Rock Physical Modelling with Respect to the Structure of the Pore Space

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Motivation

The volume and geometry of the pore space, and the physical properties of the pore fill influence some physical properties of rocks. In this paper, we investigate the influence these pore characteristics have on the elastic properties of a gneiss core from KTB VB.

Different pore geometries can occur over a wide scale of dimensions, so that measurements with limited integration areas include only a part of the pore space. Furthermore, interactions between the solid and fluid phase (components) of the rock can result in frequency dependencies of certain physical properties (e.g. induced electric polarization, damping of elastic waves by "fluid-flow"-effects).

Scale- and frequency effects therefore often make it difficult to compare measurements with different integration areas and measuring frequencies (see Tab. 1).

Table 1: Integration areas and measuring frequencies for the determination of elastic properties.

	Laboratory	Bore hole	Field
Integration areas	cm - dm	dm - m	m - km
Frequency range	kHz - mHz	Hz - kHz	Hz - mHz

The Modelling of Elastic Properties

In a first test we applied a new model to the elastic properties of a gneiss core of the KTB pilot hole. This model includes the relations between the rock composition, structure of the pore space and the physical rock properties and, furthermore, it considers interactions between fluid and solid by a "squirt flow" mechanism.

It also considers different scales by introducing a fractal conception. The model was originally developed for porous sedimentary rocks (Spangenberg, 1994). It is possible to optimize the model for an application to crack porosities, but for this first test we added no improvements.

The basic idea of the model is a connection of essential geometric parameters of the rock skeleton (main pore or grain sizes, aspect ratios, the alignment of longitudinal grain axes,...) with the physical properties of the rock components. The model consists of the solid matter or rock matrix (1), the pore fluid in a surrounding pore channel (2) and a contact region (3). The contact region is described by the properties of models that are similar to the base model and fit to the contact region.

The geometry of the model is given by six geometry parameters. As is shown in the cross section of the model (Fig. 1), this concept results in a discrete pore size distribution and an enlargement of the internal surface.

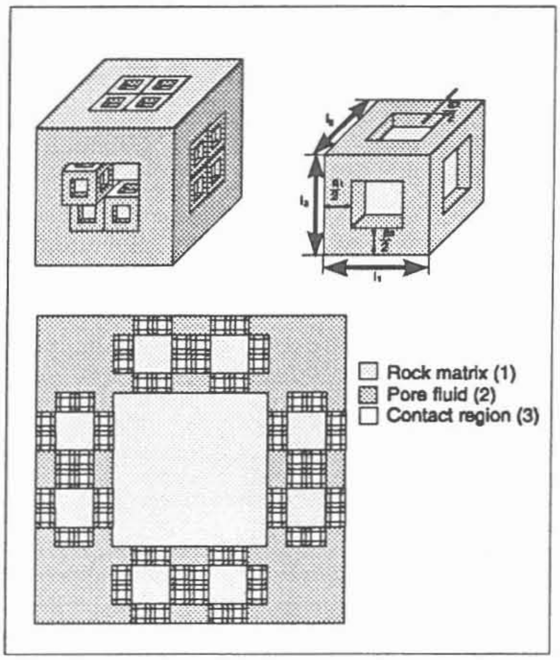


Fig. 1: Fractal rock model

The input parameters for the model are:

- information about the rock matrix (mineralogical composition, structure and texture) and
- the geometry of the pore space (crack orientation, mean aspect ratios, mean width of crack opening, pore volume and specific internal surface).

The **composition of the rock matrix** was determined by x-ray diffraction analysis and microscopic methods.

For the determination of the **pore geometry** the specimen was saturated with fluorescent epoxy resin. In the thin sections the cracks become visible by focusing ultra violet light over the microscope on the surface of the specimen. The resulting fluorescent crack images were recorded by a video camera and transmitted to a computer. The geometry of the cracks was determined with an image analysis system.

The **pore volume** was determined from the vacuum dry weight and the weight water saturated. The specific internal surface was measured by nitrogen absorption (BET-method).

Characterization of the investigated rock

A gneiss from the KTB pilot hole (core section 598c1F, depth: 2449m) was used. The material consists of nearly 50% plagioclase, 35% quartz, 10% biotite and 5% other minerals. The crystallographic preferred orientations of quartz and plagioclase are very weak and their effects are not considered by the matrix model.

Biotite is assumed to be ideally aligned within the foliation plane. Due to these assumptions the matrix model is transversal isotropic.

The porosity of the gneiss is 0.3%. It is very fine grained, homogeneous and the foliation plane is nearly parallel to the core axis. Most of the cracks of the specimen are aligned in the foliation plane. The mean width of crack opening is about 1μm and the mean aspect ratio is about 1:100.

Experimental Investigations

Sonic velocities were measured under water for better coupling conditions between the core and the transceivers. To get information about the influence of water saturation, the dry core was put into the water basin of the measuring equipment and was measured after 15 minutes (very low water saturation), 1 day (medium water saturation) and after 10 days (very high water saturation) (Fig. 2).

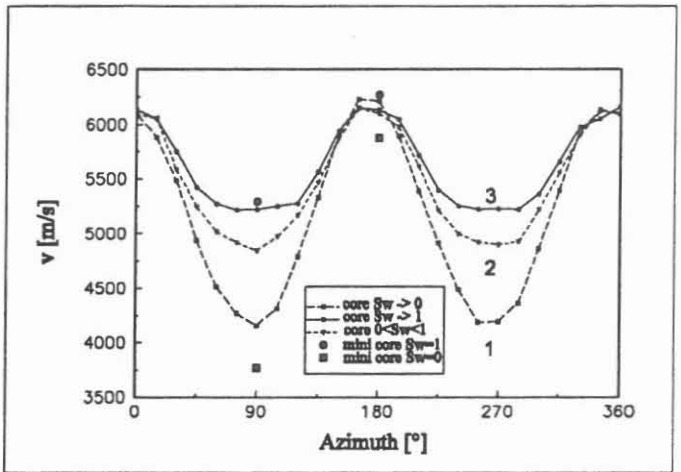


Fig 2.: Sonic wave velocities for different saturation times
Wave velocity after 15 minutes (1), 1 day (2) and 10 days (3)

From the measurements with different propagation directions concerning the foliation plane (azimuthal steps of 15°) the following becomes clear:

- the anisotropy of the nearly dry specimen is very high,
- the anisotropy decreases with increasing saturation and
- a porosity of only 0.3% exerts a strong influence on the velocity of the core.

Furthermore, two mini cores were drilled out of the specimen, one parallel and one perpendicular to the foliation plane. The sonic velocities were measured on both mini cores in the dry and water saturated state. Both, drying and saturating were carried out in a vacuum. Because the saturation conditions for the measurements on the mini cores were well defined, we used their velocities to calibrate the model.

Fig. 3 shows two crack orientations measured using different microscope magnifications from the same thin section. The crack orientation measured with higher magnification shows a higher amount of irregularity. Because the UV light beam is focused by the microscope optics, higher microscope magnification results in a higher energy density of the UV light beam and smaller cracks, filled with luminous epoxy resin, become visible.

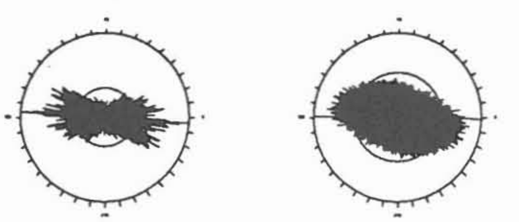


Fig. 3 left: crack orientation measured with 25x lens
right: crack orientation measured with 63x lens

The increase of irregularity with increasing resolution reflects the increasing amount of very small irregular grain boundary cracks. For this reason we described the pore space of the specimen by two models.

The first model represents the larger cracks, well aligned in the foliation plane with opening widths of about 1µm and aspect ratios of about 1:100 (90% of the pore volume).

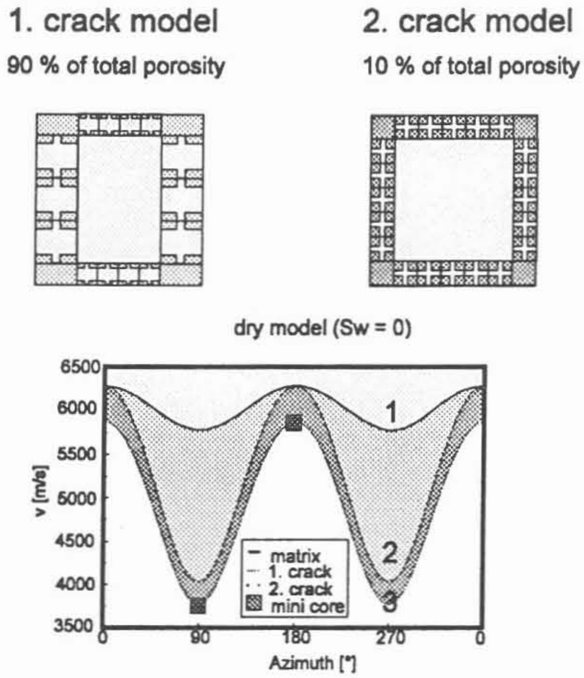


Fig 4: crack models, calculated and measured velocities of the dry specimens

The second model involves the very small irregular grain boundary cracks (10% of the pore volume).

In the plot of velocity versus angle to the foliation plane (Fig. 4) curve 1 represents the influence of the matrix material. The squares are the measured values of the dry mini cores. Curve 2 results from the first pore space model, which shows a high velocity anisotropy. This model can not explain the observed velocity decrease of the mini core drilled parallel to the foliation plane compared to the matrix velocity The combination of both pore space models (the matrix material of model 1 is described by model 2) shows velocities (curve 3) which agree with the measured values.

Cracks are probably water saturated under in-situ conditions. For this reason the transition from the dry to the saturated state is of particular interest.

A well known theory for this transition is the GASSMANN conversion. The application of this theory to the calculated velocities for the dry state results in a velocity increase of 15 - 30m/s for the saturated state.

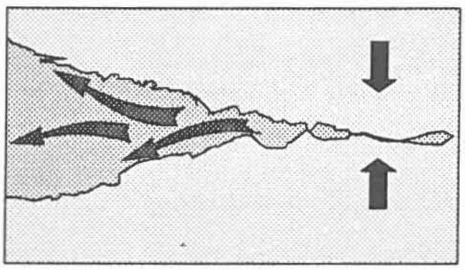


Fig 5: Example of a fluid flow model - Squirt model

A basic assumption of this theory is the absence of a pressure gradient in the pore fluid. This assumption is valid, if the squeeze out of pore fluid from regions of higher deformation takes place so slowly that no pressure gradients are generated. This theory is, therefore, called static derivation and it describes the lower limit of the effectiveness of the pore fluid.

For the model used in this investigation, the assumption is that no fluid flow occurs. This assumption is valid if the compression and dilation is so fast that friction and inertia avoid fluid flow. In this case pressure gradients occur in the pore fluid. This theory describes the upper limit of the effectiveness of the pore fluid.

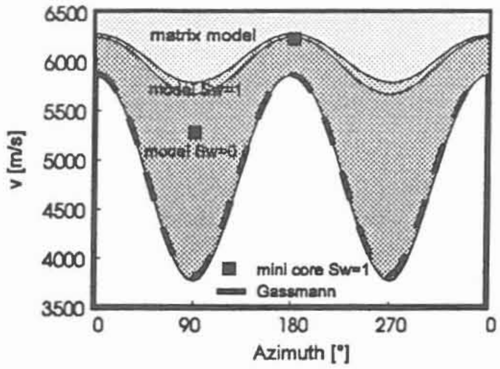
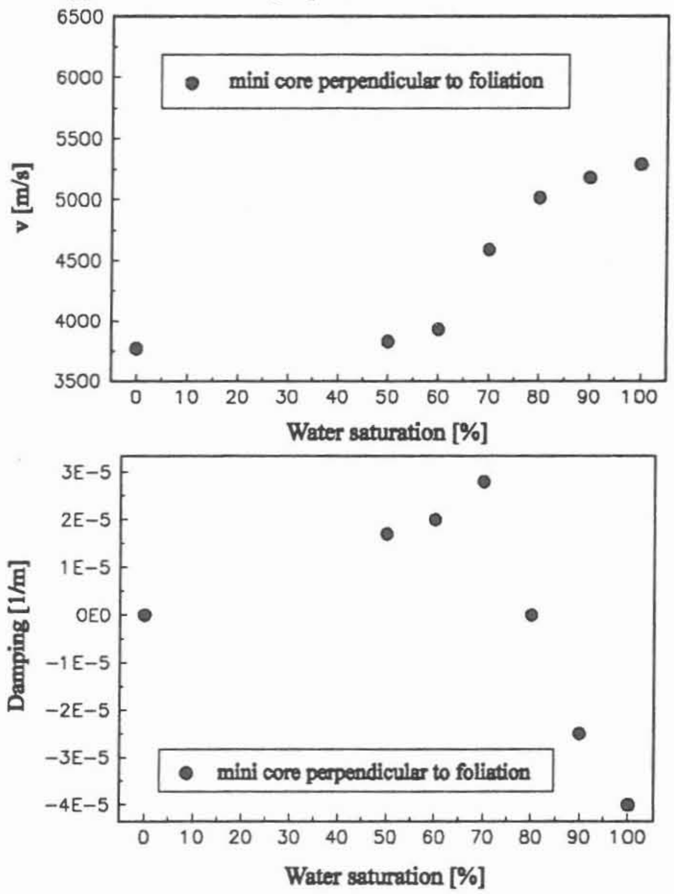


Fig. 6: Transition to the water saturated case Sw=1

The calculated velocities for wave propagation parallel to the foliation plane agrees very well with the measured values. For wave propagation perpendicular to the foliation plane the model predicts velocities which are higher than the measured (Fig. 6). This behavior indicates that fluid flow mechanisms are active.

Measurements of velocity and damping as function of saturation can give information about the occurrence of fluid flow mechanisms (Fig. 7).

The damping refers to the dry specimen. This means that positive values represent a lower transmission of wave energy and negative values a higher transmission of wave energy than in the dry specimen.



Up to a saturation of about 60% the velocity increase is very weak and the damping increases. This behavior indicates that the fluid reacts with fluid flow. For higher saturations the velocity increase is much stronger due to an increasing elastic reaction of the pore fluid.

These investigations show that in the case of partial water saturation fluid flow effects exists but there is no evidence for the occurrence of these effects in the saturated state.

The decrease of damping for saturations higher than 70% confirmed with this interpretation.

Fig. 7: Velocity and damping versus saturation

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Summary

We have attempted to describe the elastic properties of gneiss core of the KTB pilot hole using a fractal model.

As input parameters the model uses information about the mineralogical composition, the texture and structure of the rock. The orientation and geometry of the cracks were measured with an automatic image analysis system. An observed scale effect (increase in irregularity of crack orientation with increased magnification) was taken into account for the modelling.

The calculated velocities for the dry case compare very well with the measured velocities. For the saturated case, the measured and calculated velocity for the mini core drilled parallel to the foliation plane agree. For the mini core drilled perpendicular to the foliation, the calculated velocity is higher then the measured, which indicates that fluid flow mechanisms occur. The investigation of velocity and damping as function of saturation provides evidence for the occurrence of these effects in the partially saturated state.