Chapter 6

Conclusions

This thesis presents the theory and the first applications of the stress sensitivity approach for anisotropic media under arbitrary effective stress. This approach represents an extension of the previously introduced Piezosensitivity approach which was limited to isotropic rocks under isostatic load. The stress sensitivity approach is one of the few theoretically based attempts which describe the dependence of elastic rock characteristics, and thus seismic velocities, upon confining stress and pore pressure. It enables a rock physical interpretation of seismic velocity observations as a function of confining stress and pore pressure in terms of already established and new rock physical quantities, introduced in this thesis.

The main objective of this thesis was to validate the key aspects of the theoretical results by analyzing stress dependent seismic velocity observations obtained from very different rocks in ultrasonic laboratory experiments. Therefore, an algorithm was developed and implemented that allows for an almost automized analyzis of the data.

In the theory of elasticity seismic velocities of a material are a function of the materials stiffness, formulated by Hook's law in terms of the stiffness or, likewise, the compliance tensor. In isotropic rocks the corresponding elastic moduli are the bulk and the shear modulus. If the porous nature of a material is considered more than one stiffness has to be taken into account. It is widely accepted that only the stiffness of the dry rock matrix is significantly sensitive to stress variations up to 200 - 300 MPa.

Many laboratory experiments on dry and saturated isotropic and anisotropic rocks show a typical response of compressional and shear wave velocities on confining stress and pore pressure variations. Over the first few tens of MPa applied load the velocities increase non-linearly. This increase reaches quite often 30% or more of the initial velocities in the unloaded state. For higher stress the velocity increase tapers off into a flat linear dependence upon stress. Moreover, the slope of this flat backend part of the velocity-stress relation is often negligible.

Although it is intuitive to relate this velocity behavior to a stress induced porosity closure, laboratory experiments have shown that variations of the total porosity with stress are usually at least an order of magnitude smaller than the observed velocity variations. The stress sensitivity approach takes this discrepancy into account by using the widely accepted hypothesis that the response of velocities to increasing stress reflects the progressive closure of two mechanically distinct porosity domains. The non-linear increase of velocities is addressed to the closure of the easily deformable compliant porosity. This part or the porosity comprises cracks and grain contact vicinities. The remaining stiff part of the porosity hardly deforms over a stress range up to 200 - 300 MPa and is assumed to represent the flat backend part of the velocity-stress relation.

The stress sensitivity approach formulates the stress dependence of velocities in terms of the variations of the dry rock matrix compliances via stress induced variations of the pore space geometry. Therefore, physical considerations about the mechanics of pore space deformation and empirically based assumptions are used to derive a quite general description of porosity variations in arbitrary anisotropic rocks under arbitrary load. The pore space is described in terms of a new tensorial quantity, the generalized porosity. This property is always a function of confining stress and pore pressure and closely related to the porosity. It is shown that the porosity is also generally a function of both confining stress and pore pressure. An important result of the stress sensitivity approach is that the porosity depends only on the pure difference between confining stress and pore pressure if the rock matrix is homogeneous and/or the porosity is low. The derivation of the stress sensitivity approach and its application presented in this thesis work within the limitation to such rocks.

It is shown that the most important rock characteristic for the stress dependence of various rock properties is the tensor of stress sensitivity. This rock property represents the first derivative of the dry matrix compliance tensor with respect to the compliant part of the generalized porosity. It comprises the wide range of possible reactions of elastic rock properties to stress variations and is closely related to the non-linearity of rocks.

Theoretical considerations show that in the case of isotropic rocks the tensor of stress sensitivity can be reduced to one scalar quantity, previously introduced as the piezosensitivity. In anisotropic rocks the tensor of stress sensitivity has more than one independent and non-zero entry. However, it was shown that it is reasonable to assume that there are anisotropic rocks where the differences of the magnitudes of the independent entries are negligible and the tensor of stress sensitivity can be reduced effectively to one scalar quantity. It was shown previously that this quantity is proportional to the inverse of the effective crack aspect ratio.

When an arbitrary anisotropic rock, which shows such an „isotropic“ tensor of stress sensitivity, is subjected to an isostatic load all elastic compliances and seismic velocities in each direction can be described by an equation of the form:

$$\Gamma(P) = A_\Gamma + K_\Gamma P - B_\Gamma \exp(-DP),$$

where Γ is the property under consideration. An empirically derived equation which was successfully used by many researchers to fit velocity observations to isostatic stress shows exactly this form. Thus, the stress sensitivity approach provides the physical meaning of the fit parameters A, K, B, and D with respect to the rock property under consideration.

Parameter A characterizes the rock lithology. It is a function of the grain moduli and the stress independent part of the stiff porosity. Parameter K is a measure for the influence of stiff porosity closure on the considered rock property. It was found that this parameter is usually negligible, reflecting the small relative change of stiff porosity with effective stress. Parameter B reflect the response of the considered rock property to compliant porosity closure with stress. The closure of compliant porosity is mainly controlled by parameter D. This parameter reflects the actual symmetry properties of the tensor of stress sensitivity. The theoretical considerations showed that the parameter D is a universal quantity for all mentioned properties.

In order to check if there are rocks with such a universal parameter D, the stress sensitivity approach was applied to P- and S-wave velocity-stress observations from different rock types ranging from isotropic and anisotropic dry and saturated sedimentary rocks to dry anisotropic metamorphic rocks from KTB deep drilling site. In order to check the postulated universality of the fit parameter D a two-step fit procedure is suggested. This algorithm combines a non-linear and a linear least squares fit. It was possible to define a criterion for a data driven calculation of the initial fit parameters required for the non-linear least squares fit. This criterion was successfully applied to almost all rocks. This enabled a nearly automized analyzis of the data sets.

For almost all samples it was possible to find a universal parameter D. This indicates that many different rocks apparently have an „isotropic“ tensor of stress sensitivity. A linear regression of parameter DP vs. DS obtained from all used independent P- and S-wave fits, respectively, revealed a relation among both parameters that is very close to the postulated equality (DP = DS) with a coefficient of determination of 82%.

The stress dependence of elastic moduli was used to derive the stress dependence of Poisson's ratio. It was found that for a certain rock the Poisson's ratio is the most sensitive measure to evaluate if parameter D is a universal quantity.

It was also found that the stress dependence of electrical resistivity can be formulated in terms of the stress sensitivity approach. This requires the limitation to rocks where the electrical resistivity can be described using Archie's law. The derived formalism provides a rock physical interpretation why electrical resistivity is usually assumed to be independent from stress in many rocks. An analyzis of the stress dependent static bulk moduli and logarithmic formation factors of different low-porosity crystalline rocks confirmed the result of a universality of parameter D. As fas as we know it is the first time that such a close and physically based connection between the stress dependence of elastic moduli and electrical resistivity was theoretically established and confirmed by data.

The potential of the stress sensitivity approach for time-lapse seismic experiments is illustrated with an example from the KTB test site. The stress dependent velocity observations on dry rocks of the KTB pilot hole were used to estimate reflectivity pattern changes of the SE2 fault zone induced by pumping and injection tests. In contrast to a pure mathematical regression of the laboratory data, the application of the stress sensitivity approach provides first order approximations of required rock physical parameters, e.g., the moduli of the grain material.

6.1 Open questions and outlook

The stress sensitivity approach is based on first order approximations and heuristic assumptions. Some of them, e.g., a homogeneous rock matrix, might be too restrictive for many rocks. A series of especially designed laboratory experiments may help to quantify the limitations of the approach. Such experiments should cover a detailed mineralogical analyzis of the rocks and the simultaneous observation of different rock properties, e.g., P- and S-wave velocity, dilatancy, and porosity. Moreover, it would be useful to conduct these experiment under uniaxial and triaxial load with different confining stress and pore pressure levels.

A crucial aspect for the application of the stress sensitivity approach in time-lapse seismics is the scale dependence of the stress sensitivity tensor with respect to the wave length on the one side and the dimensions of the cracks and fractures on the other side. It is possible that an upscaling of laboratory derived stress sensitivities is as problematic as in the case of the permeability. However, a combined analyzis of pore pressure induced in situ and laboratory velocity variations might help to solve the upscaling problem.

Of special interest for the hydrocarbon industry is the stress sensitivity of typical reservoir seals, especially clays. Many clays show porosities beyond the validity of the stress sensitivity approach as presented here. However, only a small fraction of the porosity in claystones is effective for fluid flow. Therefore, it is reasonable to assume that stress sensitivity can be applied to clays, if other effects, i.e., de-watering can be neglected. Unfortunately, an adequate data set has not yet been available to us.