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The Effects of Pore Pressure on the Mechanical and Physical Properties of Shales

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Résumé — Effets de la pression de pore sur les propriétés physiques et mécaniques des argilites — Le titre de cet article pose immédiatement deux questions : qu'entend-on par argilites, et qu'entend-on par pression de pore dans les argilites ? Je fournirai des réponses incomplètes mais utilisables, et j'examinerai comment la structure des argilites influence leurs propriétés mécaniques et physiques.
Mots-clés : argilite, pression de pore.

***Abstract — The Effects of Pore Pressure on the Mechanical and Physical Properties of Shales** — The title of this paper immediately raises two questions: what is meant by a shale, and what is meant by pore pressure in a shale? I will provide incomplete but workable answers to each of these, and discuss how the structure of shales influences their mechanical and physical properties.*
Keywords: shale, pore pressure.

1 THE STRUCTURE OF SHALES

My working definition of a shale is a rock that is very rich in clay minerals (typically more than 50 wt%), where there is a continuous network of compacted clay throughout the rock rather than a continuous network of hard, more-or-less equiaxed particles such as silica or calcite silt particles (Fig. 1). Clay mineral particles are usually very small, and plate-shaped; this gives the clay matrix of a typical shale a much higher specific surface area and a much lower permeability than a typical sandstone. The particles usually also have a high surface charge; this gives the material a very high water content and considerable sensitivity to the chemistry of its environment. Finally shales are often highly anisotropic (through variation of its depositional conditions, and the establishment of marked bedding or fissility), and often very weak. Many people would regard the definition in the first part of this paragraph as that of a mudrock, and would say that only fissile mudrocks should be called shales; in the oilfield, however, shale is used as a “catch-all” term, and this is how I shall use it.

There is a structural consequence of the above, which means that shales are not the end-member of a sand/shaley sand sequence, but a distinctly different structure. This is illustrated in Figure 2, which shows two hypothetical rock structures, consisting of spherical hard grains (e.g., silica) and wet clay. The constitutions of these examples (i.e., the ratio of clay content to hard particle content) are very similar, but the physical and mechanical behaviours are expected to be very different. Transport properties will differ because the shaley sand structure can sustain void spaces between the hard grains, as shown, but the matrix of the sandy shale will yield and flow to fill up such voids. The mechanics will differ because the continuous, load-bearing phase of the shaley sand is relatively stiff silica, but in the sandy shale it is relatively weak, compliant, wet clay.

For example, the permeabilities of the two structures shown in Figure 2 should be very different. In the shaley

Figure 1

Scanning electron microscope image of Jurassic shale from the Kimmeridge clay formation at Kimmeridge Bay, Dorset, England. The image shows a matrix of illite and kaolinite clay plates with good local alignment, containing more equiaxed and (in general) much larger particles of silica and calcite. Note that very few of the latter touch one another; the continuous phase is the clay. The image width is 37 microns.

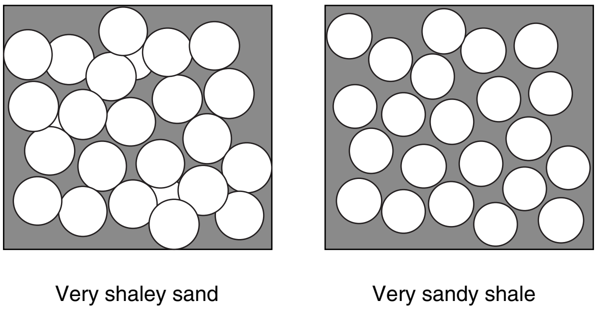

Figure 2

Hypothetical pictures of two rocks with very similar constitutions, but very different properties. The structure on the left (a network of hard particles in contact, with the intergrain space filled with a clay-water mixture and some void space) would be relatively stiff and relatively permeable, and its total porosity would decrease if the ratio of clay to hard particle were increased, i.e., if more clay were added. The structure on the right (hard particles embedded but not touching, in a matrix of clay-water mixture) would be relatively compliant and relatively impermeable, and its total porosity would increase if the ratio of clay to hard particle were increased.

sand, its value will be dominated by fluid flow though the void spaces; in the sandy shale, there are no voids, and all fluid must flow through the clay matrix. This generally has a very low permeability, and so the permeability of the rock will be much lower than that of the shaley sand. This is difficult to verify with natural materials, but an analogous system, on a different length scale, has been investigated by Shakoor and Cook (1990). They mixed rounded stones with a water/kaolinite clay paste, in a range of proportions, then measured several parameters as a function of the proportion of stones in the mixture. Between 0% and 50% stone content, the permeability was very low and relatively constant, being controlled by flow through the clay paste. At 60% and 70%, the permeability was 5 orders of magnitude higher, as the slightly higher content of stones forms a load-bearing network that allows the existence of void space. Shakoor and Cook also measured porosity as a function of stone content; as expected, porosity initially decreases from the 100% clay value as stones are added (since the non-porous stones are replacing an equal volume of clay-water mixture, in which the water occupies some porosity), then increases again (at 50-60% stones—as the stones make contact and begin to allow the presence of void space). This effect was also shown by Marion *et al.* (1989) using more fine-grained materials, and varying the compaction pressure as well as the hard particle content.

This view of the structure of shales can be used to build models for their near-DC electrical properties, and their acoustic properties, but these topics are beyond the scope of this paper.

2 THE NATURE OF PORE PRESSURE

There are several reasons why one should be careful about evaluating the pore pressure inside the pore space of a shale:

– The pore spaces are very small indeed—small-angle neutron scattering gives values of 3-8 nm (Hall *et al.*, 1983). If we construct a simplistic model for compacted clay, consisting of single layers of a clay mineral separated by water, then at 50% porosity, the pore spaces are of the order of 1 nm thick. There may be too few water molecules present in such small spaces to give a meaningful thermodynamic definition of pressure; the closeness of the clay surface may mean that the mobility of the water is restricted or even anisotropic there; on a more philosophical level it is impossible to make, or conceive of, a gauge that could measure pressure within the pore space.
– The clay surface is not generally electrically neutral; this means that there must be a high concentration of ions near the clay surfaces, and these will contribute to the rate of momentum transfer across any surface near them (which is the way that pressure is defined mechanically).
– It may not be valid to partition a macroscopic response into separate stress and pressure terms, when microscopic phenomena play such an important role.

In order to make progress, I will make a limited but workable definition of shale pore pressure—pore pressure in a shale is equal to the pressure in a permeable, non-chemically-active, medium that is in long-term equilibrium with the shale. This glosses over the problem of the microscopic definition, and helps us discuss kicks (fluid influxes into a well from permeable formations in long-term contact with highly-pressured, low permeability, shales), compaction analysis, and laboratory studies of the mechanics of non-swelling shales, but is not good enough for wellbore stability, swelling pressure, and chemomechanics.

3 IMPACT OF PORE PRESSURE ON MECHANICS

Shales have a pronounced history-dependence in their loading behaviour; their porosity is strongly-dependent on the maximum effective pressure that they have encountered in their past, and weakly-dependent on their current effective stress state. The former of these generates the compaction behaviour that is at once the source of much overpressuring in oil and gas fields, and also the means of detecting it from well-log data.

Because this aspect of shale behaviour has been extensively discussed elsewhere, and in order to keep this paper at a manageable length, the rest of this discussion will focus on the dependence of properties on the current effective stress state, i.e., the experiments shown below in this section and the next did not involve significant changes in shale porosity.

3.1 Undrained Deformation

Consider a sample of shale under a given external pressure (applied, say, through a rubber membrane, to the entire outer surface of the rock, as in a rock physics experiment) and a given internal pore pressure (evaluated as discussed in Section 2). Fluid cannot enter or leave the sample, except in the negligible quantities needed to perform a pressure measurement; i.e., any changes to the sample are “undrained”. Now if the external pressure is increased, part of the additional loading on the rock will be taken by the framework of the rock, and part by increased fluid pressure (because the rock has become smaller, but fluid cannot escape, and the rock grains are much stiffer than the fluid). The ratio of the increase in pore pressure to the increase in external pressure is called (in soil mechanics) Skempton's *B* parameter (Skempton, 1954). It is important in experiments on shales for two reasons. Many stress changes in shale are undrained, not because the boundary of the sample is a membrane but because there is not enough time to allow fluid to drain away through the very low permeability of the shale. The stiffness of shales is also in general very low (because their properties are controlled by the clay matrix), so a substantial proportion of the external pressure change can be transferred to the pore fluid.

Figure 3 shows Skempton's *B* parameter measured for a Jurassic shale, with about 12% porosity, under a range of effective pressures (external pressure-pore pressure). Measuring the *B* parameter is very demanding experimentally; the sample must be small so that drainage occurs on a reasonable timescale, and all valves, transducers and their associated volumes must be much smaller. Each datapoint covers a range of effective pressures, because both external and pore pressures change in the course of a measurement. It is clear, however, that the *B* value falls from a value close to unity as the effective pressure is increased from zero. The initial increase may be real but is more likely to be a consequence of gas present in the pores of the shale. At low effective pressures, then, these results tell us that any increase in the external pressure on a shale is almost entirely, and immediately, borne by the pore fluid; the frame has so little stiffness that it behaves more like a plastic sponge than a rock. If the pore fluid is allowed to drain away, the rock remains elastic, however, so the shale is not behaving like a soil, where drained changes are used to decrease the porosity irreversibly. The high initial *B* value, the low stiffness and the very low permeability mean that taking a sample of shale under laboratory conditions and pressurizing it in a triaxial cell, does not in fact substantially change its effective stress state, unless it is allowed to drain for what can be a very long time. Rock mechanics experiments are usually drained through the ends of the cylindrical sample; for shales it is usually necessary to drain radially instead (as in soil mechanics), shortening the path and improving the drainage geometry.

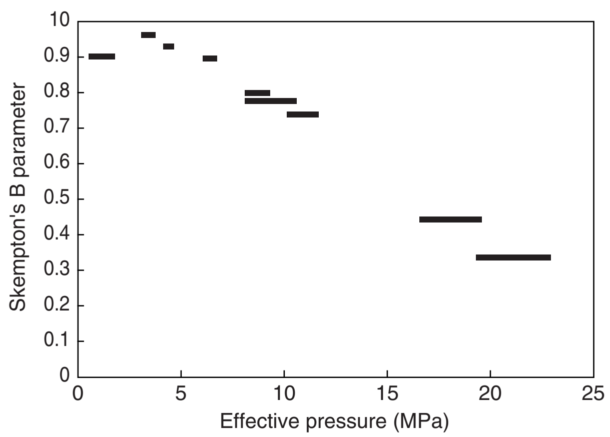

Figure 3

Skempton's *B* parameter for a Jurassic shale (porosity 12%) as a function of effective pressure. The sequence of testing was as follows: equilibrate at given values of external and pore pressures; change external pressure; wait for stabilization of pore pressure, and measure change; open pore space to atmosphere to drain fluid from system; close pore space valve and wait for equilibration again at new effective pressure value. Since the dead volume in the pore pressure measurement system must be minimized, it is not possible to use radial drains for this type of experiment, and consequently such measurements are extremely time-consuming.

3.2 Slow Deformation

It is clear from the above that in order to observe the dependence of mechanical properties on effective pressure in shales (i.e., to see the influence of changes in pore pressure), it is necessary to allow enough time to drain the pore pressure generated by external pressure changes (even though the porosity of the shale is not changing appreciably, as would normally be the case for drained testing of soils), and to apply any continuous changes (such as increasing the deviatoric stress in a triaxial test) very slowly, so that any pore pressure change built up by this has time to dissipate. Figure 4 shows peak stress (i.e., strength) versus effective pressure for a Jurassic shale, obtained when these conditions are satisfied (each datapoint taking about 8 h to collect, using 25 mm diameter samples with radial drainage). There is a significant dependence of rock strength on effective confining pressure, although it is not as strong as that typically seen for sandstones and other "conventional" rocks, and there seems to be little if any independent dependence on pore pressure alone. Thus it is safe to say that shale strength depends on effective pressure (confining pressure-pore pressure).

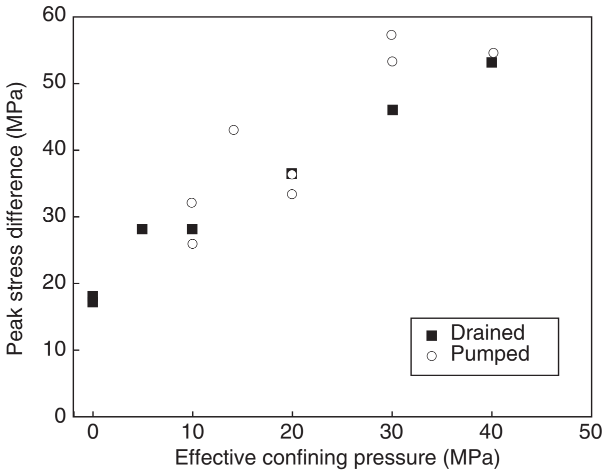

Figure 4

Peak stress difference (axial stress at peak—confining pressure) versus effective confining pressure (confining pressure—pore pressure) for Jurassic shale, loaded normal to bedding, using radial drainage and very slow deviatoric loading rates (on the order of 1E-6 s^{-1}) to assist pore pressure equilibration. The drained points have pore pressure equal to atmospheric (0.1 MPa); the pumped points have elevated pore pressure values generated by a servo-controlled pump.

3.3 Fast Deformation

If the deviatoric loading rate is increased, a different dependence of strength on effective pressure appears. This is illustrated in Figure 5, showing tests at high loading rate (well above that needed for drainage—these tests take a fraction of a second), and under conditions of constant external confining pressure (50 MPa) and various values of initial pore pressure, giving a range of initial effective confining pressures ranging from 0 to 50 MPa. Note that there is much less variation in the strength, and that the strength is high even at low initial effective pressure. For example, at zero effective pressure, we should expect, from Figure 4, the strength to be around 18 MPa; it is in fact about three times this value. At high strain rates, then, the shale appears to be much stronger than at low rates, and to have much lower dependence on effective pressure.

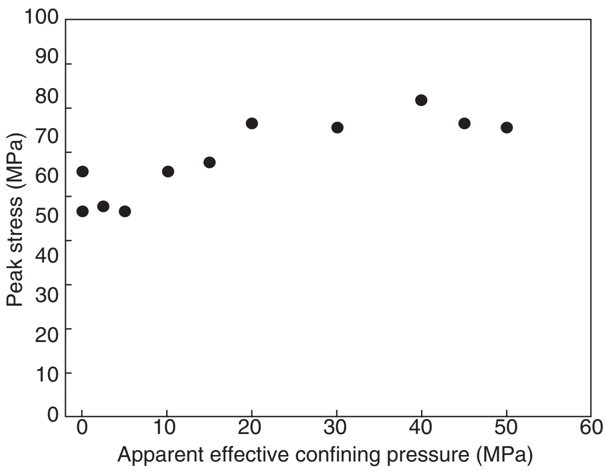

Figure 5

Peak stress difference versus apparent (i.e., initial) effective confining pressure, for a Jurassic shale tested at a strain rate of 0.27 s^{-1}. The total confining pressure was 50 MPa for all the tests.

The reason for this appearance lies in the micromechanics of deformation at high rates. Figure 6 shows an idealized picture of tensile wing crack propagation under compressive loading of an angled flaw in a brittle material—this is a widely-accepted model for rock deformation and failure (Brace and Bombolakis, 1963; Horii and Nemat-Nasser, 1985). As the axial compressive stress increases, the wing cracks lengthen, and will eventually coalesce, causing failure of the rock sample. This lengthening, however, is strongly hindered by lateral stress on the crack, holding the faces together (Ashby and Hallam, 1986). If fluid flow is included in this geometry, and the crack growth is assumed to be hindered by the *effective* stress acting on the faces, the origin of the influence of strain rate becomes clear. As the crack grows, its internal volume increases; this volume is full of fluid, and so the pressure in the fluid drops, and fluid flows in from the matrix. Under slow loading conditions, the flow of fluid is adequate to keep the fluid pressure in the crack close to the matrix or far-field pressure, and the stress acting on the crack faces is the effective confining pressure. If the rate of loading is increased, the crack tries to grow at such a rate that the additional volume cannot be refilled by fluid flow through its walls, so the pressure inside it drops, and the effective stress acting to hold the faces together increases. The growth of the crack is hindered, and becomes controlled by fluid flow rather than by external loading. If the loading rate increases further, or the permeability of the rock is very low, the fluid pressure in the crack can drop to zero (but no further), and then the stress acting to hold the crack faces together is the *total* confining pressure. This leads to the situation shown in Figure 5; the loading rate is so high, and the shale permeability so low, that as soon as microcracks form, the pressure inside them drops to zero. This means that the rock is strengthened, even at low initial effective pressure, and the dependence on effective pressure becomes a dependence on total pressure. Results from a simplified model of this process are shown in Figure 7, and its relevance to the process of drilling oilwells is discussed in Gray-Stephens *et al.* (1994).

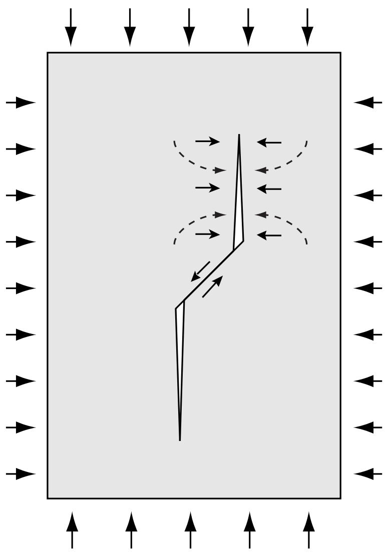

Figure 6

Idealized micromechanics of crack growth in a rock under compression. The stress state induces sliding on a pre-existing angled flaw, and tensile wing cracks grow from the tip of the flaw in the direction of the maximum principal stress. The lateral stress acts to close the crack; because it acts over the entire crack face, small lateral stresses have a big influence in hindering the growth of the wing cracks. As the wing cracks grow, fluid tries to flow from the rock matrix into the new empty space. If the flow is not fast enough to repressurize this space, the normal stress on the crack faces is increased, and the growth of the crack is further hindered.

It might be argued that the statement above (that the dependence of strength on effective pressure becomes a dependence on total pressure at high rates) is not strictly true; the mechanics of deformation on a microscopic scale are still in fact responding to effective pressure, but locally this is not equal to the apparent imposed effective pressure. This is in accord with Brace and Martin (1968) who, following an investigation of rate effects in crystalline rocks, said that the rock always obeyed the effective stress law, provided that the correct value for the effective stress was used.

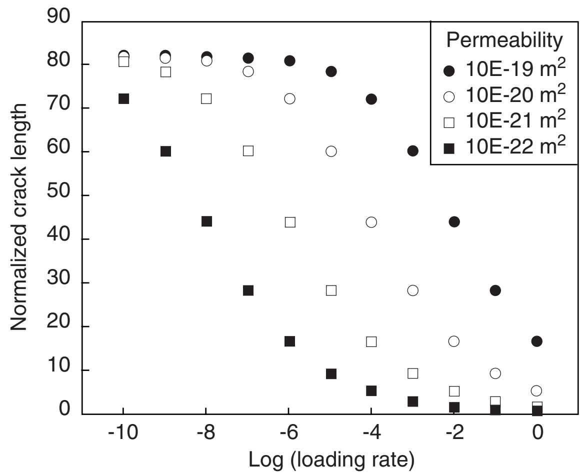

Figure 7

Results from the model of Atkinson and Cook (1993) for the hindering of crack growth caused by restricted fluid flow into the crack interior. The vertical axis is the wing crack length at the end of the loading period, normalized by the initial flaw length; the horizontal axis is the logarithm of the loading rate (rate of increase of the maximum principal stress). Crack lengths are shown for four permeability values; these bracket the very low values that have been measured for shales. As loading rate increases, or permeability decreases, the final crack length decreases; this would delay crack coalescence, and failure of the rock, until higher stresses were applied, i.e., it would strengthen the rock.

4 IMPACT OF PORE PRESSURE ON PHYSICAL PROPERTIES

Shale acoustic velocity and electrical resistivity are important in several areas of hydrocarbon exploitation: for example, both are used in the prediction and evaluation of over-pressure; seismic surveys of reservoirs make use of waves passing through the overlying shale, so improved understanding of the shales response, often anisotropic, can help to improve seismic interpretation; they can be used to estimate rock strengths for drilling mechanics and wellbore stability control.

The nature of shales makes these investigations very difficult: it takes very long times to change the effective stress state; there can be strong effects from both deviatoric and isotropic stresses; it can be very difficult to get representative samples (especially of swelling shale); there is usually pronounced anisotropy and nonlinearity; and there can be a strong influence of chemistry, especially on resistivity. The data that have been collected indicate that pore pressure (at least in nonswelling shales) has a straightforward influence on properties, through the effective stress state. Figure 8 shows the resistivity of a hard, low porosity shale, as a function of effective confining pressure. The effective pressures are obtained through different combinations of total and pore pressures, but all collapse onto a single curve, which indicates that resistivity increases with effective confining pressure, as for other rocks. This is presumably through crack closure shutting down fluid conduction pathways. Unfortunately this picture does not fit the data shown in Figure 9, which shows the resistance of the same shale under deviatoric loading (unconfined compression, normal to bedding). Here the resistance initially goes down as the applied stress increases (this phase of deformation is where it would again be expected that cracks were closing), then increases again (in the phase where we would expect new cracks to be formed, producing better fluid pathways for conduction). Similar experiments on a sandstone produced the expected behaviour. The author has no satisfactory explanation for these discrepancies.

CONCLUSIONS

Shales are exceptionally difficult materials to work with, for a variety of reasons discussed above. Some progress has been made in understanding their properties, by simplifying and restricting the areas which have been investigated. In the work above, for example, the shales contained negligible montmorillonite clay, and had negligible swelling response. They were also kept at essentially constant porosity, by ensuring that the effective stress state did not exceed the previous maximum value. Their anisotropy has been neglected (in the discussion, rather than in the experiments). It is possible to carry out experiments when these restrictions are relaxed, but they become even more difficult; for example, drainage times for a shale undergoing irreversible compaction, rather than the reversible changes in effective stress state discussed above, are much longer, as much more fluid must be expelled. If the shale contains montmorillonite, great attention must be paid to the ionic chemistry of its environment during the experiment.

There is therefore a good deal of work still to be done in the area, which can have a significant impact on the economics of hydrocarbon extraction.

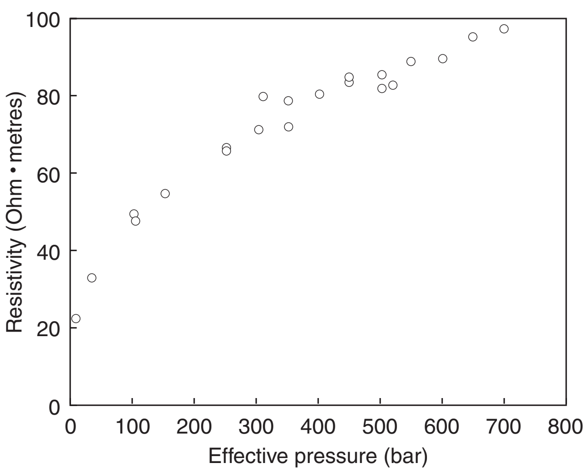

Figure 8

Electrical resistivity normal to bedding (at 5 kHz) versus effective confining pressure, for a hard Carboniferous shale. The datapoints include both atmospheric and non-atmospheric pore pressure values.

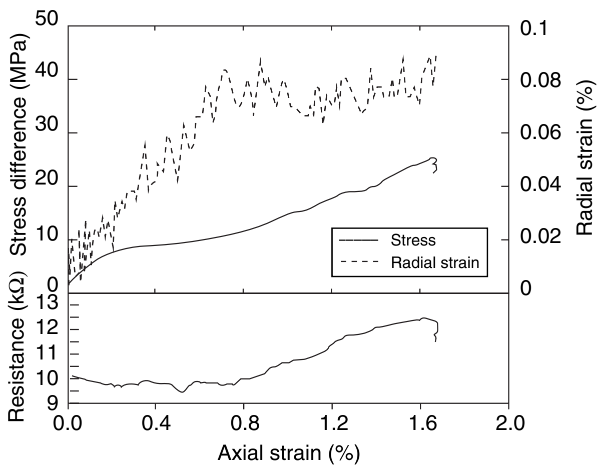

Figure 9

Axial stress, radial strain (somewhat noisy) and axial electrical resistance (at 5 kHz) versus axial strain, for a hard shale under uniaxial compressive loading.

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