6 Conclusions

In this thesis a new migration-based procedure for location of seismic sources is presented. The procedure requires three-component data in a preselected time interval around the direct P-wave as well as a velocity model. The approach is based on the principles of wavefield back-propagation and uses a technique inspired by Gaussian-beam migration. As presented in this work, the polarization information can be obtained by analyzing instantanous polarization as well as by analyzing the average polarization in a selected time window. For both estimates of the polarization information the kernel of the location method is very similar. The polarization information is used as a starting direction for initial-value raytracing and the energy back-propagation along the rays is performed with Gaussian beams. The summation of all Gaussian beams over all receivers yields regions of distinct high energy and the maximum is interpreted as the hypocenter of the event.

The approach was applied to synthetic data examples which were modeled with different source types, different acquisition geometries and different noise levels. Successful estimates of the source locations were obtained independent of which method for polarization estimation was used. Nevertheless, it was observed that the acquisition geometry influences the shape of the likelihood area in which the hypocenter is located. Moreover, it indicated that the signal-to-noise limits for the applicability of the method depends on the acquisition geometry. Using two different acquisition geometries the limits of the method concerning the signal-to-noise ratios were estimated from synthetic data. From these tests it is possible to conclude that the location method allows for successful hypocenter determination for P-wave signal-to-noise ratios down to 6.9 dB when receivers are placed arbitrarily (at the surface) to obtain a wide aperture. For limited apertures, such as it occurs when only a single monitoring well is available, the limit for signal-to-noise ratio is in the order of 9.1 dB. For smaller signal-to-noise ratios the estimated polarization becomes unreliable and might lead to wrong locations. Arrival-time based procedures allow for location as long as manual arrival time picks can be made. Assuming that manual picking of arrival times performed by an experienced seismologist is possible down to 3.1 dB P-wave signal-to-noise ratio it can be concluded that standard arrival time-based methods can handle noisier environments. However, these methods do not provide the possibility for real-time monitoring since manual picking is time-consuming.

In any event, the detection algorithm designed in the frame of this work ensured that only events with sufficient signal-to-noise ratios were used for location. Therefore, STA/LTA ratios, spectrograms and rectilinearity values were analyzed using moving time windows. Only if a sharp onset of all three characteristics was observed an event was declared. For phase identification acquisition geometry specific features were used. Such a phase identification procedure cannot be automated easily to work for all kind of data sets since geometry specific features may change from data set to data set. However, once the setup works for a particular data set it can be applied to the whole records to support fast detection.

Since the location approach presented in this thesis is designed for applications where real-time monitoring is important (e.g., the monitoring of reservoir treatment) it was reasonable to apply the method to the data set of the Carthage Cotton Valley hydraulic fracture experiment. All the locations obtained using the presented migration technique are in a very good agreement with its corresponding locations obtained by arrival-time based location procedures. Nevertheless, it was observed, that seismicity induced during hydraulic fracturing is characterized by very small magnitudes. This means, the P-wave of the events might not always exceed the signal-to-noise limit in which the method is applicable. A suggestion for future work is to implement slowness driven estimates of emergence angles as well as the usage of S-wave polarization which will certainly reduce the current S/N limits.

The location approach was also applied to a data set of naturally induced seismicity from the San Andreas Fault. The recording network consisted of 80 3C seismometers (an array from P/GSI which is normally used for industrial VSP applications) installed into the Main Hole of the San Andreas Fault Observatory at Depth (SAFOD). One of the major aims of SAFOD is to drill directly into the hypocentral region of the repeating microearthquake clusters. For this challenging drilling project high precision locations of these repeating target events are mandatory. The waveforms recorded with a high-quality industrial standard provided an unique opportunity to identify and locate these target events. As described in this thesis, the acquisition geometry was unfavorable for the migration-based location of target events. In order to overcome this pitfall the additional use of arrival time differences was implemented in the location method. The data set contained numerous events which were successfully located as they passed the rectilinearity threshold which was defined to ensure polarization reliability. Moreover, the obtained locations were very consistent with the San Andreas Fault surface trace. Several velocities were provided with the SAFOD data set. The robustness of the target event location was tested with six different 3D velocity models. All obtained locations are in a very good agreement and their relative deviations are within the error bars of the estimated location uncertainty.

The application of the location method to very different data sets (natural and man-made seismicity) showed successful locations when the signal in the time interval around the P-wave exceeded the signal-to-noise limit. However, it was also important to test the robustness of the method applying it to time intervals which did not contain a direct P-wave arrival and hence did not fulfill the basic requirements of this method. Two intervals contradicting the basic requirements were utilized for this test, one did not contain any coherent arrival (or at least none that could have exceeded the signal-to-noise limit) and the other one contained a coherent phase arrival which was not associated with a direct P-wave. Both resulting images did not produce an interpretable hypocenter and hence the method behaved robust producing zero output when using wrong data for input. This result together with the successful locations in the two case studies supports the potential of the method. The use of a migration-based location technique has the advantage that accurate phase arrival picking becomes redundant (at least for most conventional acquisition geometries). This, in turn allows for the algorithm to be implemented as a highly automatic location procedure in order to support real-time monitoring.