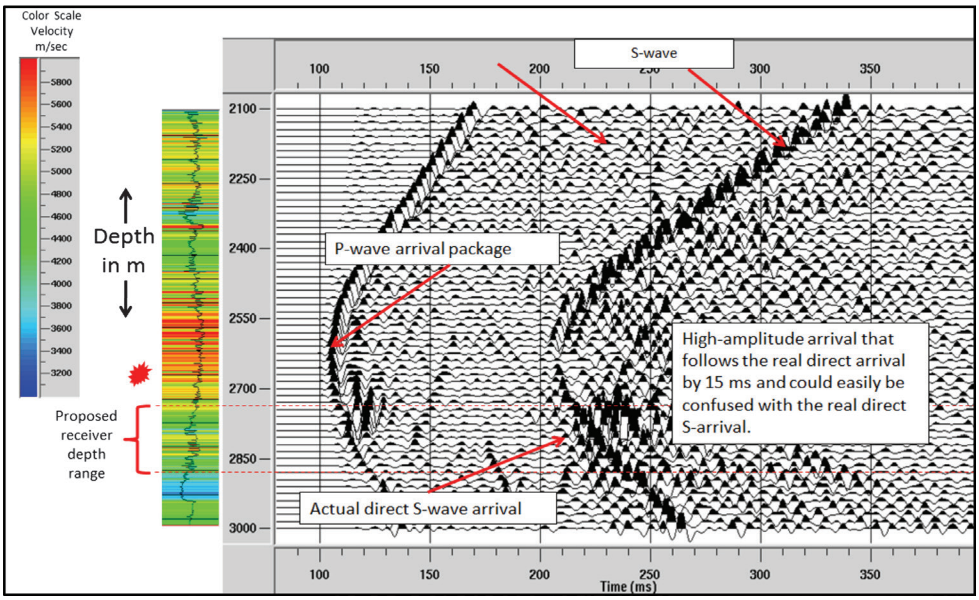


Figure 9. Source depth 2750 m, 15 m receiver depth interval, horizontal component of particle motion.

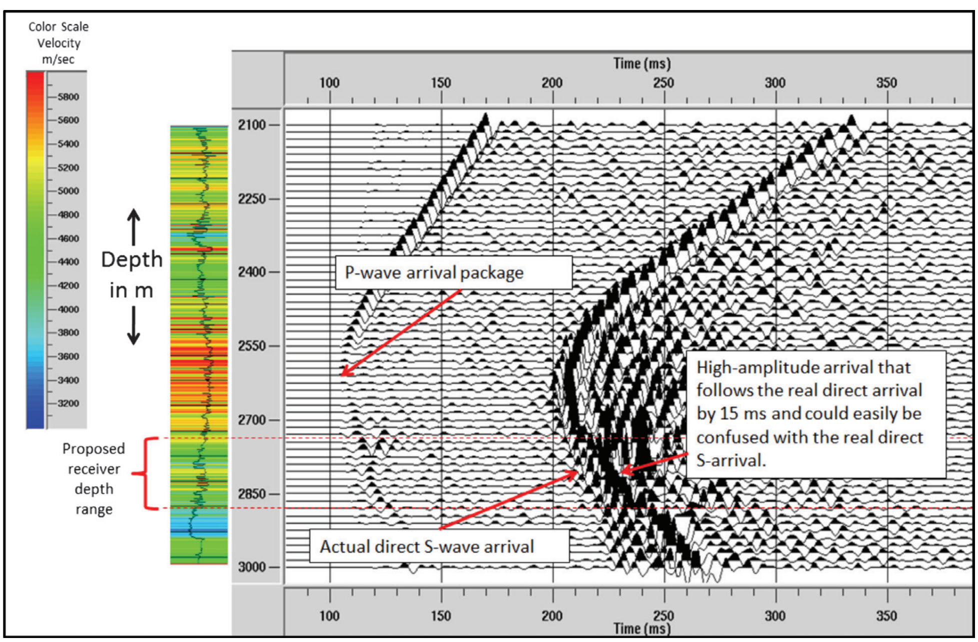


Figure 10. Source depth 2750 m, 15 m receiver depth interval, vertical component of particle motion.

Although the recommendation for optimal geophone placement to capture more of the useful part of the seismic wave field was in the interval 2775 m to 2340 m, with a long array of 30 geophones, other factors constrained this recommendation.

In summary, from the velocity model and pre-job modeling results, it was concluded that there were three possible arrays:

Option 1: 2730m to 2592m (10 geophones – current number proposed but moved upward)

Option 2: 2878m to 2592m (20 geophones – extend array to capture cleaner wave field)

Option 3: 2775m to 2340m (30 geophones – strongly recommended)

To assure optimal results of such modeling efforts, it is also essential to include anisotropy and faults and fractures where sufficient information is available to constrain these factors.

VELOCITY MODEL

The most critical component to a microseismic survey is the development of a legitimate velocity field. It has been demonstrated that including both VTI and HTI seismic velocity anisotropy is necessary to correctly locate microseismic events associated with hydraulic fracture stimulation (Van Dok, *et al.*, 2012). As discussed earlier, critically refracted head waves may cause a tenfold (1000%) increase in localization bias. It is therefore important to consider zones within the velocity field with risk of head wave effect (Coffin, *et al.*, 2012). In the following example (Figure 11), for the well A, we show an example for an isotropic 1D-model.

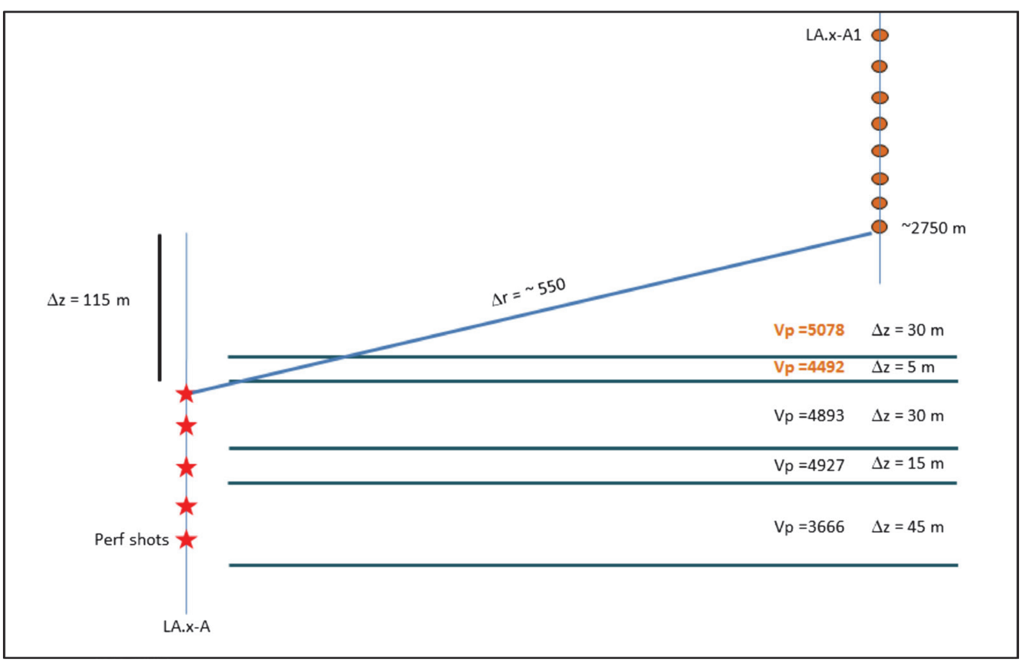


Figure 11. On the case study there is a contrast of velocity in m/s which contributes to a depth error of over 100 m.

The head wave propagates from a low velocity medium (VP=4492 m/s) to a high velocity media (Vp=5078 m/s) and for simplicity we consider only the P-mode. The localization bias is a function of source microseismic range (or straight line distance) weighted by the biased first break picks on both the compressional and shear waves. In this example the localization bias from mistakenly picking a critically refracted head wave may lead to an induced depth error of over 100 m.

EFFECTIVE DATA ACQUISITION AND ARRAY GEOMETRY / RELIABLE AND CONFIDENT EVENT LOCATION POSITION AND CONTROL

It is very important to decide which methodology is more suitable in order to have an effective data acquisition and array geometry and also to consider that each case is different from the previous cases. For this purpose, it is considered the depth of investigation, geological constraints, stimulation parameters, velocity contrast, facilities and economics. Based on this, the first decision is to select vertical arrays, horizontal arrays, or both. In this paper, based on the case study, we refer only the first type.

Regarding arrays in vertical wells, Bardainne *et al.* (2009) analyzed different processing methodologies based on a case study in Neuquina Basin, and they concluded that the waveform migration technique had allowed reliable detection and localization of twice (200%) of the original triggered database using a conventional technique. In addition, they mention that the 3C migration method is never affected by the radiation pattern because uses both P- and S-waves polarizations, which increases the signal to noise ratio by stacking the energy. In other words, this methodology improved their interpretation and reliability.

So, the migration approach has two key advantages: (1) an improvement in the signal-to-noise ratio by cross-correlating and stacking a fully sampled wave field; and (2) the migration technique leverages the normal move out analysis which permits reliable and effective wave mode identification and discrimination.

In the case presented, the two wells stimulated, LA.x-A and LA.x-B had for the first one two vertical monitoring wells LA.x-A1 and LA.x-A2 and for the second only one monitoring well, LA.x-B, at distance of 500 meters approximately. The acquisition company processed with earthquake location method and the data was reprocessed with waveform migration method. Since the processing methods are different, it is desirable to understand the differences on the results. In the following table we show the array for each stimulated well where the spacing between levels varied from 15 m to 30 m and was provided by wire interconnects.

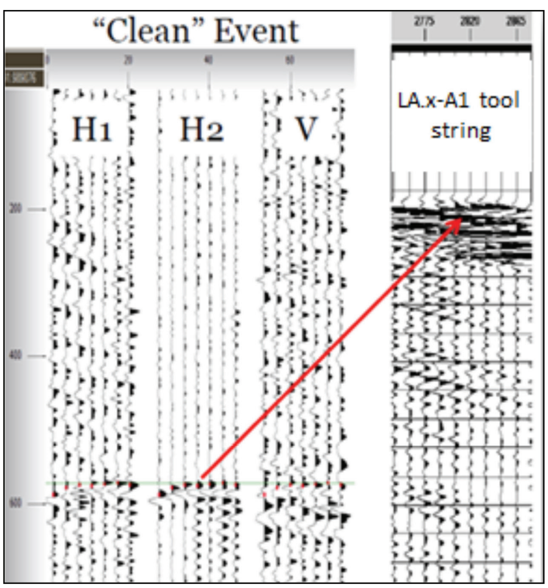
For the B well, although there is one monitoring well, the geology and velocity contrasts on the stimulated well B contributes to a marginally acceptable event location control. For the well

LA.x-A it was found a low confidence in result primarily due to a short aperture array with too few sensors to adequately sample the useful part of the wave field. It is reported that noise issues could not be resolved in the monitoring wells LA.x-A2. In LA.x-A1 well, the position of the array resulted in minimal sampling of the wave field (Figure 12).

Stimulated Well	Monitor Well	# geophones	Earthquake location	Waveform migration
B	B1	11	Low - Constrained	Constrained
A	A1	8	Poorly- constrained	Poorly constrained
	A2	8		

Figure 12. Array description of the case study.

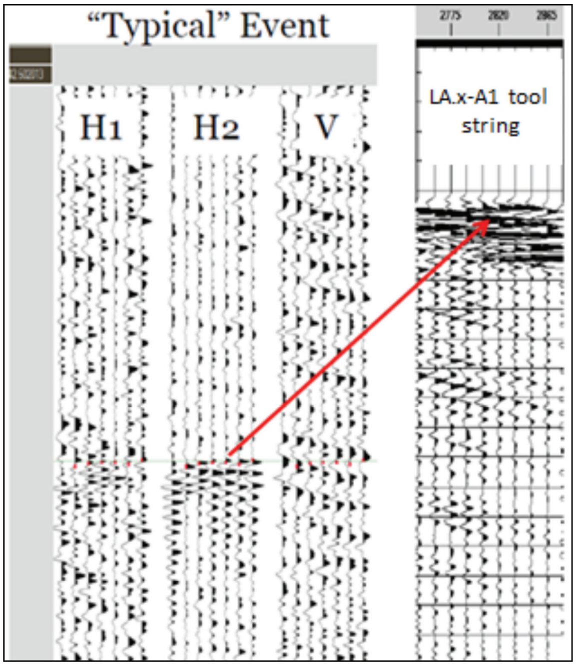
In the following (Figures 13-15), we present a series of comparisons between modeled and measured data with an 8-level 3C geophone array in the LA.x-1 monitor well from the Pan American microseismic survey. A sequence of Clean, Typical and Noisy events are presented. For the avoidance of confusion, each figure following presents actual data sorted by geophone component with red dots demarcating an arriving wave field compared to the modeled data from the finite difference wave field.



Observation from LA.x-A1 well

- Clean events represent ~5% of all events observed
- Wavefield observed is complex such as modeling suggests
- Difficult to image confidently, especially in the presence of noise
- No shear energy observed

Figure 13. An example of a high quality microseismic event as measured on the 8-level LA.x-A1 geophone array decomposed to North, East and vertical components (left) and contrasted by the finite difference modelling (right). Note that this class of events represented approximately 5% of the total event catalog. It is also of note that we observed no shear wave energy.



Observation from LA.x-A1 well

- Typical events represent ~55% of all events observed

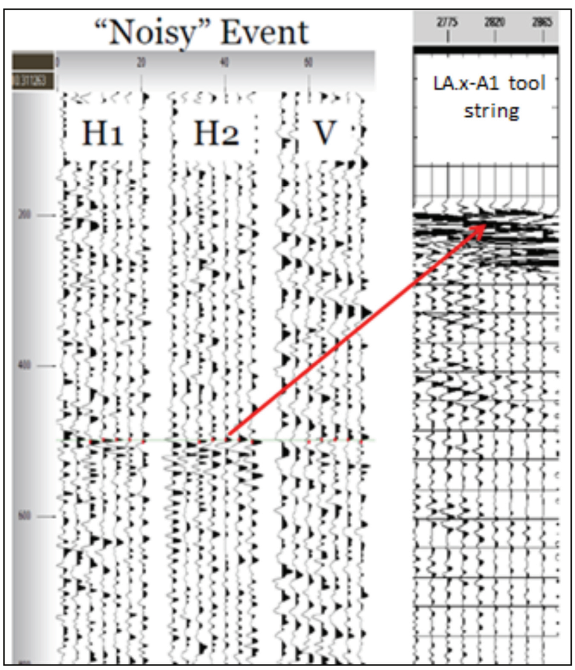
- Increased noise levels

- Wavefield observed is complex such as modeling suggests

- Difficult to image confidently, especially in the presence of noise

- No shear energy observed

Figure 14. An example of a medium quality microseismic event as measured on the 8-level LA.x-A1 geophone array decomposed to North, East and vertical components (left) and contrasted by the finite difference modelling (right). Note that this class of events represented approximately 55% of the total event catalog. It is also of note that we observed lower signal to noise ratio from this class of microseismic events.



Observation from LA.x-A1 well

- Typical events represent ~40% of all events observed

- Severe noise levels

- Wavefield observed is complex such as modeling suggests

- Difficult to image confidently, especially in the presence of noise

- No shear energy observed

Figure 15. An example of a low quality microseismic event as measured on the 8-level LA.x-A1 geophone array decomposed to North, East and vertical components (left) and contrasted by the finite difference modelling (right). Note that this class of events represented approximately 5% of the total event catalog. It is also of note that we observed no shear wave energy.

The second approach is to acquire data with long vertical arrays and to locate the microseisms with the so called waveform migration methods. This technique includes P and, or S modes in their processing (Fuller *et al.*, 2007). The following image (Figure 16) is an example of the wave field, as it would have been sampled from a long 50-level vertical array providing 900 m of aperture from which to sample the useful part of the wave field.

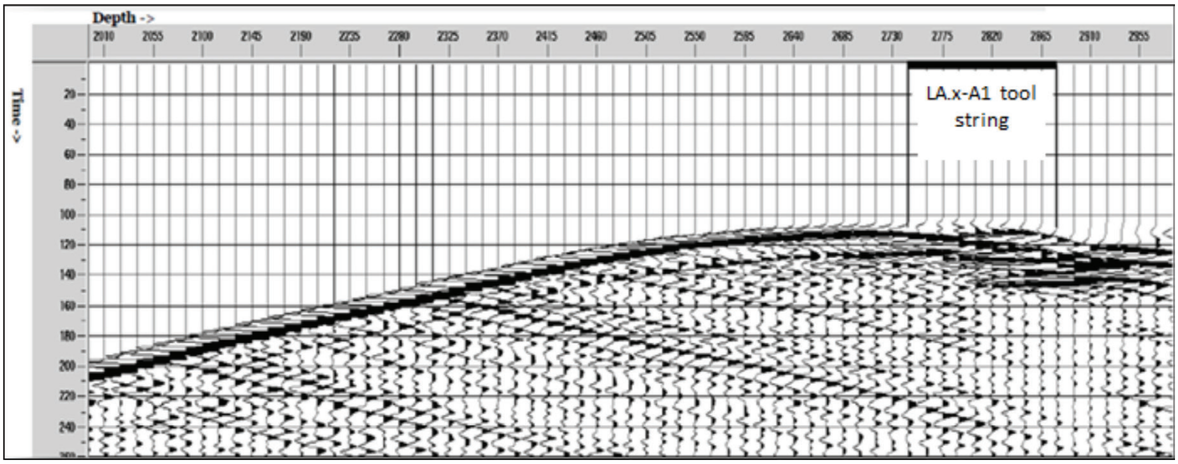


Figure 16. Predicted wave field as observed from a 50-level array more suitable for migration imaging

Regarding azimuthal errors, the number of monitor wells does not fully constrain the azimuthal uncertainty. For the well B there is a high evidence of this and for the well A as it had two monitoring wells, the constraint was better (Figure 17).

Regarding number of events detected and imaged, it was found almost the same number of events for the well LA.x-B, which constrained for both methods. However, for the well A the number is almost quadruplicated, which is related to the fact that the ´semiautomatic S/P picking´ add events and can lead to false events. This several differences are explained also under the poor constrained data (Figure 18).

Well	Azimuth (Earthquake location)	Azimuth (Waveform migration)
LA.x-A	E-W	E-W
LA.x-B	N67°	N35°-N55°

Figure 17. Fracture Azimuth calculated with earthquake location methodology and waveform methodology.

Well	Frac Stage	Earthquake location	Waveform migration
LA.x-B	1° stage	23	20
	2° stage	77	98
	Total	100	119
LA.x-A	1° stage	126	~29
	2° stage	326	~63
	3°stage	358	~58
	Total	810	160

Figure 18. Comparison of number of events from each methodology.

Regarding depth error, the thickness of Vaca Muerta formation is about 100 m, so we should consider to eliminate those microseismic events with high risk of being inside or outside of Vaca Muerta formation. For example, an event of 50 m of uncertainty, is considered a ´high risk event´.

A final comment on waveform migration method, is that is important to consider that although the performance of this method is high, it is far more effective with long vertical arrays. This means that sometimes short arrays are not suitable with this processing.

OTHER FINDINGS

LA.x-B Findings

1. Stages 1 and 2 showed upward vertical growth of 90 and 135 m, respectively. Both stages were well-constrained within the Vaca Muerta Formation
2. Microseismic event activity did not appear to correlate with the faulting along the Catriel Formation top.
3. The cumulative microseismic response produced a gross M-SRV of ~11.2 MM m^3.

LA.x-A Findings

1. By stage, the microseismic event populations generally produced well-defined, circular clouds.
2. Stages 1, 2 and 3 showed upward vertical growth of 285, 300, and 235 m, respectively. The upward growth of all three stages showed microseismic activity in the overlying Quintuco Formation.
3. None of the stages exhibited significant downward growth, and no microseismic event activity was seen in the lower Catriel formation.
4. The cumulative microseismic response produced a gross M-SRV of ~34.0 MM m^3.

CONCLUSIONS

The authors have presented a suggested workflow spanning the complete lifecycle of a microseismic project and have reinforced their case with a recent survey example from the LA.x-A (~2,700 m TVD) and the La.x-B (~2,800 m TVD) wells, Neuquén Province, Argentina on 2012. It was shown important lessons learnt and the impact of an effective acquisition on the results.

In the pre-survey 3D wave field modeling, considerations on anisotropy, velocity contrast, and the presence of faults/fracture leads to a suitable array design and tool positioning.

On the processing step, in case of a long array, several advantages can be found on waveform migration methodology. It was found several differences on the outputs between conventional and migration based microseismic processing methods due to the characteristics of the array. Those lessons and considerations contributed to understand the best technologies and define the most appropriate designs for future operations.

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