Chapter 1

Motivation

1.1 Introduction

Since the early days of plate tectonics it has been recognized that the Earth's crust has been subjected to permanent reshaping. Not only the building of huge orogens like the Alps or the Andes impressively proof the activity of various forces over geological times. However, earthquakes along active fault systems show that the mechanical stresses induced by the tectonic forces may change rapidly. One intensively investigated and discussed example is the seismicity of the San Andreas Fault near Parkfield, located at the transmission from the locked section of the fault zone in the south to the creeping section in the north. Since 1875 six earthquakes of magnitude 6 have taken place with a recurrence time of 22 years (e.g., Eberhart-Phillips & Michael, 1993). One favorite model to explain the regular occurrence of the Parkfield earthquakes is the temporal change of pore pressure within the earthquake cycle. Beside the widely discussed reasons for possible changes of pore pressure, most models agree that pore pressure increases after an earthquake. This increasing pore pressure decreases the normal stress acting on the fault. When this decrease reaches a certain level the rock fails due to the acting tectonic stress and an earthquake occurs. The resulting rock damage increases the pore space and thus rapidly lowers the pore pressure. Then, the increase in pore pressure starts again.

If the assumptions about the role of fluids in the mechanics of such earthquakes as occurring at Parkfield is valid then the state of stress in the Earth's crust has to be understood as a dynamic variable which may rapidly undergo natural variation significant for initiating even large earthquakes. The state of stress at a given point within the brittle solid part of the Earth denotes the actual look of the effective stress tensor. This tensorial quantity comprises the stresses resulting from the weight of the overlying strata and possible tectonic stress acting from the sides as well as the pore pressure. Taking reasonable modification rates of the three components of the stress tensor into account, it is clear that the mentioned dynamics of the state of stress results from the dynamics of the pore pressure.

Moreover, in many field experiments artificially induced microseismic events have been identified as additional hints for a crucial role of pore fluid in the mechanics of the Earth's crust. For instance, even slight increases of formation pressure due

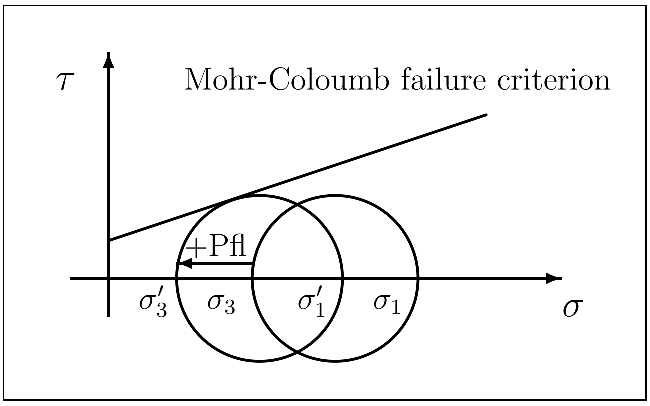

Figure 1.1: Illustration of the role of pore pressure in rock failure. At an initial state of stress the maximum and minimum principle stresses are σ_1 and σ_3, respectively, and the resulting shear stress τ is below the critical shear stress where failure occurs (right circle). If the pore pressure is increased by $+\mathrm{P}_{\mathrm{fl}}$ all normal stresses are reduced by the same magnitude, i.e., the radius of the Mohr-circle is constant but the circle moves towards lower stresses and may hit the failure criterion (left circle).

to the injection of fluid into the main hole of the German Continental Deep Drilling project (KTB) triggered microseismic events. The spatio-temporal evolution of these events is assumed to result from a diffusive like relaxation process of pore pressure perturbation (e.g., Shapiro *et al.*, 1997). An injection induced pore pressure signal propagates through the medium and decreases all principal stress components. If the rock is initially in a sub-critical state for failure even a small increases in pore pressure may lead to rock failure as illustrated in Fig. (1.1) in terms of the Mohr-Coloumb failure criterion.

The state of stress is one of the most important aspects in geomechanics. This is indeed true for the hydrocarbon industry. A detailed knowledge about the state of stress in a reservoir, its seal, and the surrounding host rock is crucial for safe drilling and an efficient reservoir exploitation. For instance, if the pressure in the drilling fluid is below the formation pressure, formation fluid may enter and destroy the bore hole. This might even lead to hazardous blow outs, especially when drilling into hard overpressurized areas. On the other side, overballanced drilling might press drilling mud into the formation and seal the bore hole.

Beside the critical effects of enhanced pore pressure and decreased principal stress components, the opposite situation of decreased pore pressure is important as well. For example, pore pressure drops after hydrofracturing and during reservoir depletion. The associated increase of effective stress can lead to rock mechanical instabilities, e.g., sanding.

However, not only the actual state of stress is important for an efficient reservoir exploitation. Also the palaeo state of stress may have to been taken into account, since it might have created the fluid flow controlling fracture systems. Moreover, it is possible that failure of the reservoir seal occurred during burial due to pore pressure gradients exceeding the seals fracture gradient and, hence, hydrocarbons might have escaped.

Over the last years the application of time lapse seismic experiments, also frequently denoted as 4D seismics, has become more important in reservoir management. Comparing production induced changes of the seismic signature of a reservoir over time is assumed to have the potential, e.g., to detect preferred hydrocarbon flow paths, bypassing oil and gas and to identify sealing or conducting faults. In this context, it is necessary to discriminate between two major effects occurring during reservoir depletion, which might have an opposite effect on changes of the seismic signature. In general, three different fluids can be found in a reservoir, i.e., oil, gas, and brine. Usually, these fluids have different properties, e.g., viscosities and densities. As a consequence, the fluids move with different velocities through a reservoir. Therefore, the spatial distribution of the fluid will change during depletion and thus the volume fractions of these fluids at a certain point in the reservoir will likely vary. As a result, the effective velocity of the reservoir rock will change. The resulting changes in time lapse seismic data have to be separated from changes induced by pore pressure variations. An illustrative example for the discrimination between fluid saturation and pore pressure changes is given by Landrø (2001).

If seismic methods are used to investigate the state of stress in the subsurface it is necessary to link changes in confining stress and pore pressure to changes in seismic velocities. It is well known from many laboratory experiments that both P- and S-wave velocities may vary strongly with effective stress. For example, Fig. (1.2) shows ultrasonic dry rock P- and S-wave velocities of a sandstone sample of 4.7% porosity (Freund, 1992). Here, velocities are plotted as a function of effective isostatic stress (also denoted as effective pressure). An effective stress increase from 8 MPa to 60 MPa increases P-and S-wave velocity by 39% and 30%, respectively.

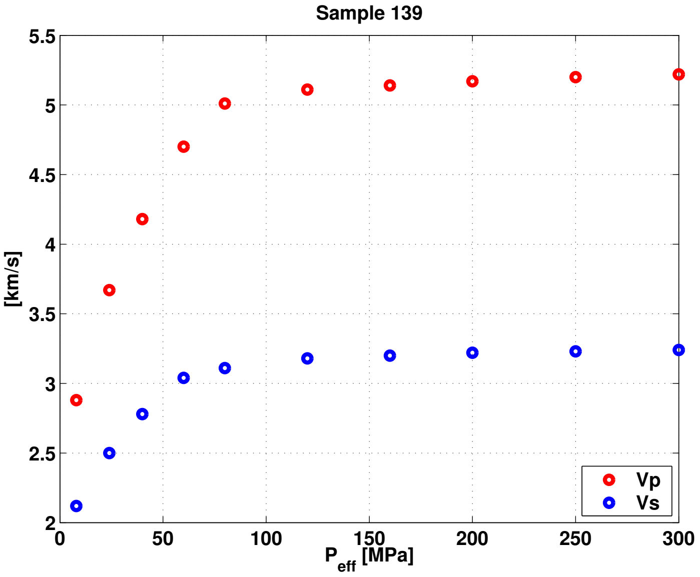

Figure 1.2: Ultrasonic P- (red circles) and S-wave (blue circles) velocity of a sandstone sample from the Salzwedel drilling site as a function of isostatic effective stress (data from Freund, 1992).

The mentioned example is typical for many laboratory observations on seismic velocities even for different rock types, ranging from high-porosity sandstones to low-porosity crystalline rocks. The velocities show a strong and non-linear increase when the load is increased over the first tenths of MPa. For higher stresses the changes in velocities become flat and linear and quite often even negligible.

Many researchers have analyzed numerous velocity vs. stress observations by means of purely mathematical regression in order to obtain a general link between velocities and stress. One frequently and quite successfully used modeling equation in terms of a least squares optimization reads (Eberhart-Phillips *et al.*, 1989):

$$V(\mathrm{P_{eff}}) = A + K \cdot \mathrm{P_{eff}} - B \exp(-D \cdot \mathrm{P_{eff}}) \tag{1.1}$$

Here, V is the velocity, $\mathrm{P_{eff}}$ is effective isostatic stress (i.e, effective pressure), defined as the difference between isostatic confining stress and pore pressure, and A, K, B, and D are fit parameters for a given data set. This phenomenologically derived equation was also successfully applied by Zimmerman *et al.* (1986); Freund (1992); Jones (1995); Prasad & Manghnani (1997); Khaksar *et al.* (1999); Carcione & Tinivella (2001); Kirstetter & MacBeth (2001).

Despite the applicability of eq. (1.1) a pure mathematical analyzis of velocity-stress relations does neither allow for an extrapolation of the obtained results to other stresses or lithologies nor does it provide a deeper insight into the physics behind the observations and, thus, obstacles a generalization. Hence, a physically constrained model is required.

Numerous theoretical approaches have been developed to explain the stress dependencies of rock elasticity. Some of these approaches take into account that rocks behave like non-linear elastic bodies or even more complex, i.e., non-linear and anisotropic. Several, quite successful attempts to use the formalism of non-linear elasticity theory for this goal are known from recent literature (e.g., Johnson & Rasolofosaon, 1996; Winkler & Liu, 1996; Rasolofosaon, 1998; Prioul *et al.*, 2001; Sarkar *et al.*, 2003). However, these models are restricted to small ranges of stress variations only. As a consequence, the resulting stress dependencies of elastic properties are principally linear functions of stress only.

The approaches mentioned above are based on a very general formulation of elastic non-linearity. It is intuitively clear that the elastic non-linearity of rocks is related to the complex heterogeneity of the rock structure. The first-order heterogeneities of rocks are their voids, i.e., pores and fractures. A general theory of elastic non-linearity does not take this into account. Several following approaches can be understood as attempts to specify models of pore space geometry in order to arrive at a more specific elastic non-linear rock characterization. These are spherical contact models (Duffy & Mindlin, 1957) or crack contact models (Gangi & Carlson, 1996; Mavko *et al.*, 1995). In fact, such approaches are used in geophysical applications (see Merkel *et al.*, 2001; Carcione & Tinivella, 2001). They lead to different quite complex stress dependencies of elastic properties. Moreover, some of them work within very limited ranges of pore pressure changes or under very restrictive geometrical or geomechanical conditions.

The above mentioned behavior of typical velocity-stress relations might be interpreted as a result of the progressive decrease of porosity due to an applied load. Although this interpretation is quite reasonable it is in disagreement with laboratory observations where velocities as well as porosity were measured. Such experiments have shown that in consolidated rocks porosity is more or less independent from an applied load or changes only slightly in the order of 1% while velocities simultaneously increase by 10-30% (e.g., Khaksar *et al.*, 1999). Thus, comparing the magnitudes of these variations shows that treating the porosity as a single scalar quantity is not sufficient.

This observation leads to one basic assumption of the so-called *Stress Sensitivity Approach* which is presented in this thesis. It is used in order to investigate the stress dependence of various rock types ranging from isotropic consolidated sandstones to anisotropic metamorphic rocks from the German Continental Deep Drilling project (KTB). Shapiro (2003) has introduced this approach for isotropic rocks under isostatic load. Since then it was extended to anisotropic media under arbitrary anisotropic load (Shapiro & Kaselow, 2002; Kaselow & Shapiro, 2003a,b; Shapiro & Kaselow, 2003). This thesis summarizes the principal aspects of the anisotropic stress sensitivity approach. These theoretically derived results and their implications to the stress sensitivity of rocks are evaluated by the analyzis of stress dependent ultrasonic P- and S-wave velocity observations on quite different rocks. Moreover, it introduces the stress dependence of the Poisson's ratio and its role in understanding the stress dependence of elastic rock properties. In addition, it shows the recent extension of the approach towards the stress dependence of electrical resistivity in low-porosity crystalline rocks as done by (Kaselow & Shapiro, 2004).

1.2 Outline

This thesis is focused on the theory of the Stress Sensitivity Approach and on the validation of the theoretically derived results of the stress sensitivity of porous and fractured rocks. Therefore, the outline of this thesis is as follows:

Chapter (2) summarizes the basics of elasticity of isotropic and anisotropic rocks as well as the fundamentals of plane wave propagation in such media. In the following the fundamental phenomena resulting from the differences between the classical elasticity and the elasticity of porous media are shortly given.

Chapter (3) introduces the theoretical background of the stress sensitivity approach. It starts with quite general remarks on stress and pressure terminology used in the literature which is often not consistent and may lead to confusion. To avoid this, a general overview of the common terminology is given as well as an introduction into the terminology used in this thesis.

The remaining part of chapter (3) gives a comprehensive summary of the theory of the stress sensitivity approach. A detailed description of the theory is given in Appendix (B) which reflects the paper of Shapiro & Kaselow (2003). The basic assumption of the approach is that the stress dependence of seismic velocities results from the stress induced changes of the dry rock compliances. Changes of the compliances are closely related to changes in the pore space geometry. This pore space deformation is then linked to changes in the dry rock compliances.

In the following, the derived relations are simplified to the case of isotropic rocks under isostatic load. The last part illustrates the definition of the stress dependence of Poisson's ratio and introduces the extension of the approach to the stress dependence of electrical resistivity.

In chapter (4) results of the application of the approach to various rock types are given in order to check the key aspects of the theoretical considerations introduced in the previous chapter.

Finally, chapter (5) shows the application of the approach in order to estimate hydraulically induced reflectivity pattern changes of the a SE2 fault zone, located at the KTB drilling site.