Feasibility of jointly locating microseismic events with data from surface and downhole receivers

Jaromir Jansky,[1*] Vladimir Plicka[1] and Leo Eisner[2] **model the feasibility and potential advantages for hydraulic fracture mapping of using both surface and downhole microseismic data.**

Using synthetic data we study the feasibility of locating microseismic activity with both surface and downhole receivers as compared to the use of surface receivers only. In the tests, we use a simple velocity model, composed of homogeneous layers and a choice of synthetic receiver and sources distribution. The location feasibility is measured by the misfit function (sum of residuums) of the travel times computed for each point of the source region. The forward synthetic data are computed for the true model and for a perturbed model with modified velocity. The inversion is performed always in the true model, so that the difference in the location feasibility in the second case illustrates the influence of unsufficient knowledge of the model velocity. This influence is partially supressed by use of a larger monitoring array, particularly by using downhole and surface receivers together.

Hydraulic fracture treatment in oil and gas reservoirs is often used to enhance production by injecting fluids under pressure to fracture the formation and create conductive paths in the reservoirs. Such treatment induces microseismic activity that can be monitored and possibly located by monitoring arrays deployed in the vicinity of the reservoirs, if a suitable velocity model of the medium is available. The distribution of events can then be used to check the response of the reservoir to the injection of fluids. However, the detection of microseismic activity is generally constrained by the distribution of the sensor arrays. In general, there are two commonly used types of sensor distributions: three-component receivers distributed in a monitoring well (Maxwell et al., 2010), or one-component vertical receivers distributed on the surface or shallow boreholes (Duncan and Eisner, 2010).

The sole use of data from surface receivers generally suffers from inaccuracy in the estimate of event depth whereas the sole use of data from receivers in a vertical monitoring well often does not yield good epicentres due to uncertainty in azimuth estimation, where often for the same event the azimuth estimated at individual receivers varies significantly. The use of data from the horizontal well gives again (as in the case of vertical well) good accuracy only in the direction of the well axis. Therefore the joint use of surface and well data promises to remove these imperfections in the ideal case or produce a combination of inaccuracies if not done properly. This approach can represent an alternative to location that uses data from two vertical monitoring wells where the problem with azimuth estimation is also reduced, though not completely removed (e.g., Jansky et al., 2010; Eisner et al., 2009).

The location of microseismic activity is generally a formidable problem, and many recent papers have been dealing with it when location uncertainties became an important issue (e.g., Rentsch et al., 2007; Grandi and Oates, 2009; Maxwell, 2009; Eisner et al., 2010).

Recently, Eisner et al. (2009) studied sources of location uncertainty for downhole as well surface microseismic monitoring in a homogeneous velocity model, and Maxwell (2009) and Zimmer et al. (2009) discuss uncertainties for downhole monitoring in a layered velocity model.

The signals recorded at surface receivers, where all receiver locations are known with sufficient accuracy, as compared with the receivers in a monitoring well, are usually very weak and it is necessary to enhance the signal-to-noise ratio by stacking the responses of 1000–10000 receivers (e.g., Duncan, 2005; Kochnev et al., 2007). Chambers at al. (2010) published a new study dealing with the ability of surface arrays to monitor microseismic activity and confirm that event depth estimation is not as well constrained as with downhole arrays. Duncan and Eisner (2010) give an overview of surface monitoring techniques where locations are obtained through stacking of signals from a large number of sensors.

Very interesting results of location of events using both surface and borehole monitoring networks were presented by Vernier at al., (2009) and Jervis and Dasgupta (2009).

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The studies mentioned above inspired us to conduct our own test to see if an addition of data from a monitoring well to the data from surface receivers will help to improve the estimation of event depth. We run this test in models composed of homogeneous layers with different *P*- and *S*- velocity ratios, using a source that mimics the position of microseismic events. We further use a set of three component receivers, distributed in the vertical and horizontal monitoring wells, and a set of vertical component receivers on the surface.

To keep the computation time reasonable we use, contrary to practice, only a very small number of surface receivers distributed on the surface of a large area. We compensate for this by assigning the same weight to the surface onsets as to the onsets recorded in the monitoring wells. Because of this our surface receivers rather represent receivers placed in shallow boreholes with higher signal-to-noise ratio. Our target is to study how accurately we can locate the synthetic source, using data from the surface receivers only, as compared with the use of data from both surface receivers and one of the monitoring well, vertical or horizontal. The influence of unsufficient knowledge of the velocity model is shown.

Configuration

To get the arrival-time data for the test we use two forward velocity models: the 'true' model and a 'perturbed' one. Both models are composed of six layers, where the thin layer 4 represents the layer where the synthetic microseismic activity occurs. The *Vp*/*Vs* ratios in individual layers are 1.9444, 1.8182, 1.6923, 1.9587, 1.6250, and 1.6283 from the shallowest to the deepest, sixth layer, respectively. The true model, shown in Figure 1 (see also Figure 2b), represents a simplification of a real model derived from sonic log data for one gas field in West Texas (Vavryčuk, pers. comm; Bulant and Klimeš, 2008). Our models have lower number of layers and contain only one layer with low velocity and high *Vp*/*Vs* ratio (layer 4, representing a sedimentary environment), but the values of the velocity and the depth are similar to those of the 'West Texas' model. The model is simple at the surface as we assume most near-surface heterogeneities would be compensated by receiver statics determined from calibration shot (Duncan and Eisner, 2010).

The perturbed model with lower velocities, is given in Figure 1 by dashed lines. This model was obtained by substracting the value of 120 m/s from *P*-wave velocity and 70 m/s from *S*-wave velocity in all layers of the true model. This represents on average about 3% of velocity decrease both for the *P*- and *S*-waves.

Figures 2a and 2b show the geometry of the receiver array in the vertical monitoring well A (these seven receivers are distributed in layers 3, 4, and 5, spanning depths from 984.7 to 1167.6 m, similarly as in one monitoring well in West Texas), as well as the geometry of the receiver array in the horizontal monitoring well B, where all seven receivers have the same Z

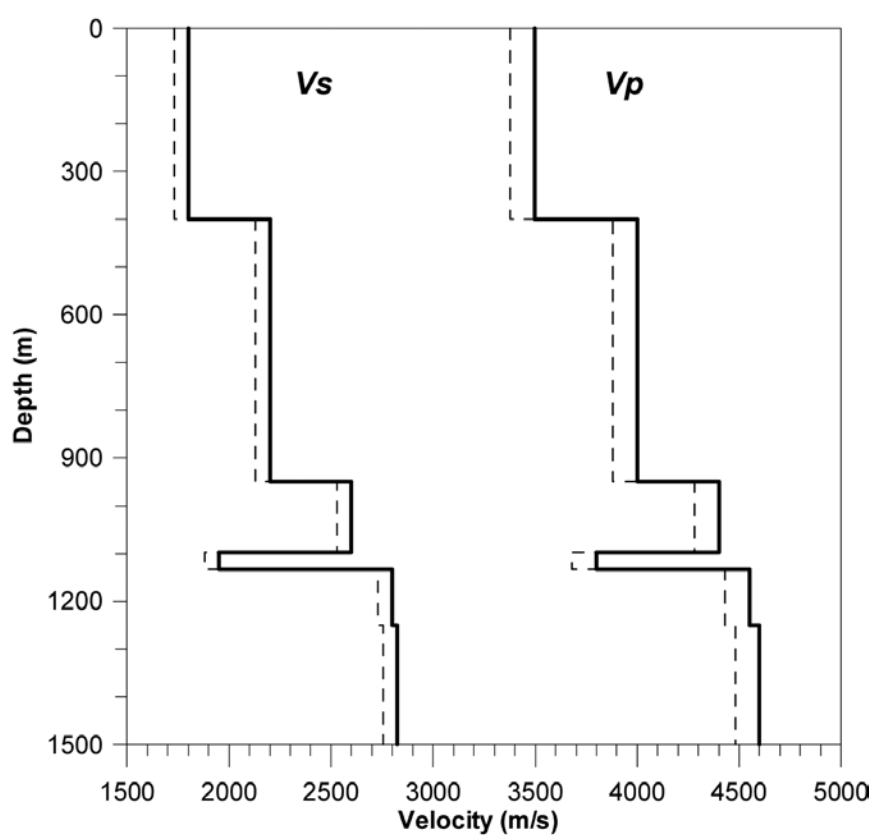

***Figure 1** Solid lines show Vp and Vs as a function of depth in the true forward model. This velocity model is used in the inversion of the travel-time data regardless for what forward model the travel-time data were computed. The dashed lines show the corresponding velocities of the perturbed forward model.*

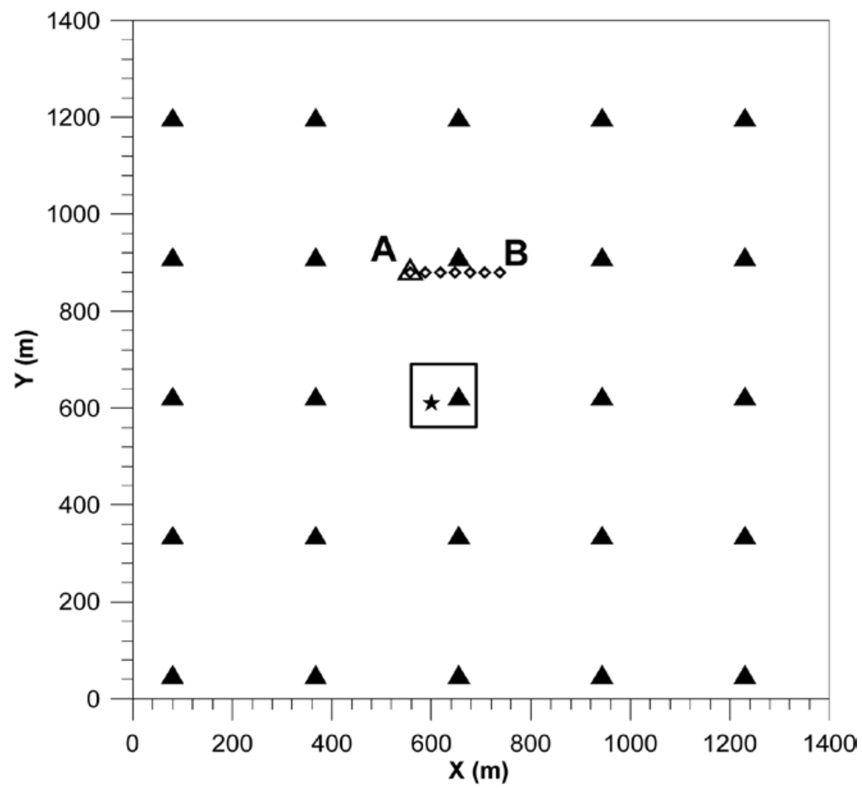

Figure 2a *Map view of the positions of vertical A (white triangle) and horizontal B (white diamonds) monitoring wells, and of surface receivers network (black triangles). Asterisk denotes the X–Y coordinate of synthetic microseismic event (source point in the model). The rectangle shows the X–Y area of grid, in which we evaluate the misfit value.*

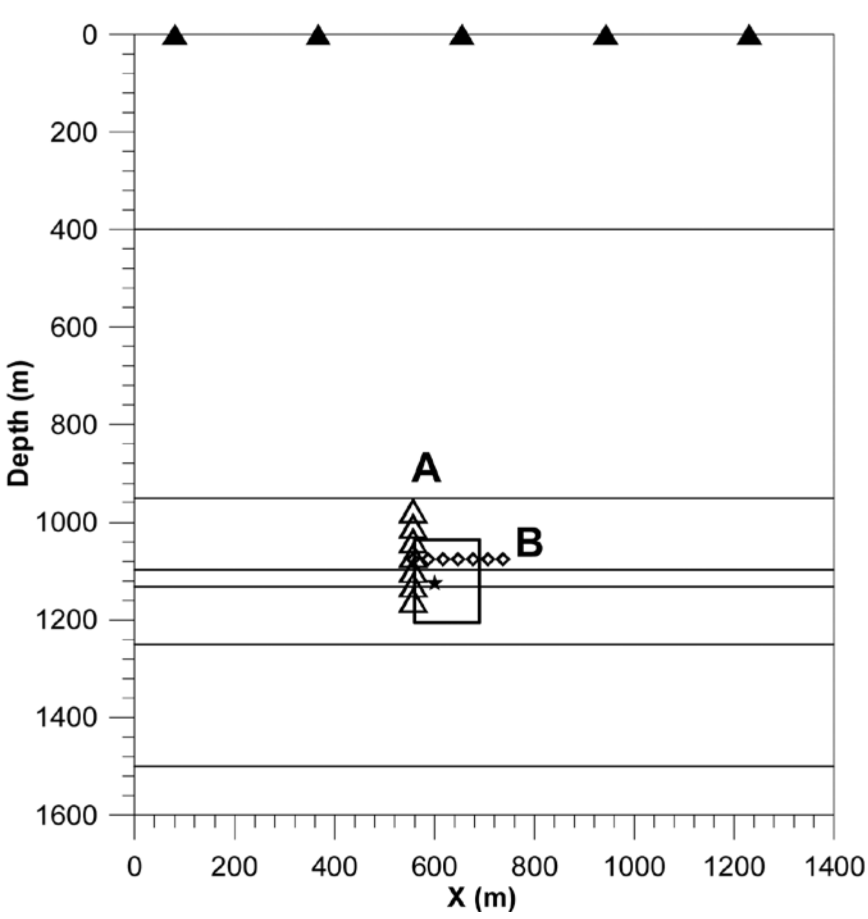

Figure 2b *The vertical (X-depth) cross-section through our receivers and synthetic source. The symbols are the same as in Figure 2a, only the rectangle shows the X-depth (X–Z) extent for our grid. Solid lines show the boundary of the individual layers.*

and Y coordinate and the X position increase from 557.7 m in steps of 30 m. The 25 surface receivers are distributed in a regular grid with a grid step of 287.5 m in both *X* and *Y* directions.

Microseismic events are represented by a synthetic source with coordinates X=600 m, Y=610 m, Z (depth)=1125 m. In this way we take the advantage that its epicentre is situated in the centre of the surface-receiver network to provide optimum azimuthal coverage. The minimum and maximum offset is about 16 m and 863 m, respectively. Hypocentral depth is at below optimal 1:1 offset to depth ratio, hence we expect worse vertical resolution. The vertical monitoring borehole spans the depth of the source at distance of approximately 300 m providing optimal depth constraint (Eisner et al., 2010).

The travel times from the synthetic source point to all receivers were computed for the true and perturbed forward models by two-point ray tracing. The first onset for waves is evaluated, taking the head waves in consideration, where appropriate (occurs only for downhole receivers). The accuracy of the ray tracing is equal to or better than 0.1 m in the X–Y plain of the receiver depth level. The computed travel times are rounded off to three decimal places, with the standard accuracy of 1 millisecond as estimated by Eisner et al. (2009). Considering that the accuracy of the data from the surface receivers is in reality worse than the accuracy of data from downhole receivers, we altered these travel times by adding or subtracting randomly 2 ms. This may be realistic if the surface data represent the data from receivers placed in shallow boreholes (see above).

Data inversion

In the inversion we consider the synthetic travel times as arrival times (i.e., in the inversion we also estimate origin times). Three approaches were taken to invert the computed travel times to get the location of the source. The first one uses only the network of surface receivers, i.e., just *P* waves. The second approach uses the vertical monitoring well A and the network of surface receivers, whereas the third approach uses the horizontal monitoring well B and the surface network. *P* and *S* waves are used in downhole receivers, but only *P* waves with the surface receivers.

The misfit function is of the form

$$misfit = \frac{\sum_{i=1}^{NS}(t_o - t_c)^2}{NS},$$

where t_0 represent the observed travel time and t_c the computed travel time, and is evaluated for each grid point, that surrounds the source point. NS is number of stations. The extent of the grid in the X, Y, and Z (depth) axes is clear from Figures 2 a, b, and the following figures. The grid step equals 10 m in all axes.

Data inversion is always performed with the true model. First we have inverted the travel time data computed for this model. Here we should expect best results, because the forward model and the model used in inversion are identical. To demonstrate the influence of unsufficient knowledge of the velocity on the microseismic event location, the inversion was run with travel times obtained from the perturbed forward model (but with the true model used to calculate travel times for each grid point).

The results of the computation are given graphically in the form of the X–Y and X–Z cross-sections through the inverted hypocentre (i.e., the grid point with the lowest misfit value) from Figure 3 up to Figure 8.

Synthetic tests assuming the true forward model

In the first inversion approach (25 surface receivers) we get good estimates of X and Y coordinates but a downward shift in depth of 20 m. These results are comparable with those of Eisner et al. (2010) and Chambers at al. (2010). This depth error is mostly due to a larger error in travel times for surface data and the use of only *P*-waves, and depends on the depth of the synthetic source (Figure 3).

The second inversion approach uses data from well A and surface receivers (i.e., we have 32 receivers). The data from the vertical monitoring well stabilized the depth estimation, and we get good estimates of all three source coordinates (Figure 4).

The third inversion approach deals with the data from the horizontal well B and surface receivers (we again have 32 receivers). Again, good estimates of all source coordinates are obtained (Figure 5). This is a somewhat surprising result as depth is worse constrained with a horizontal monitoring well. However, it is clear that traveltimes from a horizontal monitoring well add sufficient constraints to the estimation of source depth, especially in combination with a surface array.

Results from the data obtained for the perturbed forward model

In the first inversion approach (25 surface receivers) the X and Y coordinates were found reasonably well but depth was shifted upwards by 30 m (Figure 6).

The addition of the data from the vertical well A (second inversion approach) changed the depth significantly as compared with Figure 6. This time we get a shift of 20 m downward. Further, the Y coordinate is shifted by 10 m along the positive Y axis (Figure 7).

The third inversion approach (data from the horizontal well B and from surface receivers) also increases the depth error. We get a downward shift of 40 m. Further the X and Y coordinates are again not accurate. We get a shift of 10 m to smaller values in the X coordinate (Figure 8).

Discussion

All our results are quantitatively valid only for the models, source, and receivers used in our computation. In our contribution we only wanted to show and quantify by order of

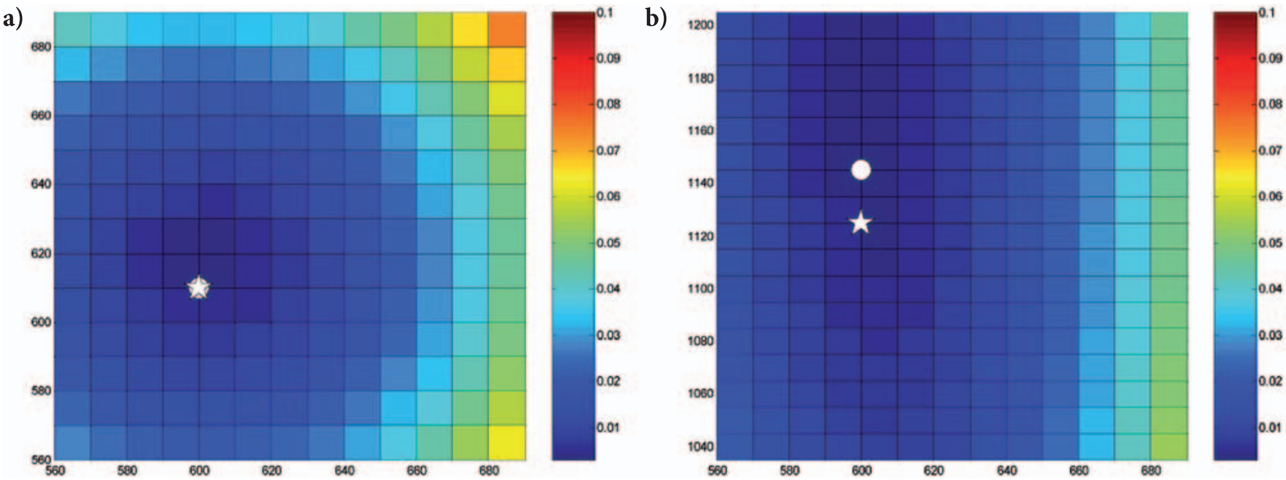

Figure 3 *X–Y at Z=1125 m (a), and X–Z at Y=610 m (b) crossections of misfit value (sec²) of the location of the source, respectively. The inversion uses the surface receivers travel-time data for the true forward model. The asterisk gives the position of the forward source, the circle the position of found hypocentre.*

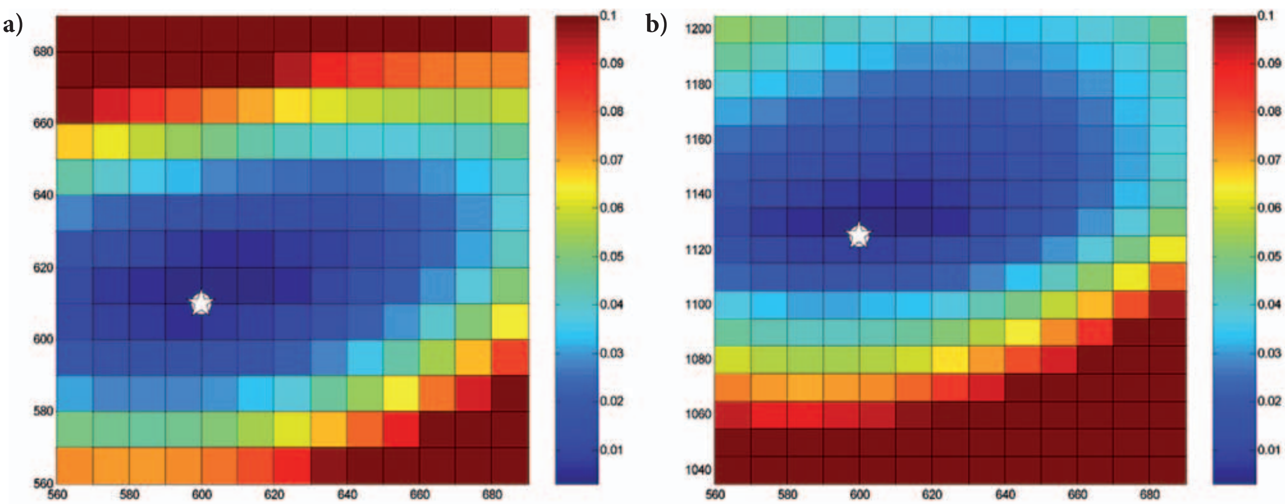

Figure 4 *The same as in Figure 3, but for inversion that uses, together with the data from surface receivers, the data from receivers in the vertical monitoring well.*

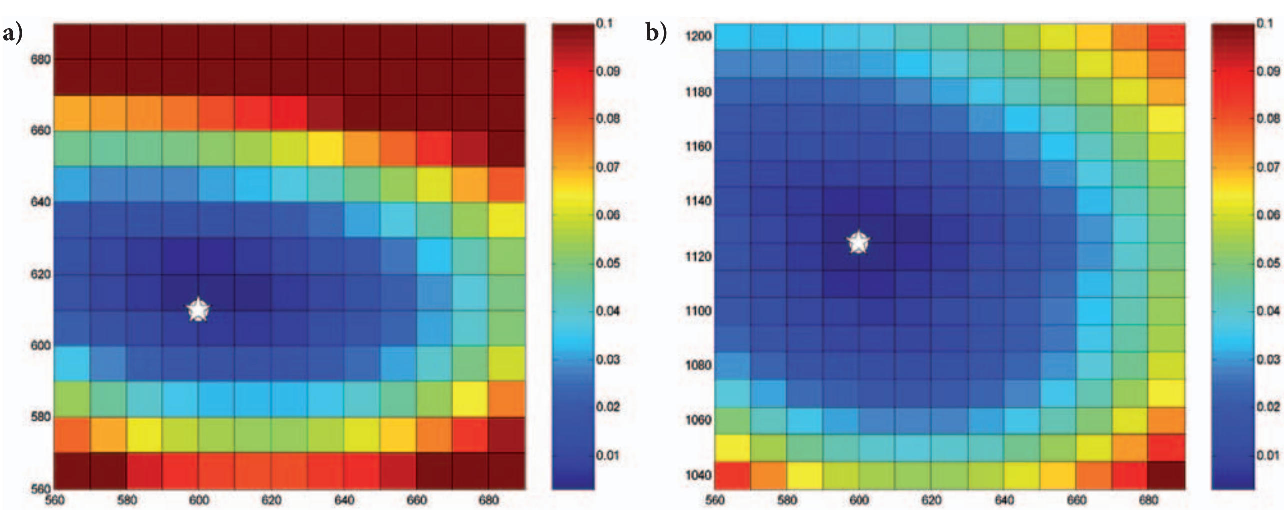

Figure 5 *The same as in Figure 3, but for inversion that uses, together with the data from surface receivers, the data from receivers in the horizontal monitoring well.*

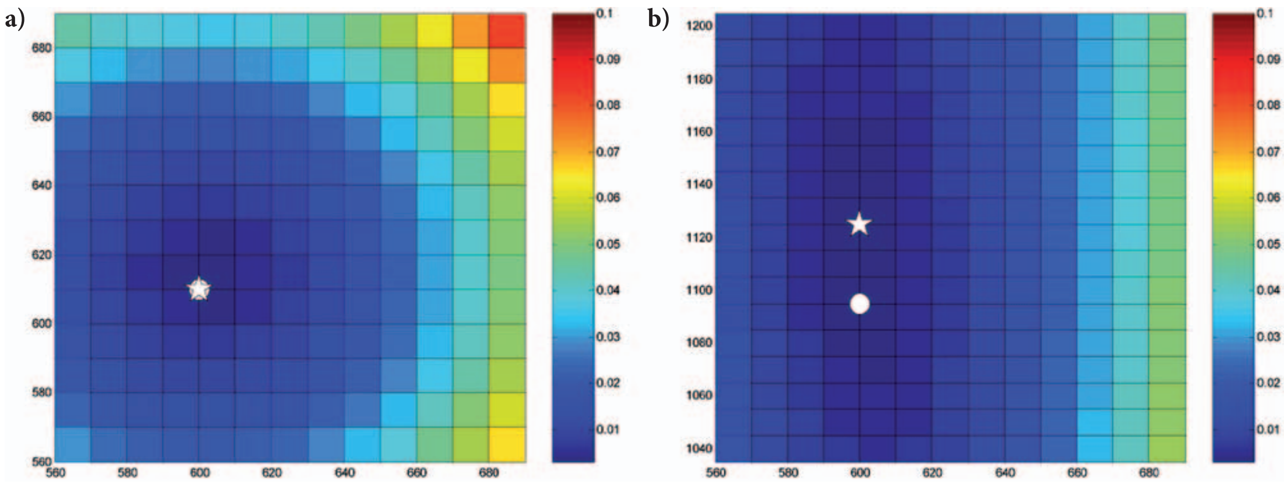

Figure 6 The same as in Figure 3, but for inversion that uses the surface receivers travel-time data for the perturbed forward model. The X–Y crossection is taken at Z=1095 m. The X–Z crossection stays at Y= 610 m.

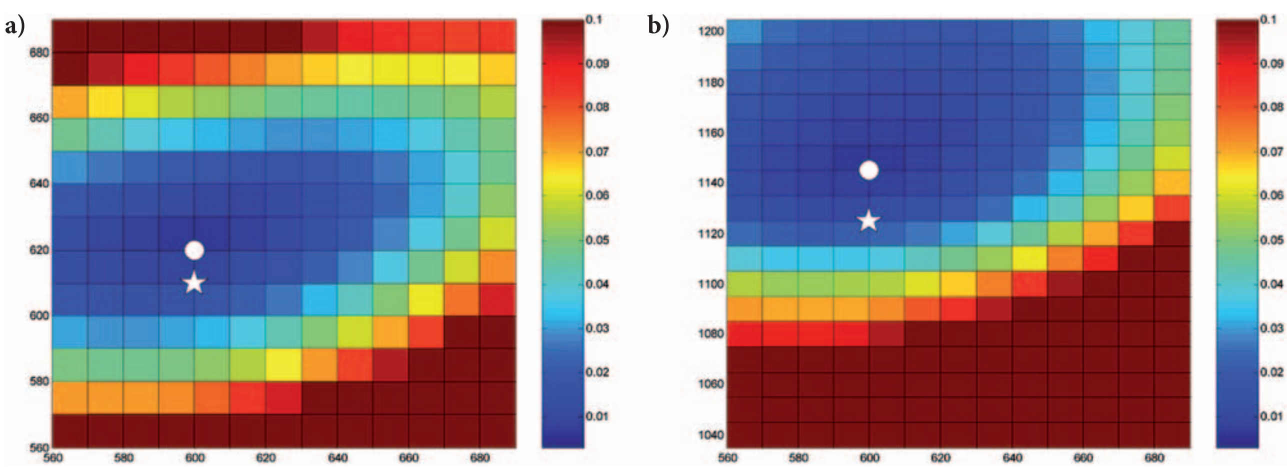

Figure 7 The same as in Figure 4, but for inversion that uses the travel-time data for the perturbed forward model. The X–Y crossection is taken at Z=1045 m and the X–Z crossection is taken at Y=620 m.

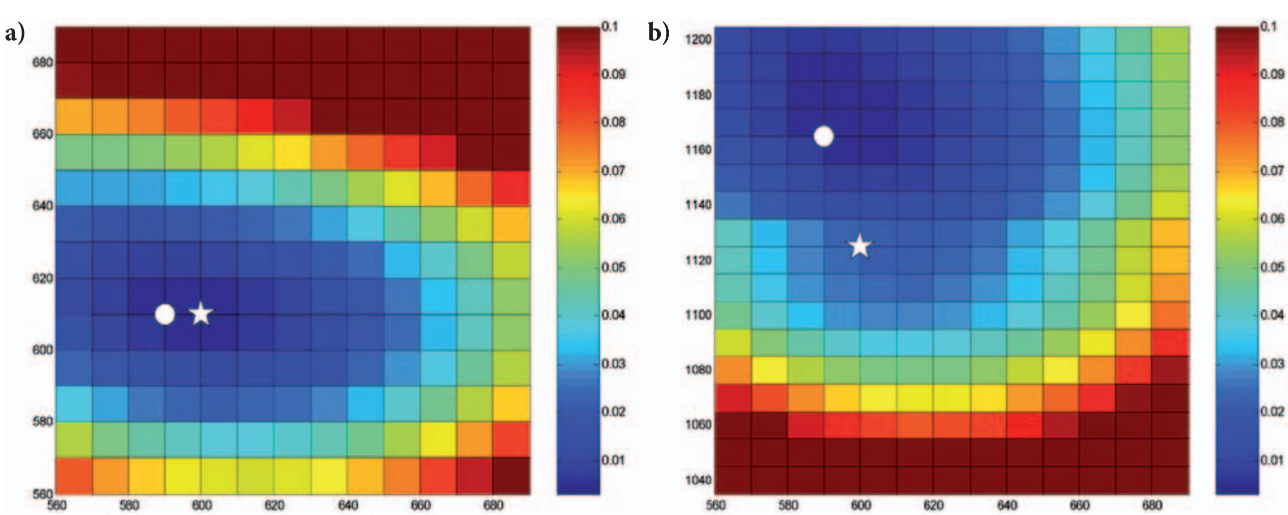

Figure 8 The same as in Figure 5, but for inversion that uses the travel-time data for the perturbed forward model. The X–Y crossection is taken at Z=1065 m and the X–Z crossection is taken at Y=610m. The asterisk in Figures 6a, 7a, 7b, and 8a is projected from its proper position.

magnitude the influence of adding data from the downhole receivers to the data from surface receivers. Further we wanted to show the influence of insufficient knowledge of the model velocities because in reality the velocities are only known with limited accuracy.

Conclusion

From the results shown it follows that for a good velocity model the source depth can be significantly improved if, together with the data from surface receivers, the data from the receivers in the vertical or horizontal well are used. For the tested configuration the location errors are reduced to 5 m or less.

The accuracy of the source depth estimation in the case of unsufficient knowledge of the model velocity is not improved by the addition of data from the vertical well and especially from the horizontal well where we partially lost the accuracy in the horizontal plane.

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