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3D Relocation Errors of Microseismic Events by Surface and Borehole Receivers for Shale Gas Stimulation

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SUMMARY

Microseismic monitoring and mapping of induced hydraulic fractures (frac) is an important tool in unconventional oil and gas exploitation. It is a key technology for completion evaluation which allows for continuous improved frac design, frac effectiveness, and ultimate resources recovery estimation and development. Formation evaluation tools provide accurate measurements of the target formation's petrophysical and mechanical properties proximal to the borehole only, distal to the borehole though, Microseismic monitoring can be a useful tool to monitor the formation's response to the frac. Shale response to hydraulic stimulation can be estimated mainly by the local density and pattern of hypocentres. Linear trends of microseismic event and their associated focal mechanisms may highlight the reactivation of faults due to hydraulic stimulation, while the location of events outside the target formation may suggest a need for future Improvements to the completion/ stimulation plan, and in some cases, re-stimulation. However, errors in the hypocentre locations may convert clear trends into "fuzzy" clouds, hampering our understanding of how the simulation interacted with the formation. The accuracy of hypocentral coordinates of micro-earthquakes is critical for understanding and proper planning for the hydraulic stimulation jobs of a shale play.

Introduction

Microseismic monitoring and mapping of induced hydraulic fractures (frac) is an important tool in unconventional oil and gas exploitation. It is a key technology for completion evaluation which allows for continuous improved frac design, frac effectiveness, and ultimate resources recovery estimation and development. Formation evaluation tools provide accurate measurements of the target formation's petrophysical and mechanical properties proximal to the borehole only, distal to the borehole though, Microseismic monitoring can be a useful tool to monitor the formation's response to the frac. Shale response to hydraulic stimulation can be estimated mainly by the local density and pattern of hypocentres. Linear trends of microseismic event and their associated focal mechanisms may highlight the reactivation of faults due to hydraulic stimulation, while the location of events outside the target formation may suggest a need for future Improvements to the completion/ stimulation plan, and in some cases, re-stimulation. However, errors in the hypocentre locations may convert clear trends into "fuzzy" clouds, hampering our understanding of how the simulation interacted with the formation. The accuracy of hypocentral coordinates of micro-earthquakes is critical for understanding and proper planning for the hydraulic stimulation jobs of a shale play.

In this study, we examine the microseismic event location errors associated with a frac job in Saudi Arabia. This was accomplished by examining a realistic surface and borehole array geometry and a realistic seismic velocity model to attain reliable hypocentral estimates, for either surface or borehole microseismic surveys, a detailed 3D velocity model for both P- and S- waves is needed. Vesnaver *et al*. (2010) demonstrated that the joint inversion of surface and borehole data may provide a far superior tomographic image of the reservoir, even when it is thin. Menanno *et al*. (2013) showed that borehole receiver orientation must allow for 3D inhomogeneities and ray bending; otherwise, the errors in the hypocentre coordinate become relevant, if the wave polarization is used to estimate the hypocentre direction. In this paper we quantify the relocation errors in three synthetic models that mimic a real experiment performed in Saudi Arabian shale stimulation. In this study, we examine key items such as the accuracy in the time origin estimation, the Earth model complexity and the surface-vs-borehole recording geometry.

3D relocation and recording geometry

Measuring the traveltimes of the perforation shots in a treatment well can improve the accuracy of the hypocentre location, by providing either an empirical depth-traveltime relation, or just an average velocity model between sources and receivers. However, as hypocentres move apart from the treatment zone, this calibration becomes less reliable. This reduction in certainty is mainly due to potential changes in the reservoir itself such as an increase or decrease in natural fractures, change in lithology, change in porosity, etc. In addition, the frac itself modifies the original rock properties in the reservoir by the induced fractures, increased pore pressure and new saturating fluid. Therefore, a full 3D Earth model, ideally evolving in time (i.e., 4D), to get accurate hypocentres' locations is needed.

An active 3D seismic survey may provide a fairly accurate 3D model in depth, via pre-stack depth migration or reflection tomography. Nevertheless, having such a model may still be insufficient if the receivers do not surround the rock volume being fracked. Figure 1 illustrates the layout of a real frac where the receivers were deployed in three different configurations:

- 12 receivers in a vertical borehole close to the fracking area, spaced 25 m apart;
- 38 receivers in shallow boreholes ranging from 600 to 750 m depth from the Earth surface;
- 38 receivers at the surface, on top of the shallow boreholes.

The information available for this study included the formation tops in 6 nearby wells, scattered irregularly in the area of about 15x30 km, but the P and S velocities in one well only. Table-1 summarizes the values at of the well with both P- and S- velocity information, along with the local depth of the formation top. Therefore, homogenous layers are assumed in all of the study's models.

Layer	Formation Top	Vp (m/s)	Vs (m/s)	Vp/Vs
1	0	2830	1415	2.00
2	141	2777	1388	2.00
3	802	3614	1612	2.24
4	857	4087	2351	1.74
5	1000	4801	2660	1.80
6	<1000	4740	2581	1.84

***Table 1** Depth of formation tops, P and S velocities, and Vp/Vs ratio in Model A and C. Model B is composed of 62 layers and is not reported here for brevity. Depth been referenced from 0-1000 depth unit.*

Figure 2 shows the three models we built with increasing complexity, i.e. a coarse 1D macro-model composed of 7 layers (left), a finer 1D model with 62 layers (centre) and a 3D model with irregular interfaces but 7 homogeneous layers (right), indicated by A, B and C, respectively.

The topography is not flat, as elevation differences exist up to 200 m, and even less flat is the target formation, where such a range exceeds 400 m. The topographic changes are taken into account in all our tests for the receivers' coordinates, while the structure variations at the target are allowed for in the Model C only. A key feature is the strong changes in the Vp/Vs ratio at the boundaries of the target formation, i.e., at the interfaces 3 and 4. This is the main cause for the observed errors in the time origin estimates (see also Vesnaver *et al*. (2010)).

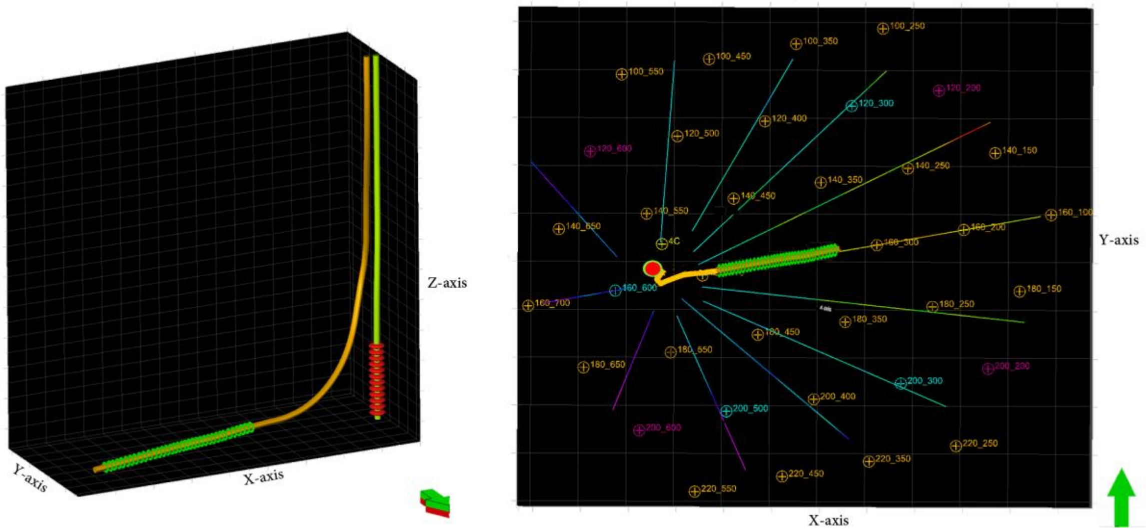

***Figure 1** Recording geometry: the receivers in the main borehole (left) are depicted by red circles and the location of the perforation shots by green circle. The plane view (right) highlights the receivers at the Earth surface geophones by colored seismic recording lines, and buried array are marked by crossed circles in orange, cyan and magenta colour. We can see also the projection of the vertical borehole in red, and the perforation shots in green.*

Estimation of relocation accuracy

Our inversion algorithm adopts the "shrinking grids" method (Vesnaver *et al*. 2008, 2010), whose accuracy is comparable to the method of Lomax *et al*. (2000). For all following tests, the dimension of the shrinking grids are 5x5x9 in the *x,y,z* directions, respectively, with an initial search range of 500x500x300 m and 25 iterations. The time origin is estimated initially by the Wadati method, followed by a few small perturbations. When both surface and borehole data are inverted, only the surface data was used for estimating the time of origin, as this reduction improves significantly the relocation accuracy.

In the actual frac that is mimicked in this study, the exact location of the source and the time origin are known, i.e., the shooting time, for the perforation shots. To assess the precision of our method, we first ran a few tests to locate the perforation points, assuming that we know both their shooting time and approximate location, used as an initial guess. Table 2 provides some numerical details in the first 3 rows: the coarse models A and C produce average errors in the hypocentral coordinates smaller than 20 m in both the Δz vertical and Δr radial direction when the surface receivers are involved, but errors increase when only borehole receivers are used for the very fine Model B, for this and for all following cases.

After the pumping is initiated, micro-earthquakes are generated: initially in the vicinity of the perforation and later, in most cases, within an expanding front that may be described by the diffusion equation (Shapiro and Dinske, 2009). We may assume as an initial guess for our hypocentres the location of the perforation, although we may not assume the time origin as known any more. This case is spanned by the second group of 3 rows in Table 2. The errors in *x* and *y* remain marginal, but a cross-talk shows up between depth and time origin errors.

After a significant time from the beginning of pumping, the hypocentres may be located at significant distances from the perforation: if preferential flow pathways show up along reactivated faults, such a distance may exceed several hundred meters. In that case, it makes sense to not assume any initial guess or constraint about the hypocentres, and instead rely only on the available traveltimes. This is the case covered by the last 3 rows in Table 2, where we again notice the same features as for the previous case: errors are large when using borehole receivers only, but are acceptable in the x and y dimensions when the surface receivers are included in the relocation. The borehole receiver contribution, when jointly inverted, is reducing the ambiguity between depth and time origin estimation.

Model	Borehole only			Surface only			Surface + Borehole			Known time origin	Guessed hypocentre
	Δz	Δr	Δt_0	Δz	Δr	Δt_0	Δz	Δr	Δt_0		
A – 1D coarse	138	462	0	-43	24	0	-43	27	0	Yes	Yes
B – 1D fine	111	672	0	-3	220	0	506	112	0	Yes	Yes
C – 3D coarse	49	415	0	-3	23	0	-3	23	0	Yes	Yes
A – 1D coarse	158	25	-13	196	16	4	158	25	-13	No	Yes
B – 1D fine	510	174	-25	-3	220	-3	-92	1005	-864	No	Yes
C – 3D coarse	150	27	-18	150	27	-18	138	12	-31	No	Yes
A – 1D coarse	88	2083	16	14	194	2	23	158	-15	No	No
B – 1D fine	-92	1097	-863	220	266	-970	-92	1097	-863	No	No
C – 3D coarse	-131	2019	12	159	27	-16	139	13	-30	No	No

***Table 2** Average errors in relocation (m) and time origin (ms) for different models, recording geometries and information about time origin and guessed hypocentre using the injection locations.*

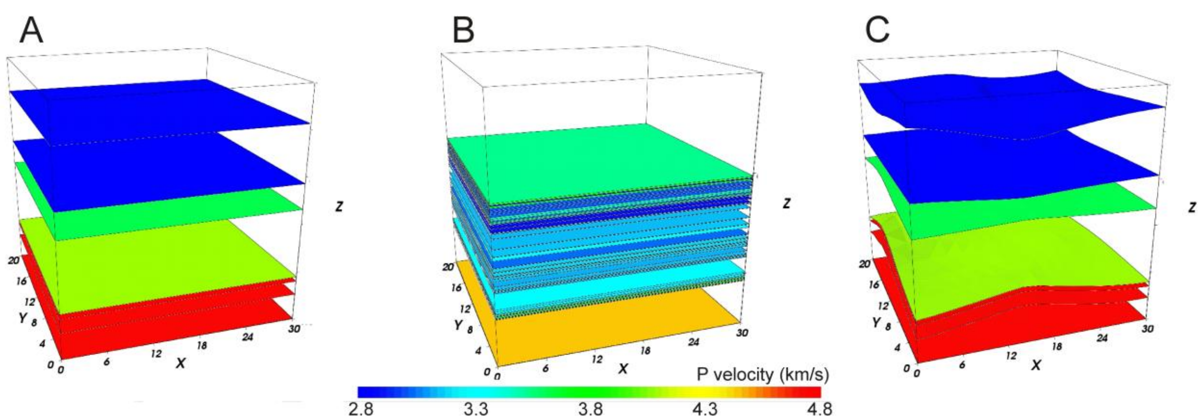

***Figure 2** Earth models used to test the relocation accuracy: coarse 1D (A, left), fine 1D (B, centre) and coarse 3D (C, right).*

The traveltimes that we generated were computed with the same model and algorithm used for the inversion. For this reason, the obtained results do not allow for traveltime picking errors and discretization, and so provide a very optimistic framework with respect to real experimental conditions. Thus, the presented results may be considered a kind of upper limit to our expectations in the accuracy.

A mismatch exists in real experiments between the actual Earth and the model we adapt to approximate it and estimate the hypocentres. This problem is not addressed here, but we send the reader to Vesnaver and Urpi (2013); where they showed that a simplified macro-model for the Earth provides fairly accurate epicentral locations, when the (micro)-earthquakes are located in an area well covered by the receivers, even when the errors in the velocity model exceed 10%, while the hypocentre depth is affected by major errors. This experience is consistent with the results we obtained, although in a different geological framework.

Conclusions

The errors of hypocentral locations depend heavily on the recording geometry and the velocity model adopted. When receivers are available only in a single borehole, these errors may be not acceptable even when the perforation shots are inverted, i.e., when the time origin is known. The intrinsic weakness of this recording geometry may explain why often, when processing the same data, different geophysicists may get so different results.

Very detailed blocky models obtained by well logs, closely representing the Vp/Vs ratio variations, perform much worse than macro-models where P and S velocities are averaged in a few macro-layers. Such an average reduces the deviation from the Wadati assumption of a constant Vp/Vs ratio for estimating the time origin. A possible further explanation is that modelling a few thick layers avoids possible unrealistic wave-guide effects in thin layers: fast ray-paths may exist for the ray tracing code, which do not correspond to energetic observable signals.

The joint inversion of surface and borehole data reduces significantly the relocation errors, but ambiguities remain between errors in the hypocentral depth and time origin, when the Wadati method fails. Thus, challenges remain for shale formations, even when an accurate 3D Earth model is available for P and S waves, when the Vs/Vs ratio changes significantly.

These conclusions have a quantitative meaning only for the presented cases, but they can provide clues for similar geological cases and encourage further studies.

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