Chapter 1

General Introduction

1.1 Summary

This thesis is about a method developed for the characterization of reservoirs in terms of the large scale distribution of hydraulic parameters. Parts of the approach used here were already proposed during the last years and represent a unique method for providing information about in-situ diffusivity and permeability distributions in 3D on large spatial scales. The results of the method are interesting and important for industrial reservoir geophysics. The focus of this thesis is the numerical verification of the approach using finite element algorithms in 3D space. Such a verification is important for the practical application of the method. Furthermore, validity ranges of the equations derived and examinations of the estimations can be performed. With these numerical simulations it is possible to study the hypotheses proposed in the SBRC approach in detail and help to better understand the underlying physical processes for the triggering of microseismicity.

It is shown how the method can be used in geophysical applications. The estimation of hydraulic parameters of reservoirs using data of fluid-induced microseismicity is an important issue for rock characterization. A numerical modeling scheme in 2D and 3D is presented to simulate the process of pore pressure diffusion in rocks during fluid injection experiments. The hypothesis that microseismic events can be released due to such a process will be studied. It is shown how the equations derived can be used to characterize seismically active parts of the rock for hydraulic parameter characterization. Furthermore, improvements of the algorithms are proposed in order to obtain more precise estimates of such parameters. Moreover, two data sets obtained during injection experiments are analyzed. The results help to better understand the physical processes for the triggering of microseismicity and show the applicability of the method.

The thesis is organized as follows: in this chapter the basic problems which will be the subject of subsequent chapters are summarized. Chapter 2 gives an overview of the theory of the 'Seismicity Based Reservoir Characterization' (SBRC). Equations will be derived for the analysis of the spatio-temporal evolution of microseismic data observed during reservoir experiments. With these equations – based on the poroelasticity theory – it is possible to analyze such data in order to characterize rocks in terms of hydraulic parameters in 1D, 2D and 3D. In chapter 3 a numerical modeling scheme is presented in analogy to the hypotheses proposed in the SBRC method. Fluid injections in boreholes are simulated which yield to the analysis of processes during such experiments. The assumptions of the SBRC approach are verified and synthetic microseismicity clouds are created for a large range of models, geometries and pore pressure source functions. The events will then be analyzed using the equations derived in chapter 2. Observed signatures will be compared and interpreted. In chapter 4 an application of the method to a data set registered at the German Continental Deep Drilling Site (KTB) is presented. This analysis confirms the hypotheses proposed in the method and yields results for the interpretation of microseismicity. Furthermore, a correlation of seismic hypocenters and results of seismic reflection experiments is shown, which provides further interesting interpretations. In chapter 5 the SBRC-method is applied to data of a hydrocarbon reservoir. This case study shows the potential of an industrial application of the SBRC approach for oil and gas environments. Finally, the conclusion and a discussion of some open problems are given in chapter 6. The appendices contain detailed information about parameters used for the numerical simulations.

1.2 Fluid induced microseismicity and reservoir characterization

It is well known that the characterization of fluid-transport properties of rocks is one of the most important and difficult problems of reservoir geophysics. Active seismic methods have some fundamental difficulties in estimating fluid mobility or the permeability tensor (see e.g., Shapiro and Müller [1999]). On the other hand, it would be highly attractive to use seismic methods to characterize hydraulic properties of rocks because of their large penetration distances and a potentially high resolution.

The attention to the microseismic monitoring during operation of geothermal or hydrocarbon reservoirs has grown considerably over the last several years. The observation of microseismicity occurring during borehole fluid injections or extractions has a large potential in characterizing reservoirs at locations as far as several kilometers from boreholes (Talwani and Acree [1985]; Adushkin et al. [2000]; Fehler et al. [2001]). The most common application has been hydraulic fracture imaging and growth characterization (e.g. Phillips et al. [1997]; Urbancic et al. [1999]). Longer-term microseismic monitoring has been used to map oil-producing, natural fractures (e.g., Rutledge et al. [1998]) and also shows promise in tracking flood fronts in the case of enhanced oil recovery (e.g., Maxwell et al. [1998]). Beyond delineating conductive fracture geometry and inferring fluid-flow paths, microseismic data could potentially be used to measure in-situ hydraulic properties of rocks at interwell scales, providing information that could further guide operations to optimize field production.

An approach is described, demonstrated and verified with numeric simulations that combines the above mentioned advantages of seismic methods with an excellent potential to provide in-situ estimates of the hydraulic diffusivity or permeability tensor. The corresponding estimates of hydraulic parameters characterize geothermal or hydrocarbon reservoirs on the large spatial scale of the order of $10^2m - 10^3m$. This approach, which is called "Seismicity Based Reservoir Characterization" (SBRC), uses a spatio-temporal analysis of fluid-injection induced microseismicity to reconstruct the permeability tensor (see Shapiro et al. [1997, 1998, 1999a] and Audigane [2000]; see also the discussion in Cornet [2000] and Shapiro et al. [2000a]).

The approach assumes the following main hypothesis: Fluid injection in a borehole causes perturbations of the pore pressure in rocks. Such perturbations cause a change of the effective stress, which, if large enough, can trigger earthquakes along pre-existing zones of weakness. The SBRC approach considers that most of the seismicity is triggered along critically stressed, pre-existing fractures. Rather broad experience shows that even small pore-pressure fluctuations seem to be able to modify the effective normal stress and/or the friction coefficients in rocks to an extent, which is enough for triggering of microearthquakes (Talwani and Acree [1985]; Nur and Booker [1972]; Zoback and Harjes [1997a]). Evidently, the triggering of microearthquakes occurs in locations where rocks are in a near-failure state. Such locations can be randomly distributed in the medium.

Already since the year 1997, Shapiro et al. [1997] proposed to interpret the spatio-temporal evolution of the clouds of such microseismic events in terms of pore-pressure relaxation in media with (an)isotropic hydraulic diffusivity (Shapiro et al. [1997]). They derived an equation for the microseismicity triggering front in homogeneous anisotropic poroelastic media. The propagation of the triggering front is controlled directly by the permeability tensor. Using this equation, Shapiro et al. [1999a] proposed a variant of the SBRC method, which considers real heterogeneous rocks as an effective homogeneous anisotropic poroelastic fluid-saturated medium. The permeability tensor of this effective medium is the permeability tensor upscaled to the characteristic size of the seismically active region.

In the following chapter a systematic approach is proposed to characterize heterogeneous distributions of the permeability in reservoirs. Firstly a theoretical introduction into SBRC for the case of homogeneous anisotropic poroelastic media is given. It is shown that in a homogeneous medium the microseismicity triggering front has the form of the group-velocity surface of the anisotropic diffusion wave of the pore-pressure relaxation (which is the low-frequency Biot slow wave). Then the concept of the SBRC approach is described to the 3-D mapping of heterogeneously distributed hydraulic diffusivity. A differential equation is derived which approximately describes kinematics of the microseismicity triggering front in the case of quasi harmonic pore pressure perturbation. This approximation is similar to the geometrical optics approach for seismic waves. The propagation of the triggering front is considered in an intermediate asymptotic frequency range. This means that it is assumed that the dominant frequency of pressure perturbations is much smaller than the critical Biot frequency. On the other hand it is assumed, that the slow-wave dominant wavelength is smaller than the characteristic size of the heterogeneity of the hydraulic diffusivity. Then an algorithm for the mapping of hydraulic diffusivity in 3D is suggested in the both cases, the quasi-harmonic and quasi-step-function medium excitation.

1.3 Motivation

The purpose of this thesis is twofold: on the one hand, the algorithms derived in the 'Seismicity Based Reservoir Characterization' (SBRC) approach are verified and validity ranges are studied by using numerical simulations. Moreover, these simulations are important for further reasons: The equations the SBRC approach is based on were derived in a quasi-heuristical way. The numerical verification approach helps to inspect the potential of application of the equations for real data. Furthermore, the SBRC algorithms can be calibrated in order to obtain more precise estimates of hydraulic parameters of rocks. Moreover, the numerical simulations support further developments of the SBRC approach. On the other hand the SBRC method was never applied to data observed in oil and gas environments. The applicability of the approach for such environments is of special interest for industrial purposes.