

Estimates of the hypocenter location errors of passive microseismic events located by using a 3-C VSP downhole geophone array

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Summary

Hypocenter location errors of passive microseismic events located by using a 3-C VSP downhole geophone array are estimated through numerical experiments. In the case of employing the conventional hypocenter location algorithm, which combines backazimuth and P-wave first arrival times of passive events, the hypocenter location error distribution depends on the location, accuracy of the measurement of backazimuth, and the picking error of P-wave first arrival times. The depth range and the number of the geophones in an array can also influence the error distribution. In addition, we developed a more reliable error estimation algorithm than is generally used today.

Introduction

Hypocenter location of a passive microseismic event in oil reservoirs is often accomplished by using a technique which combines the information of backazimuth and P-wave first arrival times of the event recorded by the 3-C geophones of a VSP array (Oye and Roth, 2003; Phillips et al., 1998). The problem of optimizing a seismic array to obtain information on microseismic events cost-efficiently and precisely is of special importance.

However, the hypocenter location error distribution in this method has rarely been analyzed systematically. In this paper, we try to estimate the error distribution under some pre-conditions by numerical experiments, and provide some guidelines for the future design of VSP downhole geophone arrays.

Methodology

Hypocenter location algorithm based on backazimuth and P-wave first arrival times

A comparatively detailed description of the mentioned hypocenter location algorithm is schematized in Figure 1. The backazimuth of an event defines a vertical plane through the VSP downhole array that contains the source location. The backazimuth is determined by a best fit solution to the microseismic data using hodogram analysis methods for the P-waves by taking a time window containing the first cycle of the impulsive P-wave first arrival (Flinn, 1965; Vidale, 1986). Hodogram linearity is used as an estimate of the accuracy of the backazimuth measurement (Vidale, 1986).

After the determination of the backazimuth of the event, hypocenter location is carried out within the vertical plane. Generally, a layered velocity model is used for hypocenter location. As most VSP downhole geophone arrays are

deployed closely to the oil reservoir to monitor the passive microseismic activity, it is reasonable to make the approximation that the P-wave velocity between the top and the bottom geophones is constant. Using the least squares method, the *RMS* of the differences between observed and calculated arrival times is minimized. The picking accuracy of the P-wave first arrival times depends on many factors, such as sampling rate, *S/N* ratio, and slope of an impulsive first arrival.

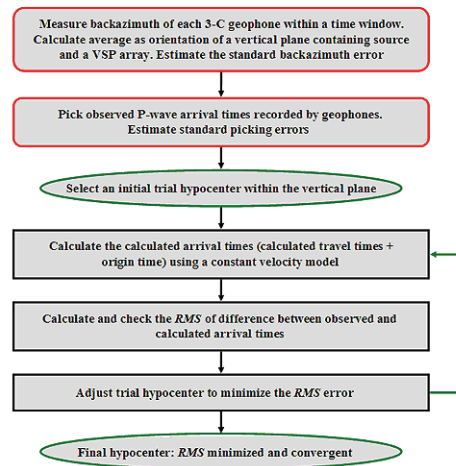


Figure 1: Flow chart for the hypocenter location algorithm based on backazimuth and P-wave first arrival times.

For convenience, the hypocenter location error is defined in cylindrical coordinates by the backazimuth (or transverse, T), the depth below the surface of the earth (Z), and radial distance (R) between the source location and the VSP geophone array. The corresponding hypocenter location of an event j (β_j , L_j , and Z_j) are illustrated in Figure 2.

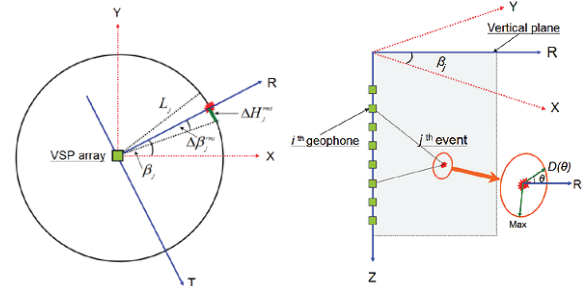


Figure 2: (Left) Plane view of the cylindrical coordinates used in the calculation of the transverse hypocenter location error ΔH_j . (Right) 3-D view of the hypocenter location errors within the vertical plane.

Hypocenter location errors of passive seismic events by a VSP downhole array

Approach to estimate the hypocenter location error in the transverse direction

From geometry (Figure 2), it is obvious that the hypocenter location error in the transverse direction, ΔH_j , is related to the backazimuth error and the radial distance of the microseismic event with respect to the VSP array. Suppose the standard backazimuth error of the event determined by geophone i to be $\Delta\beta_{ij}$. Then the corresponding *RMS* error for the whole geophone array ($\Delta\beta_j^{rms}$) is derived by

$$\Delta\beta_j^{rms} = \left(\sum_{i=1}^m \Delta\beta_{ij}^2 / m \right)^{1/2}, \quad (1)$$

where m denotes the number of geophones in the VSP array.

Using this value, the standard hypocenter location error in the transverse direction is simply obtained from the equation

$$\Delta H_j^{rms} = L_j \sin(\Delta\beta_j^{rms}). \quad (2)$$

Approach to estimate the hypocenter location error within the vertical plane

Hypocenter location errors within the vertical plane are due to the random picking error of the P-wave first arrival times, and systematic arrival time errors due to the difference between real and assumed velocity models. The conventional hypocenter location error estimate is generally performed by using the covariance matrix of an error ellipse after the hypocenter location procedure. Unfortunately, a number of studies suggest that this error estimate method is unreliable due to the violation of several basic statistical assumptions: Gaussian, zero mean and uncorrelated error processes (Bondár et al., 2004). In fact, it is obviously unreasonable to estimate location error by only considering the travel time residuals without taking into account of the error of hypocenter location.

In a typical hypocenter inversion procedure, an optimal hypocenter is determined by minimizing the sum of squared first arrival time residuals (*SSR*) in a least squares method:

$$SSR_j = \sum_{i=1}^m (t_{ij}^{obs} - t_{ij}^{cal})^2. \quad (3)$$

where t_{ij}^{obs} , t_{ij}^{cal} and $t_{ij}^{obs} - t_{ij}^{cal}$ denote the observed first arrival times, the corresponding calculated arrival times, and the time residual at geophone i respectively. m is the number of geophones.

In difference to the previous time residual error estimate method, which assumes a prior picking error to each first arrival time, and then to produces error ellipse (Evernden, 1969), this new error estimate algorithm is established in a reversed way. The basic aim is to determine the in-plane angular variation due to the dislocation of the a hypocenter, as shown in the following steps:

Firstly, it is certain that when there is no picking error and the assumed velocity model matches the real one, a hypocenter will be located at its real location, and the time residual will be zero. Suppose the case that due to the picking errors of first arrival times, a hypocenter is located a small fixed distance (ΔS) away from its real location, and hence the possible calculated hypocenters form a circle of radius ΔS around the real one. The $SSR_j(\theta)$ of any point on the circle is calculated based on its location, the geometry of the VSP array, and the local velocity, where θ is the angle from the center to the point. $SSR_j(\theta)$ can be viewed as an index to show the angular difficulty for the event to be located at angle θ .

By taking the square root of the average of $SSR_j(\theta)$, a normalized $SSR_j^{norm}(\theta)$ is obtained by

$$SSR_j^{norm}(\theta) = (SSR_j(\theta) / m)^{1/2}. \quad (4)$$

Clearly, $SSR_j^{norm}(\theta)$ represents the normalized *RMS* of the whole time residuals, and inherits the same physical meaning. Conversely, we defined another index, $\Delta D_j(\theta)$, by using the ratio between ΔS and $SSR_j^{norm}(\theta)$ as follows:

$$\Delta D_j(\theta) = \Delta S / SSR_j^{norm}(\theta). \quad (5)$$

Here $\Delta D_j(\theta)$ indicates the distance shift with the change of a unit of $SSR_j^{norm}(\theta)$ residuals (1ms) due to the picking errors. It reflects the shape of the error distribution around the real hypocenter.

Numerical experiments and results

Data and pre-conditions

The concrete model of the downhole VSP array used for estimating hypocenter location errors in this study is based on VSP monitoring carried out in Violet Grove near Drayton Valley, Alberta, for a CO₂ EOR and storage study (Lawton et al., 2005).

The VSP geophone array consists of eight 3-C geophones deployed from approximately 1500 to 1640 meters in depth. The P-wave velocity close to the oil reservoir is approximately 4000 m/s based on surface reflection data.

Numerical experiments are accomplished based on the following pre-conditions:

1. The standard backazimuth error of each of the eight geophones is assumed to vary randomly from 0° to 5°.
2. The standard picking error of P-wave first arrival times

Δt_{ij}^{pick} of geophones is estimated to be less than 2ms.

3. There is no difference between the assumed and real velocity models. Thus, P-wave arrival times are only affect by the random picking error.

Error distribution in the transverse direction

The general distribution of hypocenter location errors in the transverse direction is calculated and depicted by assigning

Hypocenter location errors of passive seismic events by a VSP downhole array

the locations of events distribute at an interval of 5 meters (Figure 3). Note that due to the random variation of the standard backazimuth of each geophone, errors fluctuate even the radial distances are the same. The fluctuations become more severe as the radial distance increases. In general, the hypocenter location error in the transverse direction shows a trend of a series of concentric circles around the VSP array.

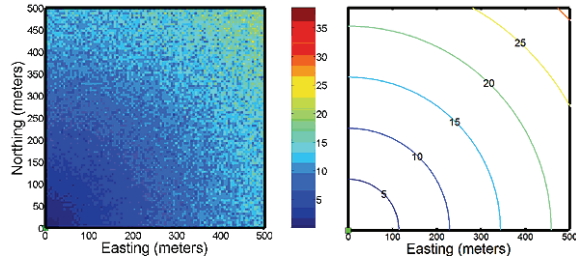


Figure 3: (Left) Distribution of hypocenter location errors in the transverse direction with random backazimuth errors ranging from 0° to 5° . (Right) Contour map of the hypocenter location errors with backazimuth errors fixed at 2.5° . Microearthquakes are distributed at 5 meter intervals; the projection of the VSP array on the surface is marked by a green square. Errors are shown in meters.

Error distribution within the vertical plane

Statistical distributions of hypocenter location errors within the vertical plane are carried out by assigning the locations of events are distributed at 20 meter intervals. Figure 4 shows the orientations and the configuration of hypocenter location errors around the assumed events, where ΔS is calculated to be 8 meters based on the assumed picking error (less than 2ms) and a P-velocity of 4000 m/s. The orientations and the corresponding values of the hypocenter location errors vary with both the radial and depth directions. The most obvious features of the error distribution are summarized as: both the radial and depth errors of the events are smallest near to the lateral side of the VSP array; with the increase of the radial distance, depth errors become dominant while radial errors change little in value. When events occur straight above or below the VSP array, radial errors is large and increase rapidly with the distances from the nearest geophone. The contour map also shows the maximum error distributions located by the VSP array. In this case, the extent of the reference contour approximately coincides with the depth range of the VSP array.

Discussion

Effect of the number of geophones in a VSP array on hypocenter location errors

Although a VSP array with a large number of geophones is likely to enhance the accuracy of hypocenter location, costs will increase correspondingly.

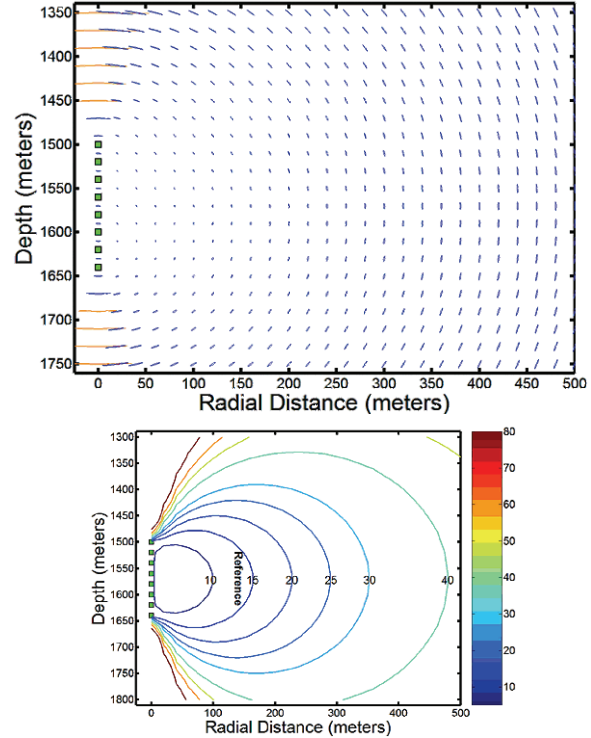


Figure 4: (Top) The orientations and hypocenter location errors within the vertical plane. For clarity, error values are reduced 8 times, and some very large errors are marked in orange. (Bottom) Contour map of the maximum hypocenter location errors at aligned points. The depths of the geophones of the VSP array are shown on the left side by green squares. Errors are shown in meters.

Suppose the picking errors of the P-wave first arrival times and backazimuths follow a Gaussian normal distribution. According to the central limit theorem of statistics, the relationship between the number of geophones deployed and the confidence interval of backazimuth β (that is the orientation of the vertical plane) is $\pm\beta/m^{1/2}$. This relationship states that when the number of geophones in a VSP array surpasses eight, the confidence interval will be reduced to more than half. Another merit of using numerous geophones is that they provide more options for selecting better backazimuth and first arrival time measurements, and for excluding those with larger deviations. No doubt, this will increase the accuracy of hypocenter locations and lower the error estimates.

Effect of the depth range of a VSP geophone array on hypocenter location errors

The depth range of the VSP array, or the distance between the top and bottom geophones, affects the hypocenter location errors within the vertical plane.

Hypocenter location errors of passive seismic events by a VSP downhole array

To examine the effect of the depth range, we increase the interval between the eight geophones in the VSP array from 20 to 30 meters, and calculate the error distributions (Figure 5). Although the pattern of orientations of errors remains similar to the previous one, the errors are reduced both laterally and vertically. The depth range of the selected reference contour coincides with the depth range of the larger VSP array. Thus, a VSP array with a larger depth range can lower the hypocenter errors within the vertical plane.

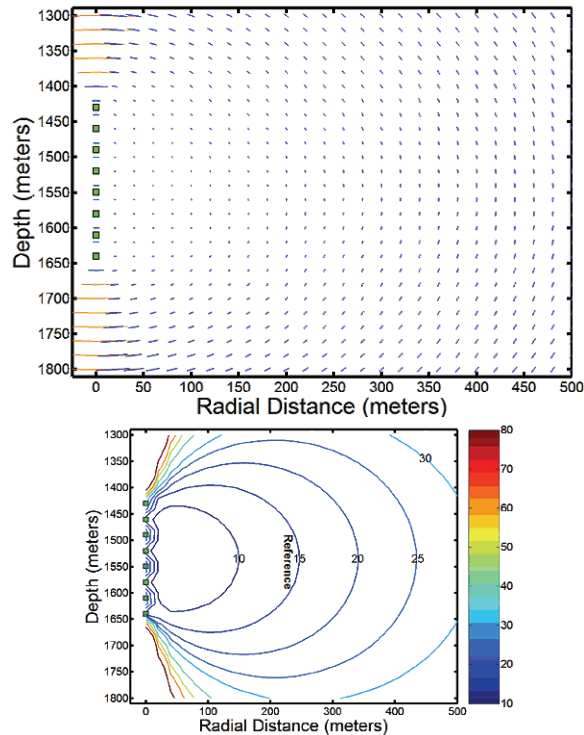


Figure 5: (Top) The orientations and hypocenter location errors within the vertical plane calculated by the larger depth range VSP array. For clarity, error values are reduced 8 times, and some very large errors are marked in orange. (Bottom) Contour map of the maximum hypocenter location errors at aligned points. The depths of the geophones of the VSP array are shown on the left side by green squares. Error is shown in meters.

Conclusions

There are many factors which affect the distribution of hypocenter location errors located by using a VSP geophone array. In these the numerical experiments, hypocenter location errors expressed in local cylindrical coordinates are estimated and summarized as follows:

1. The hypocenter location error in the transverse direction is proportional to the standard backazimuth error and the radial distance of an event with respect to the VSP array.

2. Within the vertical plane, the orientations and the corresponding values of the hypocenter location errors vary with both the radial and depth directions. Both the radial and depth errors of the events are smallest near the lateral side of the VSP array. The depth errors increase with radial distance, while radial errors become worst when events occur straight above or below the VSP array.

3. The depth range of reference contour approximately coincides with the depth range of the VSP array. Presumably, a VSP array with a large depth range of geophones can expand the small-error area.

4. The number of geophones deployed in a VSP array can reduce the confidence interval of the orientation of the vertical plane. In addition, numerous geophones can provide more options for selecting better backazimuth and first arrival time measurements and excluding larger deviation ones, and hence reduce the errors of hypocenter locations.

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Acknowledgments

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