IDENTIFICATION OF HYDRAULIC FRACTURE ORIENTATION FROM GROUND SURFACE USING THE SEISMIC MOMENT TENSOR

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Abstract. Microseismic monitoring from ground surface is applied in the development of hard-to-recover reserves, especially in the process of hydraulic fracturing (HF). This paper compares several methods of HF microseismic monitoring from the surface, including diffraction stacking, time reverse modeling, and spectral methods. In (Aki and Richards, 1980) it is shown that signal enhancement from seismic events under correlated noises significantly improves when applying the maximum likelihood method. The maximum likelihood method allows to exclude influence of the correlated noise, and also to estimate the seismic moment tensor from ground surface.

Estimation of the seismic moment tensor allows to detect type and orientation of source. Usually, the following source types are identified: “Explosion Point” (EXP), “Tensile Crack” (TC), “Double-Couple” (DC) and “Compensated Linear Vector Dipole” (CLVD). The orientation of the hydraulic fracture can be estimated even when there is no obvious asymmetry of the spatial distribution of the cloud of events.

The features of full-wave location technology are presented. The paper also reviews an example of microseismic monitoring of hydraulic fracturing when there is no obvious asymmetry of microseismic activity cloud, but due to the estimation of the seismic moment tensor it becomes possible to identify with confidence the dominant direction of the fracture.

Keywords: Microseismic monitoring, seismic moment tensor inversion, fracturing, seismic event, maximum likelihood method

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Introduction

The task of locating deep microseismic events from the ground surface in the oil and gas industry has become particularly relevant recently when there is a depletion of conventional hydrocarbon reserves, and the development of reserves difficult to recover is usually carried out by hydraulic fracturing (Islamov, 2017). Knowledge of the real parameters of the fracture formed as a result of the hydraulic fracturing allows optimizing development of the field.

The most important parameter to be determined in the monitoring of hydraulic fracturing is the direction in which the fracture spreads. Knowledge of the fracture direction allows optimally orienting the horizontal trunk of the following wells, and also optimizing the locations of vertical wells to optimize the drainage area. The fracture direction is parallel to the direction of the main stress axis in the geological environment, which makes it possible to use this information for geomechanical simulation in order to optimize the construction of nearby wells.

Location technology

The direction of fracture propagation is usually determined by the orientation of the cloud of events accompanying the process of fracture formation. To localize microseismic events, various techniques for observing and processing microseismic information are used. The most well known is the technique of diffraction stacking, which is used to localize microseismic events for more than 50 years (Krey, 1952; Hagedoorn, 1954). The main principle of the diffraction stacking method is to calculate the time delays corresponding to the time of the signal travel from the analyzed points of the geological medium to the receiving points. After

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applying the calculated delays, the amplitudes of records are summed.

The method of computations in reverse time is also known (Gajewski and Tessmer, 2005); this method is based on the numerical simulation of the process of elastic waves propagation. The signals received during the monitoring are inversed on the time domain and used as sources at the location of sensors. For a time equal to the time of travel from the source to the observed group of receivers, the pulses are localized at the place of origin.

The spectral method (Kushnir, 2014) of the microseismic location and a number of other less well-known approaches are also known.

In (Aki and Richards, 1980) it is shown that the reliability of location of seismic events against the background of correlated noises increases significantly when using the maximum likelihood method. The authors use it to locate one center of an earthquake against the background of another. However, the presence of correlated noise is not typical for seismology, given the considerable spacing of seismological stations.

When microseismic events are located, on the contrary, correlated noises from operating equipment (hydraulic fracturing fleet, oil and gas infrastructure) make up the bulk of the noise. As shown in (Birialtsev, Demidov, Mokshin, 2017), the maximum likelihood method allows to exclude the correlated noise component, and also allows to determine not only the coordinates, but also the tensor of the seismic moment when localizing from the ground surface.

The definition of the seismic moment tensor makes it possible to calculate the direction of the fracture causing the microseism in a single event. Thus, it becomes possible to clarify the direction of fracturing at the site of the hydraulic fracturing, even if the cloud of microseismic events is not clearly expressed.

To apply the maximum likelihood method, we need to know the form of the useful signal. In the general case, a useful signal is the full-wave response of the medium to the impulse action. Calculating the shape of a useful signal in a geological medium is possible by using full-wave 3D numerical simulation (Birialtsev, Berezhnoj, Birialtseva, Hramchenkov, 2008). To calculate the seismic moment tensor, it is necessary to simulate 6 types of impulse actions of various types (Birialtsev, Demidov, Mokshin, 2017).

Full-wave 3D numerical modeling and event location using the maximum likelihood method require significant computational capacity, thus supercomputer calculations are used to obtain the results at an acceptable time (Galimov, Birialtsev, 2010).

The full-wave location technology is characterized by a number of features:

1. Registration during monitoring of hydraulic fracturing is performed from the ground surface by independent sets of broadband highly sensitive seismometers installed in the quietest areas of the territory (Ryzhov, Sharapov, Birialtsev, Feofilov et al., 2015);
2. Due to the use of full-wave 3D numerical simulation, the complete information about the signal at the sensor installation sites is used during localization by three components (full-wave response, including compression, shear, exchange, and re-reflected waves) from single impulse actions;
3. Event location is performed using the maximum likelihood method – theoretically the most noise-immunity method of signal isolation against the background of noise, which best localizes the event at a low signal-to-noise ratio.
4. The tensor of the seismic moment is calculated for each seismic event, which allows determining the type of event and the orientation of fracture that formed the event. The events that are not related to the fracture opening are rejected by type, and in the orientation of events it is possible to estimate the azimuth of the crack formation without accumulating a significant event cloud for the statistics.

At the same time, a technological leap forward in the development of supercomputer computing systems (Galimov, Birialtsev, 2010; Demidov, Ahnert, Rupp and Gottschling, 2013; Birialtsev et al., 2015; Anastasiya Belyaeva, Eugeniy Biryaltsev, Marat Galimov et al., 2017), allowed the use of resource-intensive location methods (Birialtsev, Demidov, Mokshin, 2017), using the most complete information about the seismic event.

The full-wave location has been used to solve problems in the oil and gas industry since 2011, several articles with the results of its application appeared (Biryaltsev et al., 2016; Ryzhov et al., 2015; Khisamov et al., 2015; Shabalin et al., 2013).

Location results

Deformation of porous liquid-saturated rocks is a complex process during which the mineral skeleton of the rock is simultaneously distorted (under the influence of changing effective stresses and reservoir pressure gradients) and fluid filtration in the pores (as a result of the action of reservoir pressure gradients and volumetric deformation of the skeleton) (Smetannikov, Kashnikov, Ashihmin, Shustov, 2015; Shapiro, 2015).

Consequently, the zones of increased microseismic activity detected during the monitoring of hydraulic fracturing can be associated with the processes occurring in the reservoir under the influence of hydraulic fracturing and which inextricably include the following:

1. Formation/closing of fractures;
2. Fracture opening during filling with proppant;
3. Deformation of the rock in areas with a precritical state due to the spreading of the pressure front along the natural channels of filtration;
4. Deformation of the rock in areas with a precritical state due to the spreading of the pressure front through the solid rock.

When the fracture is opened, the created pressure in the port area begins to be set along the entire fracture. After that, the whole plane of open fracture, and not just the port becomes the source of pressure. Further, new fracturing zones may be formed, while the previously opened fracture may be elongated, branched off and expanded.

During the expansion of the fracture, deformation of nearby rocks occurs, causing microseismic activity in the form of a cloud of events around the fracture. Also, the reason for the formation of a cloud of events, and not lineaments, is a limitation in the accuracy of the location.

The result of the location is a set of events with space coordinates and the seismic moment tensor. On the basis of seismic moment tensor the degree of belonging of the event to the base types of events is estimated. There are several basic types of events:

1. “Explosion Point” (EXP);
2. “Tensile Crack” (TC), “Double Couple” (DC);
3. “Compensated Linear Vector Dipole” (CLVD).

The orientation of the tensile crack is evaluated only for high-weight events “Tensile Crack” (TC).

For events such as “Explosion Point” (EXP), it is not appropriate to speak about azimuth, since all three of its eigenvectors are equivalent and the azimuth parameter is determined unstable in this case. For events of mixed type, for example, 45% TC and 40% EXP, the estimate of the azimuth of fracture is valid, but with less certainty than for a more pronounced tensile crack of 80% TC. For DC and CLVD events, the determination of the fracture orientation is not performed; on the contrary, such events are excluded from processing, as events not related to the volume change (opening/closing of the fracture).

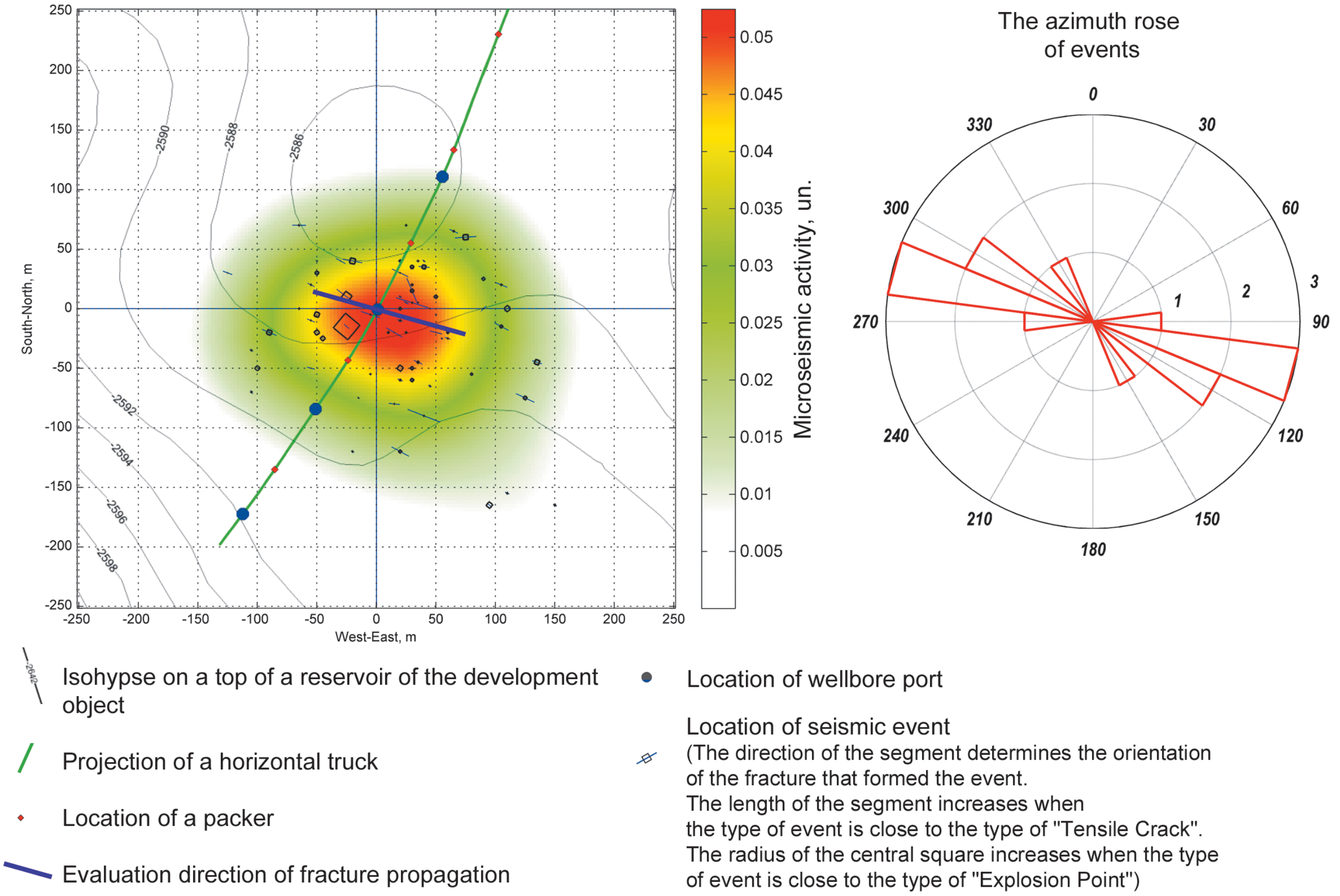

Fig. 1. An example of a result of hydraulic fracturing monitoring with the definition of the seismic moment tensor

Figure 1 presents the results of the events location from the surface by the technology of full-wave location for vertical depths of the order of 2.7 km. As a result of simulation, estimates of location accuracy for these conditions were obtained: the error of the location is not more than 35 m, the error in determining the azimuth of the crack is not more than 15 degrees.

On the resulting map, events in the port area are fairly wide spread, which does not allow us to confidently identify the direction of the fractures only at their location, but due to the azimuth rose of each event, through the seismic moment tensor, it became possible to estimate the direction of the fracture.

Conclusion

Thus, the technology of microseismic location from hydraulic fracturing using the maximum likelihood method makes it possible to determine the direction of hydraulic fractures even under conditions of low accuracy spatial location of microseismic events.

Low accuracy location of events can be caused by difficultly removable causes: high noise level of technogenic activity on the surface, low-frequency operating range (due to attenuation of the high-frequency component of the signal due to high depth), as well as the very complex nature of fracture propagation, like fracture fabric (Cipolla, Weng, Mack, Ganguly, Gu, Kresse, Cohen, 2011), which forms a network of parallel fractures.

The definition of the seismic moment tensor and the direction of fracture with its use is more stable to the listed factors, which justifies the use of a computationally more complex maximum likelihood method in a complex geological environment.

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