Imaging hydraulic fracture zones from surface passive microseismic data

Vladimir A. Kochnev,[1*] Ilya V. Goz,[1] Vitaly S. Polyakov,[1] Issa S. Murtayev,[2] Vladimir G. Savin,[2] Boris K. Zommer,[2] and Ilya V. Bryksin[2] provide some Russian examples of passive microseismic applications for imaging hydraulic fracture zones.

Most of the current microseismic methods for hydraulic fracture imaging employ multi-level receiver systems deployed on a wireline array in one or more offset wellbores. A high frequency range (over 100 Hz) of receivers is required (Rutledge et al., 2003, Li et al., 1998, Block et al., 1994, Meadows et al., 1994).

Locations of microseisms are calculated from the direction of arrived elastic waves and delays of S-waves from corresponding P-waves. To determine the direction of arrival of separate waves is not a trivial task, further complicated by a large numbers of microseismic events (microearthquakes). For robustness, multiple receiver locations are necessary.

We are assuming that a large number of low-energy microseismic events combined produce noise with a wide frequency range. Some researchers suggest that combined signals from multiple microearthquakes were sufficiently strong to be recorded at large offsets. In 2000, Khantymansiiskgeofizika and several research organizations collaborated on noise recordings in the process of hydraulic fracturing of a well at the East Surgut oil field. However, no strong events were ever recorded.

Since then, most efforts have been spent on developing methods for detecting weak yet numerous events in a presence of a strong background noise. Apart from existing methods such as static correction, filtering, and channel removal (especially where strong waves from surface sources were recorded), we developed and used special methods for stacking low-energy events. Application of the method allowed us to successfully locate the fracture zone and visualize the process of fracture development.

Theory

Assuming horizontally-layered media, a zero-order ray tracing algorithm with interpolation for intermediate rays was applied to determine arrival times. The overall idea of this low-energy stacking algorithm is the following. First, it defines the target zone for searching for low-energy sources. The uniform grid is overlaid on the zone. For each node of the grid, the coherency value P_j is calculated:

$$P_j = \frac{\left(\sum_{i=1}^{N} A(t_j)\right)^2}{N\sum_{i=1}^{N} A(t_j)^2} \qquad (1)$$

where N is the total number of receivers, I - the index of receiver, j - the index of the grid node, t_{ij} -arrival time for waves scattered at grid node to the receiver j, A - an amplitude from the seismogram.

To improve the stability of the algorithm it could be necessary to employ some form of averaging P_j values over time. If the form of the wavelet is known, then the optimal averaging algorithm can be construed. However, if the form of the wavelet isn't known, as turns out to be the case in hydraulic fracturing, only a suboptimal averaging solution can be derived. P_j will be maximized when arrival times for a given grid node coincide with arrival times for a scattering point. The spatial distribution of P_j will therefore mirror the distribution of low-energy sources.

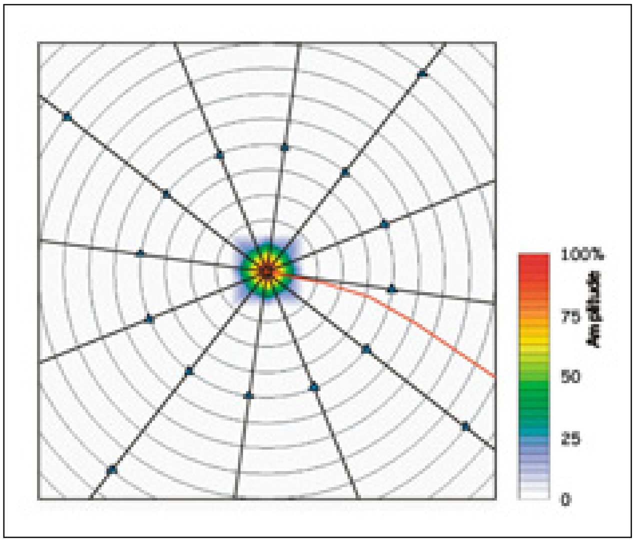

Figure 1 *Calibrating stacking algorithm by known source – perforation of the well. Orange line indicates wellbore projection.*

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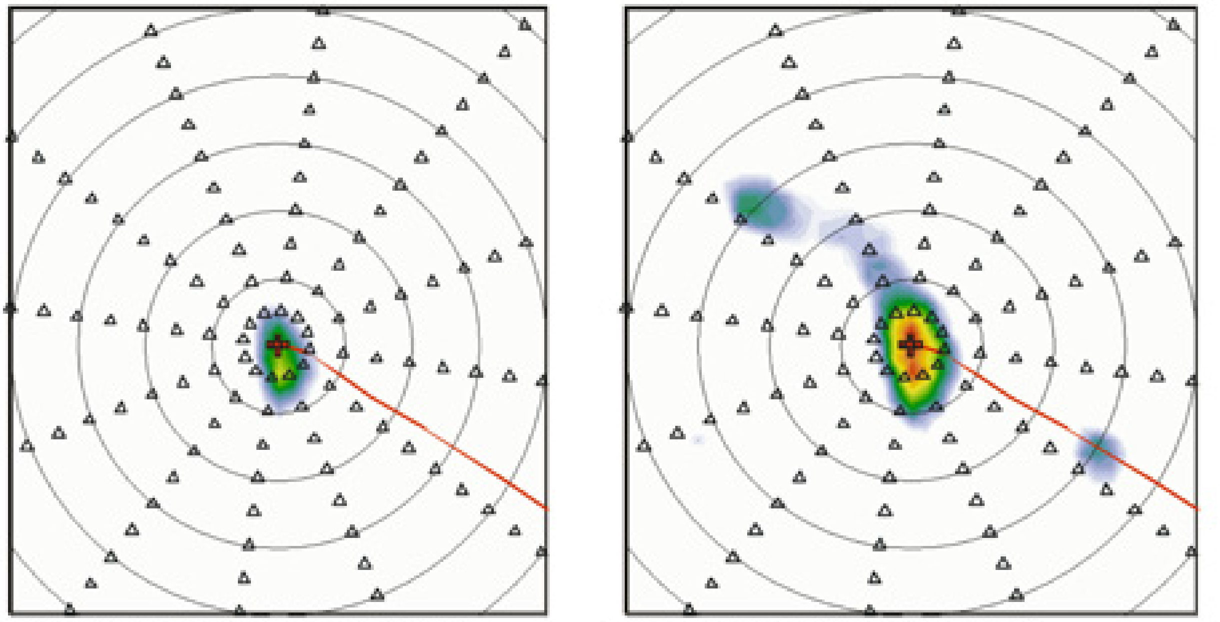
[1] *Russian Academy of Sciences.*

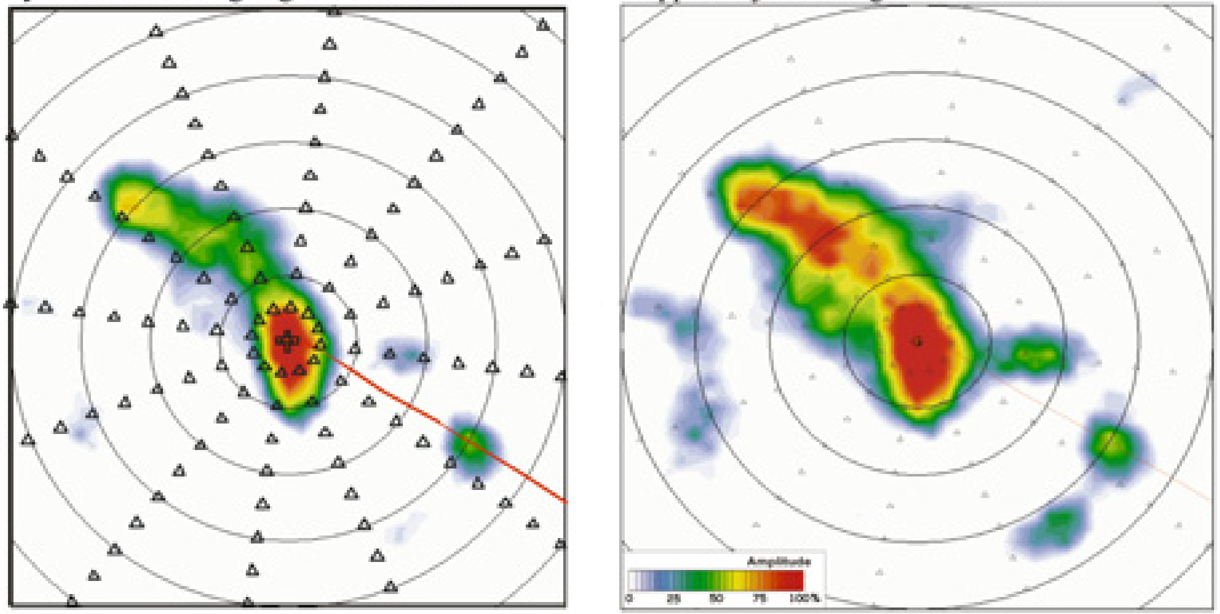
[2] *Khantymansiiskgeofizika.*

**Correspondence: kochnev@icm.krasn.ru.*



Hydraulic fracturing begins. T=1600 s.

Proppant injection begins. T=1950 s.



Proppant is forced into the layer. T=2300 s.

Map of the fully developed fracture. T=5200 s.

Figure 2 *Passive seismic monitoring of a hydraulic fracture at a depth of 2445 m in Western Siberia. Note the asymmetry of the fracture zone.*

Practical application

Assessment of previous research work and numeric modelling suggests that an optimal survey system should be symmetrical relative to the point of injection and have a sufficient number of receiving channels. Processing data from a completed survey on a well at Konitlor oil field, we successfully located the fracture zone and direction of fracture development. It should be noted that raw data appear mostly as noise and contain no evident arrivals. Only by applying special methods for stacking low-energy events, which dramatically increase signal-to-noise ratio, can the events be located.

The velocity model, static correction, and other parameters can significantly influence the quality of the results. Thus, the stacking algorithm needs to be calibrated and its parameters adjusted for the operating conditions. A perforation of the well before hydraulic fracturing provides a good, strong signal with a known source location. We calibrate the algorithm using noises from the perforation.

As shown in Fig. 1, the algorithm accurately places noise sources near the perforation point. After verifying results using this method, we can process recordings made during liquid injection.

Fig. 2 shows an example of processing data from hydraulic fracturing of the well at one of the Western Siberia oil fields. The fracture zone expands mostly in a north-west

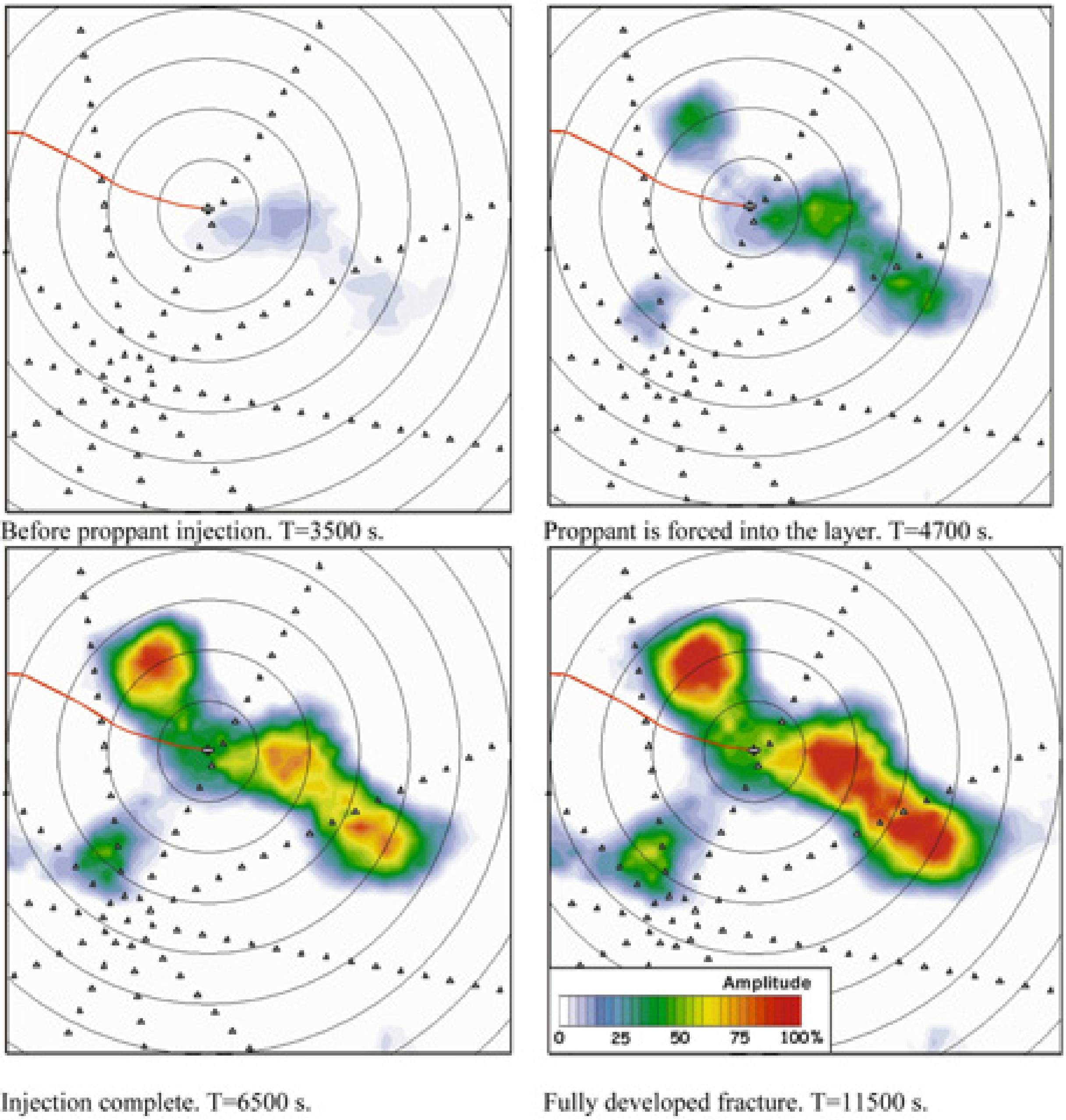

Before proppant injection. T=3500 s.
Proppant is forced into the layer. T=4700 s.
Injection complete. T=6500 s.
Fully developed fracture. T=11500 s.

Figure 3 *Another example of passive seismic monitoring of a hydraulic fracture at a depth of 2490 m in Western Siberia.*

direction. Fracture zones, in our experience, develop mostly asymmetrically relative to the injection point. Asymmetry can be attributed to geological conditions - permeability, density, and other rock properties in the vicinity of the well.

Another example is shown at Fig. 3. It is interesting to note that in this case there are two intensive microseismic activity zones: one at some distance to the northwest of the injection point, and the other to the southeast. It can be theorized that due to good permeability of the rock, injected liquid travels for some time without causing significant fracturing. Note also that seismic activity in the fractured zone continues for a significant time after the hydraulic fracturing process was completed.

Conclusions

We showed the possibility of recording microseismic events during hydraulic fracturing at the surface with standard seismic exploration equipment. These data can be successfully analyzed and used for determining their source locations. An optimal survey system should be symmetrical relative to injection point. The method makes it possible to take into account the velocity model and static correction, thereby improving the robustness of mapping fracture zones.

References

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