Chapter 6

Conclusions

6.1 Conclusions and perspectives

In this thesis an approach is presented for the in-situ characterization of rocks in terms of the distribution of hydraulic parameters (called SBRC - Seismicity Based Reservoir Characterization) . The advantage of the method is the possibility of estimating hydraulic diffusivity or permeability on the large spatial scale in 3D. For this purpose the spatio-temporal evolution characteristics of fluid-injection-induced small-magnitude earthquakes (microseismicity) is analysed. Such events can often be observed during fluid injection experiments in boreholes, which are usually used for developments of hydrocarbon or geothermic reservoirs. The physical process and the reasons responsible for the triggering of such events are still not fully understood and the nature of such a seismic activity is still under discussion.

One widespread hypothesis explaining the phenomenon of the hydraulic induced microseismicity is that the tectonic stress in the earth's crust at some locations is close to a critical stress causing brittle failure of rocks, for example, by sliding along preexisting cracks. Increasing fluid pressure in a reservoir causes pressure in the connected pore space of rocks to increase (the pore space includes pores, cracks, vicinities of grain contacts, and all other possible voids in rocks). This leads to an increase of the pore pressure at the critical locations as well. Such an increase in the pore pressure consequently causes a decrease of the effective normal stress, usually acting compressionally on arbitrary internal rock surfaces. This leads to sliding along preexisting, favorably oriented cracks.

The change of pore pressure in space and time is controlled by the diffusional process of pressure relaxation. Thus, if the hypothesis described above is correctly explaining at least one of dominant mechanisms triggering fluid-induced microseismicity, then a number of diffusion-typical signatures should be observed in the spatio-temporal distributions of the earthquakes. Several of these signatures related to the temporal evolution of microseismicity clouds are known (see e.g., Audigane et al. [2002] and Shapiro et al. [2003]). With the approach proposed it is shown that the spatio-temporal distribution of the induced earthquakes is remarkably well described by the diffusive process of pore pressure perturbation due to fluids filling the pore space in rocks. This strongly supports the hypothesis that the triggering of induced seismicity is controlled by the pore pressure diffusion. This fact opens additional new possibilities to characterize hydraulic properties of rocks on a kilometer-scale with high precision.

The main part of this thesis is the development of an approach for the numerical simulation of the triggering process. Such a simulation is necessary at first for the verification of the assumptions made in the SBRC approach and secondly for the analysis of validity ranges of the method. Furthermore, the equations which were derived quasi-heuristically in the SBRC approach can be calibrated in order to yield more precise estimates of hydraulic parameters. Therefore, the time-dependent parabolic equation of diffusion is solved using the Finite Element Method (FEM) in 2D and 3D for different hydraulic models. A criticality field is randomly distributed in space and compared with the pressure distribution in space and time. Synthetic microseismicity clouds can be generated and the spatio-temporal signatures of the evolution of the events are analyzed. Significant correlations of these signatures are found for numerical data and microseismicity observed in reality. The results of the numerical simulation support the main hypothesis of the SBRC method that fluid-induced microseismicity can be triggered due to a process of pore pressure diffusion in critically stressed rocks. The observed similarities of numerically created data and real observations support the idea that pore pressure diffusion is an important mechanism for triggering microearthquakes. The numerical simulations are applied to test the inversion approaches of the SBRC method. It is shown that if the hypothesis of the SBRC approach is valid, than the eikonal-equation based inversion method can be successfully used to reconstruct hydraulic properties of rocks.

Further, the SBRC approach was successfully applied to two data sets. The analysis of fluid-injection-induced microseismic events at the German Continental Deep Drilling site (KTB) provides the possibility to study the depth-dependency of hydraulic parameters at one single site. Moreover, the analyses of correlations between seismic hypocenter locations and seismic reflectivity intensities yield interesting results. They provide a better understanding of physical processes for the triggering of seismicity during fluid-injections in hydraulically heterogeneous regimes and may be important for the design of further experiments. The results found for the case of a tight-gas reservoir in Cotton Valley (USA) are interesting for industrial purposes because they show the possibility of a successful application of the SBRC method for hydrocarbon industry. The results clearly show the potential of application of the SBRC method in order to improve field production, optimize the development of geothermal or hydrocarbon reservoirs and the exploitation of natural energy resources.

6.2 Further developments

The approach for characterization of hydraulic properties of reservoirs on the large spatial scale using fluid-injection-induced microseismicity is intensively further developed in the moment. Besides the analysis of the spatio-temporal distribution of induced events and using the eikonal-based approach for diffusivity reconstruction, other important ideas recently arised:

6.2.1 Probability of fluid-injection-induced microearthquakes

A new approach for estimating the hydraulic parameters of rocks using an analysis of the spatial distribution of microseismic events induced by fluid injection is recently proposed by Shapiro et al. [2002] and analysed by Rentsch [2003]. The approach is also based on the hypothesis that the propagation of triggering of injection-induced microseismic events can also be described by a diffusive process of pore pressure relaxation. Due to this diffusive process, besides the signatures studied so far, a number of different diffusion-typical signatures may be observed in spatial distributions of induced events.

One signature is the number of triggered events versus the distance from the injection point, i.e., event density. An appropriate relation is derived between this number of triggered events and distances using probability considerations of event triggering. This spatial distribution of the density of microseismicity provides the possibility of large-scale in-situ estimations of hydraulic diffusivity as well. In this context large spatial scale means of the order of kilometers depending on the size of the seismically active region.

Applications of the method to numerical data and to real data of the Soultz-sous-Forêts geothermal Hot Dry Rock site (France), the Fenton Hill Hot Dry Rock site (New Mexico, USA) and the Carthage Cotton Valley gas field (East Texas, USA) are given in Rentsch [2003]. Evidence of a completely different signature of seismicity triggering supporting the SBRC hypothesis is reported. This evidence additionally illuminates the physics of the fluid-induced microseismicity. Moreover, it opens a new way to estimating hydraulic properties of natural rocks at large spatial scales with high precision. All the studies are supported by the numerical modeling approach presented in this thesis.

6.2.2 Back front of seismicity induced after termination of borehole fluid injection

Parotidis et al. [2004] study the known phenomenon by hydraulic fracturing stimulations, where events are triggered not only during injection but also after the end of injection. Based on the theory of linear poroelasticity an equation is derived that describes the distance from injection point at which seismicity is terminated at a given time after the end of fluid injection. This distance is called the back front of induced seismicity (compare

Figure 3.31 and the comments in chapter 3.5.4). Using numerical modeling following the approach presented in this thesis and real data of three case studies it is shown that the back front is observed in reality. The existence of the back front is an important phenomenon supporting the idea of the pore-pressure diffusion nature of fluid injection triggered seismicity. Moreover, it provides an additional means of rock characterization allowing the estimation of the scalar hydraulic diffusivity of the seismically active area.

The assumptions for the proposed concept are that a fluid injection experiment can be approximated with a point pore-pressure source, and the resulting pore-pressure changes propagate according to the diffusion equation. This point source is approximated with a boxcar function of duration t_0, corresponding to injection duration. The duration time t_0 of the pore-pressure source is the time of pore-pressure perturbation and not of flow rate. When pressures are not measured, a back front can still be calculated, by estimating t_0. The sensitivity analysis showed that different t_0-times simply result in a time-shift of the back front, thus allowing a rough estimation of t_0, even when no relative data are available.

Decisive for the application of the back front concept is the sensitivity of the method with respect to the hydraulic diffusivity D. This allows the use of the methodology for estimating independently a scalar diffusivity from the events triggered after the end of injection. Thus monitoring seismicity after injection end is mandatory for estimating diffusivity, by applying the back front method.

With this new development of the SBRC approach a method for analyzing seismicity triggered by fluid injection experiments is presented. Equations for the 2D and 3D cases are derived, that predict the spatio-temporal evolution of these events, when pore-pressure diffusion is the main triggering mechanism. These equations allow the definition of a back front that fits the seismic data after the end of injection. The successful application of the concept on numerical data and three case studies and the conformity with previous independently estimated results confirms the applicability potential of the here presented methodology, for determining the main triggering mechanism and characterizing hydraulically the seismically active region.

6.2.3 Reservoir characterization based on seismicity rate

As already pointed out in chapter 4, a significant relation between the injection function and the observed event rate exists in reality. With the numerical simulations proposed in this thesis it was possible to explain such correlations (see Figure 4.9 and Figure 4.15). Parotidis and Shapiro [2004] further develop the analysis of event rate and the decay of the number of events after the stop of a fluid injection. They show that it is possible to derive hydraulic properties of the seismically active volume of rock using simply the event rate. Following the assumptions of the SBRC approach, this is another indication for the importance of pore pressure diffusion for triggering microseismicity. The results and developments are supported by the numerical modeling approach presented in this thesis. An advantage of this improvement of the SBRC approach is the following: If an estimation of hydraulic parameters is successful by using simply microseismic event rates, than it is not necessarily required to precisely locate the event hypocenters by complicated and time-consuming processes. Only a detection of events is needed which is a much faster and cheaper procedure, which is of importance for industrial purposes. Of course, using such an approach, 3D properties of the distribution of hydraulic parameters can not be estimated. For effective estimations of hydraulic diffusivity describing a whole reservoir such a procedure indeed is promising and important.

6.3 Open questions and further work

The method for numerical verification of the SBRC approach presented in this thesis provides meaningful and interesting results despite its simplicity. For further developments of the approach it may be interesting to combine the numerical simulation with more physical quantities in the future. Therefore, it may be important to extend the modeling scheme towards poroelasticity theory. Here, one may think about the implementation of stresses and strains, varying porosities of different rock types, including fluid dynamic viscosities for the simulated fluid injection, multi-phase flow and temperature influences in the models. Also, it may be interesting to combine the modeling schemes with numerical simulations of hydrofracturing experiments and include hydrofracturing routines. Moreover, the release of a seismic event influences the state of stress at the surrounding points in the rock. Stress redistributions due to the triggering of one event is still missing in the present algorithms despite the attempt to model such a case by including effects like the Kaiser effect. All these improvements may help to better understand the physical processes during real injection experiments in reservoirs in the future.