Rock mechanics - relevant for the petrophysicist?

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About 10% of the drilling costs (which are in the order of 10^7 – 10^8 $ per well) can be ascribed to mechanical instability of the rock surrounding the borehole. Losses in the order of similar amounts may be encountered if solids production becomes a problem. In fact, lack of mechanical stability of the rocks that makes up the hydrocarbon reservoirs and the formations above may effectually prohibit hydrocarbon production in some cases. Rock mechanics is also a key issue for reservoir compaction, which may have a strong impact on the development of the reservoir pressure and permeability during depletion. In some cases, surface subsidence is also a problem. Rock mechanics is also an important element in the planning of stimulation and IOR operations.

For the petrophysicist, rock mechanics plays an important role in two ways:

1. Petrophysical measurements are affected by the mechanical state of the rock in which the measurements are done.
2. Prediction of sanding problems, borehole instabilities, reservoir compaction etc. require geomechanical data, which to some extent may be derived from petrophysical measurements, or obtained by similar methods.

Hence, a petrophysicist needs to take rock mechanics into account to properly correct his measurements, and he may on the other hand provide critical input for rock mechanical analyses.

Stress dependent rock properties

Rock mechanics is an issue for the petroleum industry mainly because of the fact that the formations *in situ* are subject to high stresses, due to the weight of the overlaying rock. A part of this weight is carried by the pore fluid. The net load taken by the solid framework of the rock is called the *effective stress*. For weak rocks, the effective stress is simply given as the total stress minus the fluid pressure. From a rock mechanical point of view, it is the effective stress, and what it may do to the solid framework of the rock, that is of interest.

Changes in the effective stresses may induce changes in the rock properties. Ultimately, if the stress state exceeds the strength of the rock, it fails. This is usually caused by large shear stresses, which occur when the stresses in different directions are largely different. Prior to failure, however, significant alterations of the rock properties may occur, as illustrated in Figure 1. We see that at high stress levels (indicated by the arrow on the figure), the relationship between stress and strain is no longer linear. This is an indication of damage in the rock. Also, at these stress levels the acoustic velocities are decreasing, again an indication of stress induced damage. By means of modern computer technology we may simulate the rock failure process on a grain-scale level. This gives us an indication of how the damage develops during the failure test, and allows us to visualize it (see for instance Li and Holt, 2002). Figure 1 gives an example.

Changes in the stress state of a porous rock usually changes the porosity. This makes the permeability stress sensitive too. For small stress changes, the permeability changes in accordance with the porosity dependence predicted by the Kozeny-Carman equation. As the rock is stressed outside the elastic regime and damage is developing, the permeability may change more dramatically. In dilatant rocks it may increase, whereas in compactive, high porosity rocks at high confining pressures permeability drops have been observed as a result of the development of compaction bands (Olsson and Holcomb, 2000). The stress dependence may also be anisotropic. Rock properties are not only sensitive to the current effective stresses. Also the rate of stress changes, and the long term stress history may have significant impact. In a sense, one may say that rocks have a certain memory of its own stress history, and behave accordingly. This effect complicates predictions of rock behavior, as we do not normally have a complete knowledge about the stress history of the rock. On the other hand, it also offers a possibility to extract information about *in situ* conditions from core measurements.

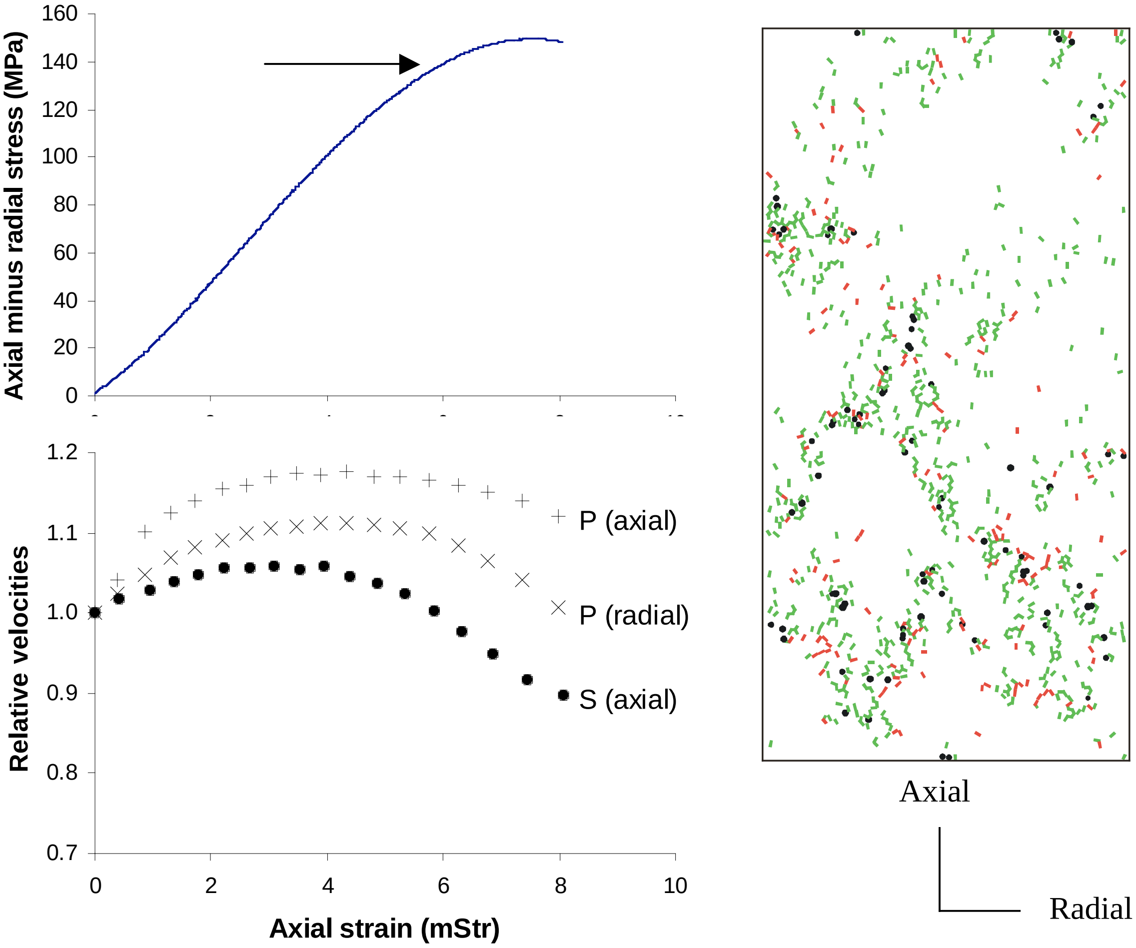

Figure 1. Failure test on a granular material. To the left is shown the stress difference and acoustic velocities versus axial strain on a core plug of a North Sea sandstone. To the right is shown a snap-shot from a PFC[1] simulation on a 2-dimensional sample of cylindrical discs, at a stress level corresponding to the level indicated by the arrow in the figure to the left. Red: tensile cracks, green: shear cracks, black: broken grains.

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Rock mechanics in the near wellbore region

The rock in the vicinity of a borehole is subject to large shear stresses, as shown in Figure 2. The figure shows that there is a region of thickness about 0.5 – 1 times the borehole radius that has a large difference between the compressive stress in the tangential and the radial directions. Rock failure leading to drilling problems is one possible consequence.

Even for an intact hole, however, stress induced rock damage may have consequences for the log measurements, as several of these are done in the part of the formation where the shear stresses have altered the rock properties. Standard long-spaced sonic tools are designed to look behind the near wellbore region, and are not affected by this. Other tools are more at risk, like the MR tool which operates at shallow depths and may be sensitive to the type of damage induced by the near well stresses (van der Zwaag *et al.*, 2002).

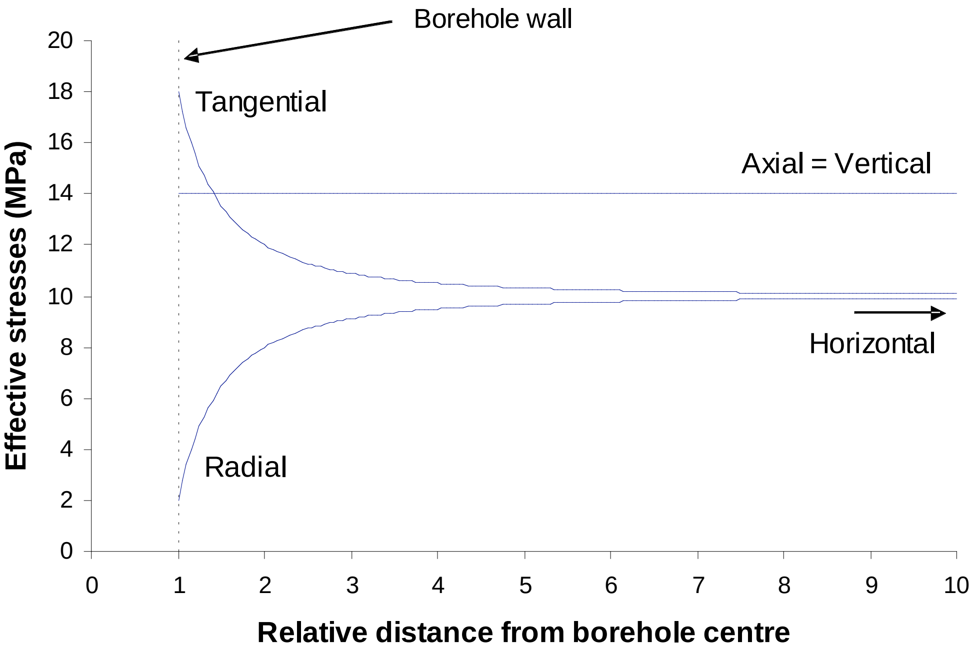

Figure . Effective stresses in the rock surrounding a vertical borehole, as predicted by linear elastic theory (*see for instance Fjær* et al.*, 1992, for an overwiew).*

Core measurements

For measurements on cores under atmospheric conditions, the consequences may be even larger. Ignoring the rocks' stress experiences may lead to significant errors in the interpretation of core measurements. A virgin rock – that is: a rock that has not previously experienced any changes in stress from its forming state – respond differently to stress changes compared to an experienced piece of rock, like a core plug. This effect is usually overlooked, since we only see the behavior of the experienced rock when we study field material in the laboratory. Studies on synthetic rocks reveal the effect, however (Holt *et al.*, 2000). In these tests, twin samples of synthetic rocks are formed by cementing sand packs under stress corresponding to a specific reservoir formation. For one of the samples the stresses are removed in a way resembling what happens to a core during the coring process. After that, the initial stress state is reestablished, and then a test simulating for instance the effect of depletion is performed. For the other sample, the same test is performed directly, without the coring-reloading cycle, to reveal the virgin behavior. It is found that the two samples respond differently; for instance, the compaction measured on the “core” may be much larger than observed for the virgin sample (Holt *et al.*, 2000). Also the stress dependence of the acoustic velocities is significantly larger for the “core” (Fjær and Holt, 1999).

It is important to notice that even a fundamental parameter as the porosity depends on the stress state and the stress history (Holt *et al.*, 2001). Proper knowledge about the *in situ* stresses, as well as suitable testing procedures, is required to obtain accurate porosity values.

Geomechanical data

Reliable prediction of borehole instabilities, sanding problems, compaction and subsidence etc. require good estimates of a set of geomechanical parameters. These are primarily the formation stresses, the pore fluid pressure, strength and stiffness of the rock. In addition, petrophysical parameters like porosity and permeability are also important. Some of these parameters, in particular the largest horizontal stress, are difficult to obtain. Also the stress changes induced during depletion are usually difficult to predict. This is very important information for prediction of reservoir compaction, permeability alterations, and drilling problems in depleted formations, for instance. It has been shown that traditional assumptions like constant overburden and no lateral deformation may be highly inaccurate (Papamichos *et al.*, 2001). New techniques for determination of *in situ* stresses based on acoustic measurements in the near wellbore region are being studied (Plona *et al.,* 1999). Others try to reveal the *in situ* stresses from the memory of the rock (Pestman *et al.,* 2002).

No technique for direct *in situ* measurement of rock strength and stiffness currently exist. Standard laboratory tests on core plugs may provide such data, however these are usually available only at a limited number of points along the well. Continuous estimates of stiffness and strength along the well can traditionally be obtained only by analyses of well logs. Such tools vary a lot in sophistication, from simple correlations with the sonic log, to more advanced analyses involving several log types. One of these is the FORMEL tool developed by SINTEF (Raaen *et al.*, 1996; a commercial version of this tool is now owned and operated by Baker Atlas), which uses the log data to provide calibration parameters for a constitutive rock model (Fjær, 1999) that is subsequently used to simulate rock mechanical tests on a fictitious core plug. The major problem with such tools is that the relations between the log data and the stiffness and strength are not trivial and well known for all materials. Another problem is the resolution, which is normally limited by the resolution of the sonic log (about 1 m). This is not sufficient in cases where the rock is layered on a smaller scale.

The most promising development towards continuous, direct strength and stiffness measurements is the scratch test. Already, this test can be used to obtain continuous logs of strength and stiffness from measurements on whole cores (Schei *et al.*, 2000). An example from a test on a core plug is shown in Figure 3. Experience indicates that the reliability of an estimate of the unconfined strength of a rock obtained from a scratch may be even better than the reliability of a standard unconfined strength test on a core plug. The resolution of a scratch measurement is typically 1”, and the test is (nearly) non-destructive. Once available, a downhole scratch tool may be the ultimate tool for *in situ* geomechanical measurements.

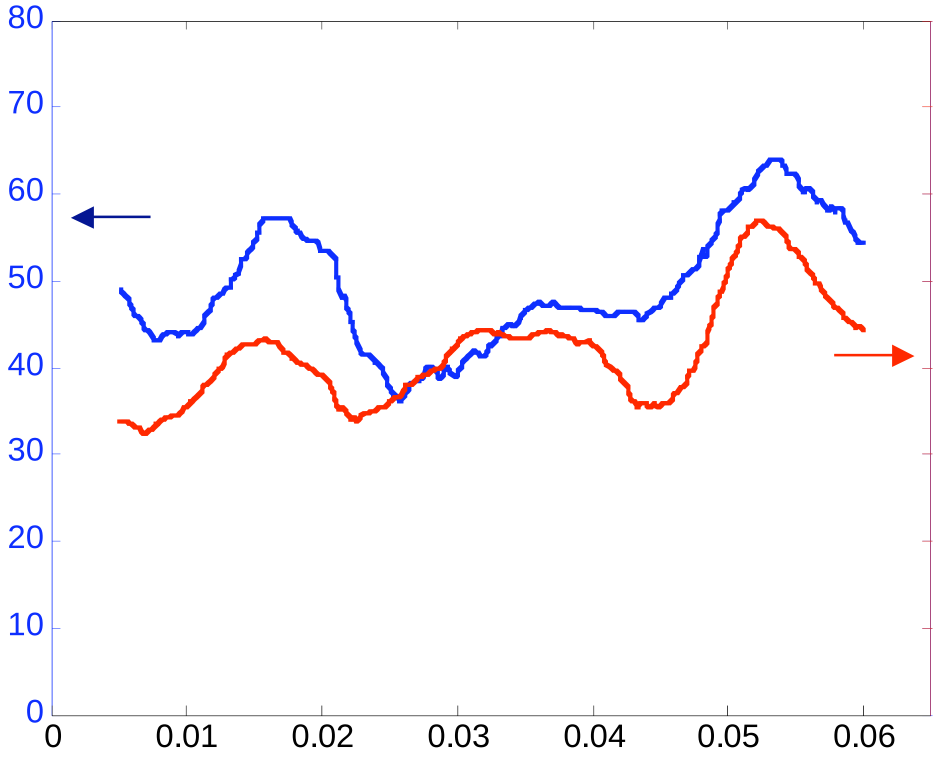

Figure 3. Strength (UCS) and stiffness (Young's modulus) versus position along a core plug of an outcrop sandstone, as derived from a scratch test. A moving average over 1 cm has been used.

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