Title
Frequency scaling for evaluation of shale and mudstone properties from accoustic velocities

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Reliable estimates of subsurface porosity is an important problem in the geosciences. Transport processes such as heat and water flow, or migration of particles are studied in many environmental applications, and rely on accurate porosity estimates. Furthermore, seismic site response studies, which determine a change in ground displacement due to stress changes during earthquakes, depend on porosity of the material under investigation. Yet current methods to determine subsurface porosity rely on point or line measurements in boreholes which are extrapolated to larger distances. It is clear that this method is very limited and produces questionable results at best. Therefore, an approach is needed that provides in-situ porosity measurements at larger scales and dimensions. In the current study, we present a method to estimate porosity over large areas based on scattered seismic energy.

Subsurface porosity occurs on all scales from micropores to large cavities. If information on the background material is available (e.g. the seismic velocity of the background matrix) it is possible to image the concentration of the larger pores in space. In this model the background information already contains the effect of micro-scale porosity and possible fracturing. Examples of larger pores are present in volcanic deposits where cooling processes have introduced gas inclusions that vary in size between a few inches up to one foot or more. Limestone deposits may also exhibit a high degree of porosity created by leaching or washout mechanisms. These voids represent strong scatterers and the application of linearized methods like the Born approximation, for example, will produce doubtful results. We explore a possibility to apply scattering theory to estimate the porosity without considering interaction between scatterers (single scattering theory). The voids in the medium affect the amplitudes as well as the phases of the scattered seismic waves , and in the Rayleigh regime the relationship between the concentration of porosity and phase shift becomes attractively simple. Thus porosity can be directly estimated from travel time measurements. We present modeling results based on laboratory data that estimate the distribution of porosity from travel times of seismic waves. A general finding is that the relative change in seismic velocity is approximately equal to 50% of the porosity value.

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Frequency Scaling for Evaluation of Shale and Mudstone Properties from Acoustic Velocities

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In subsurface oil and gas exploration, seismic wave (stress wave) measurement is one of the most important tools for determining the properties of overburden and predicting reservoir conditions such as pore pressure, fracture gradient, and stress distribution. To achieve detailed and reliable knowledge of the reservoir, an integrated analysis can be performed on the seismic properties of rocks measured at different scales ranging from laboratory core, boreholes (well logging) and reservoir itself (surface seismic). However, particularly for sedimentary rocks containing a large amount of clay minerals, such integration is not a straightforward task because of velocity dispersion that makes waves of different frequencies travel at different velocities.

The ultimate goal of this study is to devise a methodology for frequency scaling based on laboratory measurements of wave propagation at different frequency ranges. To this end, we have examined the mechanical and acoustic (seismic) properties of strongly dispersive sedimentary rocks. Shales were selected as principal rocks of interest for their predominance in the overburden and the direct impact on the well construction cost. Two types of shales were cored from outcrops(Pierre I and Mancos) and tested under varying conditions of loading (hydrostatic versus uniaxial-strain), orientation to bedding (parallel, perpendicular and oblique). Wave measurements were conducted under four ranges of frequency: Static and quasi-static (seismic frequency, approximately 7 Hz) data was obtained from high-accuracy, low-speed stress-strain measurements, and sonic data (0.4 kHz-9 kHz) was obtained from gas-confined resonant bar tests. For ultrasonic data (150 kHz-1 MHz), a frequency-domain phase analysis was applied to compute frequency-dependent phase and group velocities. Over these ranges, both Pierre and Mancos shales showed a smooth and monotonic increase in compressional and shear wave velocities with frequency. Strong velocity dispersion occurred in the range from 10 kHz to 1 MHz for Pierre shale, and 1 kHz to 1 MHz for Mancos shale. However, for both shales, resonance measurements were representative (within 20%) of static and quasi-static measurements. In contrast, velocities from the ultrasonic measurements were approximately 45% higher than the static and quasi-static measurements.

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Discrete Element Models of Seismic Wave Propagation in Sediments

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The propagation of seismic waves through heterogeneous sediments is a topic of major importance , particularly in reservoir exploration. In order to develop a better understanding of wave propagation through sediments, we employ a numerical model based on the discrete element method (DEM) used in modeling granular materials. An advantage of this method is that one can readily explore a large range of heterogeneity in grain properties, such as size and bulk modulus, as well as a variety of spatial distributions of those properties.

Discrete element models (e.g. Cundall and Strack, 1979) have been used to study the deformation of granular materials under a wide variety of conditions. In this method, a small (10^3 to 10^4) set of simple (2D circular) model grains is defined. The pore space between the grains is taken to have zero bulk modulus, so these models represent drained sediments. Grains interact with specified elastic and frictional forces. The elastic forces can be both repulsive and attractive, allowing simulation of both non-cohesive and cohesive sediments. The position, velocity and acceleration of each grain is tracked through time, in response to external loads. One side of the sample is subjected to a single time-dependent pulse in normal force, sending a compression wave into the sample. The subsequent accelerations of the opposing side give the acoustic wave speed in the granular material as well the attenuation of the wave form.

Initial experiments were conducted with non-cohesive grains in a system with a limited range of grain sizes (factor of 3). In such a system, the 2-D porosity is 18-19%. This system shows significant attenuation of the input wave and yeild a velocity that is about 15% slower than the acoustic velocity within a grain. We will examine the effect of pressure on seismic velocity and compare this with theoretical models. We will also explore the relationship between applied non-hydrostatic stresses and anisotropy.

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In situ Experimental Investigation on Rock Strength; Consequences for vertical stress profiles

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It is widely assumed that vertical profiles of stress magnitude in the upper crust are controlled by friction along preexisting faults. This is mostly based on stress determination in deep boreholes together with results from lab experiments on friction. Another approach to this problem is the analysis of failure processes induced in situ by water injection at sufficiently large flow rates. Such an experimentation has been conducted in granite at depth ranging from 2800 m to 3600m. The injection rate was increased every other day until pressure stabilized for about three days. Induced seismicity was observed in particular with downhole accelerometers. Principal stress directions are well constrained by borehole observations. Four different steps are observed: for injection pressure lower than 4 Mpa, no induced seismicity; for wellhead injection pressure ranging between 4 to about 8 Mpa, roughly axisymmetrical growth around the injection zone; from about 8 Mpa to 10 Mpa growth in a direction inclined about 30° to the maximum principal stress direction; once pressure stabilizes at 10 Mpa, growth in the maximum horizontal principal stress direction and upward. It is proposed that the initial growth of the seismic cloud is linked to the percolation of fluid through the intact rock mass. The second phase involves the failure of the rock mass in shear. The third phase, when pressure stabilizes, is associated with the growth of a zone normal to the minimum principal stress direction. Hence, clearly, in this experiment the growth of the seismic cloud cannot be linked uniquely to the permeability of the intact rock nor can the inception of induced seismicity be taken as the sign of large-scale failure inception. By analogy with results from the laboratory, the three induced seismicity phases yield clews for identifying the limit of elasticity of the rock mass and the criterion of failure that satisfies best the inception of failure. Again, by comparison with results from the laboratory, it is concluded that failure has extended throughout the rock mass and not through a single preexisting structure. At the scale of this experiment, about 800m high and 500m wide, it is concluded that the failure process is not dominated by the strength of a few well identified preexisting zones of weakness. Hence, at this scale, vertical stress profiles are not likely linked simply to frictional characteristics of weakness zones.

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In Situ Measurement of Electrical Resistivity of Deep Sea Sediments: Results From Cascadia Basin, Eastern Flank of Juan de Fuca Ridge.

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The electrical properties of deep sea sediments are linked to other physical properties through a series of empirical relationships. They allow the calculation of thermal conductivity from porosity which is derived from electrical resistivity using Archie's Law. In order to complement in situ thermal conductivity measurements made with our violin-bow type heat probe, we designed and built a sensor which is attached to the tip of our probe and allows to measure a continuous profile of electrical resistivity - and therefore porosity and calculated thermal conductivity - as the heat probe penetrates the seafloor.

The operating principle of our sensor is based on two identical 4-point electrode arrays arranged on the circumference of the sensor tip and separated by 10 cm. They are mounted in an electrically insulating, highly abrasion resistant plastic material. Both arrays are operated independently. A DC constant power source delivering 10 mA is reversed with a frequency of 1000 Hz to provide a 500 Hz alternating rectangular waveform current. The resulting signal at the electrodes is measured in a time-multipexed fashion with a final frequency of 250 Hz. Data are digitized and stored on a hard drive under control of a Tattletale data logger. Penetration is monitored by a pressure and acceleration sensor. The signal of the latter is used to convert the recorded electrical signals from time to depth.

We will present results from multi-penetration measurements along profiles located at the Eastern flank of the Juan de Fuca Ridge and also from a site on Cascadia Margin, where on previous cruises Canadian colleagues cored gas hydrate bearing sediments. The measurements were made during cruise SO-149 (fall 2000) on the German research vessel SONNE. Our data show that we are able to measure high resolution resistivity profiles over a depth range of 3 - 4 m which allow to characterize the overall porosity of the sediments and to identify turbidite layers present everywhere in Cascadia Basin. The calculated porosities are compared with existing porosity data from the same area. The developed instrument worked very reliably and delivered data of very good quality. Of course the sensor and its electronics can also be used separately for spatially detailed geotechnical work in shallow water.

URL: http://www.geophys2.uni-bremen.de