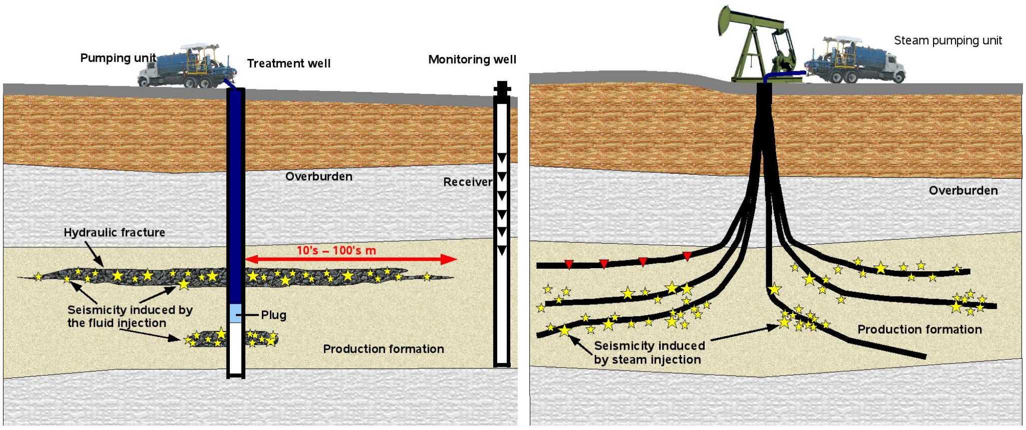
1 Motivation and introduction

The location of seismic sources (i.e., attributing events to spatial coordinates of their hypocenter) is an important issue in a broad range of geophysical applications. This includes earthquake seismology (Thurber and Rabinowitz, 2000), monitoring of hydraulic fracturing, reservoir stimulation as well as seismicity based reservoir characterization (Maxwell and Urbancic, 2001).

Especially the latter industrial applications raised the interest in the development of automated, fast and reliable location algorithms. The reason is that in the past decades the monitoring equipment improved significantly and allowed for the detection of small magnitude events. With the new generation of monitoring tools low level seismicity was observed in reservoirs. Firstly concerned about the observation many investigations were carried out to understand the occurrence of these microearthquakes. It was found that the occurrence of seismicity in the reservoir remarkably correlated with fluid extraction (production) or injection (stimulation). This correlation has been intensively discussed in the literature by Yerkes and Castle (1976); Segall (1989); Feigner and Grasso (1990); Grasso and Feigner (1990); Rutledge et al. (1990); Doser et al. (1991) and others. The observation of seismicity induced by production and reservoir stimulation opened new opportunities to characterize a reservoir and to monitor the success of reservoir stimulations (see e.g., Shapiro et al., 1997, 1999; Shapiro, 2000; Shapiro et al., 2006; Walker Jr., 1997; Rutledge et al., 1998; Rutledge and Phillips, 2002; Royer and Voillemont, 2005).

One application is for example the hydraulic fracture mapping as described in Walker Jr. (1997); Rutledge et al. (1998) and Shapiro et al. (2006). A sketch of a multi-stage hydraulic fracturing operation is shown in Figure 1.1 (a). Multi-stage means that the fracture operation is performed at different depths. These operations commonly start at the deepest target of interest where the casing is perforated. Fluid is injected at high pressure into the perforation interval to create a hydraulic fracture which extends several tens to hundreds of meters if the operation was successful. To continue the fracture operation at the shallower target of interest the deeper perforation interval is hydraulically sealed by setting a plug in order to avoid fluid and pressure loss (see Figure 1.1 (a)). As described in Walker Jr. (1997); Rutledge et al. (1998) and Shapiro et al. (2006) the size of the seismically active volume can be related to the extension of the created fracture. Hence the success of fracture operation can be estimated by locating the induced seismicity. Referring to the sketch shown in Figure 1.1 (a) a real-time location algorithm could provide the information that the deepest fracture operation was not successful. It is obvious that after perforating the upper interval a further treatment of the lower interval will become technically (as well as financially) challenging due to fluid and pressure loss into the upper perforated interval. Moreover, a real-time location algorithm can also provide faster interaction opportunities to protect a reservoir from damage (e.g., when a hydraulic fracture grows towards a water/oil contact). A detailed description about the aim and the realization of hydraulic fracturing will be given in Chapter 4.



(a) Hydraulic fracturing.   (b) Reservoir stimulation and monitoring.

Figure 1.1: Sketch of two industrial applications where reservoir stimulation induces seismicity.

Another application of reservoir stimulation is shown in Figure 1.1 (b) where hot steam is injected in order to decrease the viscosity of the production fluid (e.g., heavy oil). A detailed review about heavy oil reservoirs is published by Curtis et al. (2002). The injection of hot steam also induces seismicity in the reservoir (pers. comm., Steve Oates (Shell Exploration and Production Technology and Research), 2006 and Anupama Venkataraman (ExxonMobil Upstream Research Company), 2007). In this application the seismically active region is assumed to represent the stimulated region. Hence, the mapping of seismicity provides information about activated and non-activated regions in the reservoir (see Figure 1.1 (b)). Again, real-time mapping of the activated areas supports the reservoir engineer and enables him to interpret the success of the injection.

There are many other applications for reservoir monitoring as well as earthquake monitoring where real-time locations of seismic sources would be beneficial. In practice, real-time monitoring is very difficult for two reasons. First, the number of induced events can be very high. For hydraulic fracturing and fluid injection experiments several hundreds to thousands of events can be induced within hours (Shapiro et al., 2005). The other difficulty is caused by the location procedures. Most location procedures require the identification of seismic phases and the picking of P- and S-wave arrival times as well as the determination of the velocity structure between the hypocenter and the receiver. Geiger (1910)[1] proposed to calculate predicted arrival times for every sensor and to relate arrival time residuals to the hypocenter and its origin time. The calculation of the predicted arrival times is repeated until arrival time residuals are sufficiently small (Thurber and Rabinowitz, 2000). Many different algorithms which solve the minimization of arrival time residuals can be found in the literature (e.g., Bolt, 1960; Flinn, 1960; Lee and Lahr, 1975; Sambridge and Kennett, 1986, 2001). Another method to determine the hypocenter is to use the difference between P- and S-wave arrival times to calculate hemispheres of travel-distances. The hypocenter is assigned to the intersecting region of these hemispheres (Lay and Wallace, 1995). Furthermore, a review of advanced location algorithms such as proposed by Rabinowitz (1988); Pujol (1992); Joswig (1999) and Lomax et al. (2000) is given in Thurber and Rabinowitz (2000).

However, all these standard location procedures are characterized by a strong dependence on the picking accuracy of P- and S-wave arrival times and consequently by a low degree of automation due to the required picking. In principle, the picking of P- and S-wave arrival times can be accomplished with automatic picking algorithms. Several approaches have been proposed for the automatic P-wave arrival detection (e.g., Baer and Kradolfer, 1987; Earle and Shearer, 1994; Anant and Dowla, 1997; Bai and Kennett, 2000; Saragiotis et al., 2002; Zhang et al., 2003) using energy analysis, short-term-average and long-term-average (STA/LTA) ratios, statistical analysis, frequency analysis, wavelet analysis, polarization analysis / particle motion or a combination of those. The algorithms presented by Baer and Kradolfer (1987), Earle and Shearer (1994), Saragiotis et al. (2002) and Zhang et al. (2003) can deal with single-component seismograms, whereas the methods described in Anant and Dowla (1997) and Bai and Kennett (2000) require three-component data. The automatic picking of an S-wave arrival is more complicated since the S-phase is sometimes superimposed by a strong P-wave coda. Cichowicz (1993) presents an automatic S-phase picking algorithm using three-component data where the first arrival of the P-wave must be well defined. Nevertheless, manual picking is still performed to increase the picking accuracy. In the case of large data sets as described above this degree of user interaction makes the process of location very slow, expensive and inefficient and hence not applicable in real-time.

Removing the strong dependence on the accuracy of P- and S-waves arrival time picks and hence the time consuming picking procedures would allow for a much faster location. A sophisticated solution of this problem is provided by migration-

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[1] translated into English by Peebles and Corey (1912)

based location techniques because they can use the full wavefield around a detected event and hence do not depend on the picking accuracy of phase arrivals. Several migration techniques can be modified to locate earthquake sources. For example, McMechan (1982) presented a finite difference technique to extrapolate the earthquake wavefield backward in time for imaging of the source. At time steps that correspond to the origin time of the event, the wavefield focuses at the location of the hypocenter, and the reverse time extrapolation can be stopped. A spatially dense recording network deployed close to the source is mandatory for this approach (McMechan et al., 1985). The data set of the Long Valley Caldera, California from 1983 fulfilled these requirements and McMechan et al. (1985) show a successful application to three events from the aftershock sequence. Also Gajewski and Tessmer (2005) proposed to reverse the observed wavefield in time and then consider it as the boundary value for the reverse modeling. Assuming the correct velocity model, the reversely modelled wavefield will also focus on the hypocenter of the seismic event at a time step that corresponds to the origin time of the event. At the same time, another approach for earthquake location using Kirchhoff reconstruction was presented by Baker et al. (2005). This approach back-propagates the amplitudes of all receivers to the possible set of mesh points according to their P-wave travel time for different time steps. These steps span the time interval up to the maximum travel time observed from the target of interest to each receiver. An earthquake location is resolved when the extrapolation of all receiver signals converges, which is supposed to happen at the origin time of the event. In order to obtain the earthquake location with any of these three presented methods it is necessary to check the obtained images for the ’best-focused’ source image at every time step, which by itself can be a demanding and error-prone task.

In contrast to these migration-based approaches a fast and semi-automatic procedure which does not require a focusing-selection in time is presented in this thesis. This approach takes into account the full vector motion of three-component data in a preselected time interval around the P-wave and hence does also not rely on accurate arrival time picks.

In Chapter 2 different types of earthquakes as well as the different radiated seismic wavefields in homogeneous isotropic media are described in order to develop an understanding of three-component recordings of these wavefields. The mathematical expressions of the wavefields radiated by different sources are used to model synthetic data. Chapter 2 also contains a section about multicomponent seismology which gives a detailed review of how to estimate and carefully interpret wavefield polarization recorded with three-component receivers. In the final section of Chapter 2 the theoretical background of kinematic ray tracing as well as details about the implementation of initial-value ray tracing into the presented location method are given.

The whole location procedure, including event detection, array-based phase identification as well as estimates of location uncertainties, signal-to-noise limits and receiver fidelity are presented in Chapter 3. The principles of each algorithm developed for this thesis are explained and demonstrated on synthetic data.

Chapter 4 describes a hydraulic fracture experiment performed in the Carthage Cotton Valley gas field (East Texas, USA). The description includes the aim and principles of hydraulic fracturing, the geological settings of the site and the instrumentation utilized to monitor the experiment. I describe the processing steps, show the event locations and give a comparison of the obtained locations with results from standard location procedures. Furthermore, a robustness test for the location method is demonstrated on this data set.

In Chapter 5 the location method is applied to data from the San Andreas Fault Observatory at Depth (SAFOD). The data were recorded with an 80 level borehole seismic receiver array from Paulsson Geophysical Services Inc. deployed in the SAFOD Main Hole in 2005. The data set contained several events including the target event of May 05, 2005. The chapter will start with an overview about the tectonical and geological settings of the site. Afterwards details about the acquisition geometry and data preprocessing are given. Concering the target event location a SAFOD specific implementation of the use of arrival time differences is required and described in order to overcome a pitfall in the acquisition geometry. The identification of the target event is explained and an estimation of an effective Vp-Vs ratio is given which was needed for the target event location. The uncertainties for the target event location are estimated and the robustness of the location was tested using six different 3D velocity models. Successfull location of non-target events are also shown. The chapter closes with an identification and interpretation of repeating events with highly correlated waveforms.